Draft Technical Assessment Report:

Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025

United States Environmental Protection Agency

California Environmental Protection Agency
Air Resources Board

NHTSA
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

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Office of Transportation and Air Quality
U.S. Environmental Protection Agency

National Highway Traffic Safety Administration
U.S. Department of Transportation

And

California Air Resources Board

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List of Acronyms

2MHEV	2-Mode Hybrid
ABS	Anti-lock Braking System
ABT	Averaging, Banking, and Trading
AC	Alternating Current
A/C	Air Conditioning
ACEEE	American Council for an Energy-Efficient Economy
AEO	Annual Energy Outlook
AER	All-Electric Range
AFDC	Alternative Fuels Data Center
AGM	Absorbent Glass Mat
AHSS	Advanced High Strength Steel
ALPHA	Advanced Light-Duty Powertrain and Hybrid Analysis Tool
AMT	Automated Manual Transmission
ANL	Argonne National Laboratory
ARB	California Air Resources Board
ASI	Area Specific Impedance
ASL	Aggressive Shift Logic
ASM	Annual Survey of Manufacturers
AT	Automatic Transmissions
Avg	Average
AWD	All Wheel Drive
BenMAP	Benefits Mapping and Analysis Program
BEV	Battery Electric Vehicle
BISG	Belt Integrated Starter Generator
BIW	Body-In-White
BLS	Bureau of Labor Statistics
BMEP	Brake Mean Effective Pressure
BOM	Bill of Materials
BSFC	Brake Specific Fuel Consumption
BTE	Brake-Thermal Efficiency
BTU	British Thermal Unit
CAA	Clean Air Act
CAD	Computer Aided Designs
CAD/CAE	Computer Aided Design And Engineering
CAE	Computer Aided Engineering
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CBD	Center for Biological Diversity
CBI	Confidential Business Information
CCP	Coupled Cam Phasing
CDPF	Catalyzed Diesel Particulate Filter
CEC	California Energy Commission

CES	Consumer Expenditure Survey
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CH_4	Methane
CISG	Crank Integrated Starter Generator
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2eq	CO2 Equivalent
COP	Coefficient of Performance
CSM	Conceptual Site Model
CSV	Comma-separated Values
CUV	Crossover Utility Vehicles
CVT	Continuously Variable Transmission
CY	Calendar Year
DC	Direct Current
DCFC	Direct Carbon Fuel Cell
DCP	Dual Cam Phasing
DCT	Dual Clutch Transmission
DEAC	Cylinder Deactivation
DFMA^{TM}	Design for Manufacturing and Assembly
DGS	California Department of General Services
DICE	Dynamic Integrated Climate and Economy
DMC	Direct Manufacturing Costs
DoE	Department of Energy
DOE	Design of Experiments
DOHC	Dual Overhead Camshaft Engines
DOT	Department of Transportation
DRI	Dynamic Research, Inc.
DRLs	Daytime Running Lamps
DVVL	Discrete Variable Valve Lift
EGR	Exhaust Gas Recirculation
EHPS	Electrohydraulic Power Steering
EIA	Energy Information Administration (part of the U.S. Department of Energy)
EISA	Energy Independence and Security Act
EIVC	Early Intake Valve Closing
EPA	Environmental Protection Agency
EPCA	Energy Policy and Conservation Act
EPRI	Electric Power Research Institute
EPS	Electric Power Steering
EPS	Energy Power Systems
EREV	Extended Range Electric Vehicle

ERM	Employment Requirements Matrix
ESC	Electronic Stability Control
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FARS	Fatality Analysis Reporting System
FCEV	Fuel Cell Electric Vehicle
FCPM	Fuel Cost Per Mile
FCEV	Fuel Cell Electric Vehicle
FE	Finite Element
FEV1	Functional Expiratory Volume
FHWA	Federal Highway Administration
FMEP	Friction Mean Effective Pressure
FMVSS	Federal Motor Vehicle Safety Standards
FR	Federal Register
FRIA	Final Regulatory Impact Analysis
FRM	Federal Rulemaking
FRM	Federal Reference Method
FTP	Federal Test Procedure
gal/mi	Gallon/Mile
GCWR	Gross Combined Weight Rating
GDI	Gasoline Direct Injection
GDP	Gross Domestic Product
GEM	Greenhouse gas Emissions Model
GHG	Greenhouse Gases
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GVW	Gross Vehicle Weight
GWP	Global Warming Potential
GWU	George Washington University
HD	Heavy-Duty
HEV	Hybrid Electric Vehicle
HFC	Hydrofluorocarbon
HFET	Highway Fuel Economy Dynamometer Procedure
HIL	Hardware-In-Loop
hp	Horsepower
hrs	Hours
HP/WT	Horsepower Divided by Weight
HVAC	Heating, Ventilating, And Air Conditioning
hz	Hertz
IACC	Improved Accessories
IAM	Integrated Assessment Models
IATC	Improved Automatic Transmission Control
IC	Indirect Cost

ICCT	International Council on Clean Transport
ICF	ICF International
ICM	Indirect Cost Multiplier
ICMs	Indirect Cost Markups
IHX	Internal Heat Exchanger
IMA	Improved Mobile Assist
IMAC	Improved Mobile Air Conditioning
INL	Idaho National Laboratory
IOU	Investor Owned Utilities
IPCC	Intergovernmental Panel on Climate Change
IPM	Integrated Planning Model
ITC	Institute of Transportation Studies
IWG	Interagency Working Group
k	Thousand
kg	Kilogram
kW	Kilowatt
kWh	kilowatt-hour
L	Liter
lb	Pound
LBNL	Lawrence Berkeley National Laboratory
LD	Light-Duty
LEV	Low-Emission Vehicle
LHD	Light Heavy-Duty
LDV	Light Duty Vehicle
LNT	Lean NOx Trap
LRR	Lower Rolling Resistance
LT	Light Trucks
LWT	Lightweighted Pickup Truck
MAD	Minimum Absolute Deviation
MBPD	Million Barrels Per Day
MD	Medium-Duty
MDPV	Medium-Duty Passenger Vehicles
MEMA	Motor Equipment Manufacturers Association
Mg	Megagrams
mg	Milligram
MHEV	Mild Hybrid
mi	mile
min	minimum
min	Minute
MM	Million
MMLV	Multi-Material Lightweight Vehicle
MMT	Million Metric Tons
MOVES	Motor Vehicle Emissions Simulator

mpg	Miles per Gallon
mph	Miles per Hour
MPV	Multi-Purpose Vehicle
MSRP	Manufacturer's Suggested Retail Price
MTE	Mid Term Evaluation
MuD	Multi-Unit Development
MY	Model Year
N_2O	Nitrous Oxide
NA	Not Applicable
NAAQS	National Ambient Air Quality Standards
NADA	National Automobile Dealers Association
NAS	National Academy of Sciences
NCA	National Climate Assessment
NCAP	New Car Assessment Program
NEMS	National Energy Modeling System
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NF_3	Nitrogen Trifluoride
NGO	Non-Governmental Organization
NHTSA	National Highway Traffic Safety Administration
NiMH	Nickel Metal-Hydride
NF_3	Nitrogen Trifluoride
NOX	Nitrogen Oxides
NO_2	Nitrogen Dioxide
NO_x	Oxides of Nitrogen
NPRM	Notice of Proposed Rulemaking
NRC	National Research Council
NRC-CAN	National Research Council of Canada
NREL	National Renewable Energy Laboratory
NVH	Noise Vibration and Harshness
NVPP	National Vehicle Population Profiles
OAR	EPA's Office of Air and Radiation
OEM	Original Equipment Manufacturer
OECD	Organization for Economic Cooperation and Development
OHV	Overhead Valve
OLS	Ordinary Least Squares
OMB	EPA's Office of Management and Budget
OPEC	Organization of Petroleum Exporting Countries
ORNL	Oak Ridge National Laboratory
OTAQ	EPA's Office of Transportation and Air Quality
PAGE	Policy Analysis of the Greenhouse Effect
PC	Passenger Car
P/E	Power-to-Energy
PEF	Peak Expiratory Flow

PEV	Plug-in Electric Vehicle
PFCs	Perfluorocarbons
PFI	Port-fuel-injection
PGM	Platinum Group Metal
PHEV	Plug-in Hybrid Electric Vehicle
PLM	Planar Layered Matrix
PM	Particulate Matter
$PM_{2.5}$	Fine Particulate Matter (diameter of 2.5 µm or less)
PMSMs	Permanent-Magnet Synchronous Motors
PSHEV	Power-split Hybrid
PSI	Pounds per Square Inch
PWM	Pulse-width Modulated
R&D	Research and Development
RFS2	Renewable Fuel Standard 2
RIA	Regulatory Impact Analysis
RPE	Retail Price Equivalent
RPM	Revolutions per Minute
RSM	Response Surface Models
RTI	RTI International (formerly Research Triangle Institute)
SA	Strategic Analysis, Inc.
SAB	Science Advisory Board
SAB-EEAC	Science Advisory Board Environmental Economics Advisory Committee
SAE	Society of Automotive Engineers
$SC0_3$	Soak Control third iteration
SCC	Social Cost of Carbon
SCR	Selective Catalyst Reduction
SF_6	Sulfur Hexafluoride
SGDI	Stoichiometric Gasoline Direct Injection
SHEV	Strong Hybrid Electric Vehicles
SI	Spark-Ignition
SIDI	Spark Ignition Direct Injection
SIL	Software-In-Loop
SMDI	Steel Market Development Institutes
SNAP	Significant New Alternatives Policy
SNPRM	Supplemental Notice of Proposed Rulemaking
SO_2	Sulfur Dioxide
SO_x	Sulfur Oxides
SOC	State of Charge
SOHC	Single Overhead Cam
SOL	Small Overlap
SPR	Strategic Petroleum Reserve

Std	Standard
SUV	Sport Utility Vehicle
TAR	Technical Assessment Report
TC	Total Costs
TCIP	Tire Consumer Information Program
TDC	Top Dead Center
Tds	Direct Solar Transmittance
TFECIP	Tire Fuel Efficiency Consumer Information Program
TPE	Total Primary Energy
TRBDS	Turbocharging and Downsizing
TSD	Technical Support Document
UMTRI	University of Michigan Transportation Research Institute
UTQGS	Uniform Tire Quality Grading Standards
V2V	Vehicle-To-Vehicle
VGI	Vehicle Grid Integration
VIF	Variance Inflation Factor
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compound
VSL	Vehicle Speed Limiter
VVL	Variable Valve Lift
VVT	Variable Valve Timing
WT/FP	Weight Divided By Footprint

Executive Summary

The Environmental Protection Agency (EPA) and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) have established a coordinated program for Federal standards for greenhouse gas (GHG) emissions and corporate average fuel economy (CAFE) for light-duty vehicles.[1] This program was developed in cooperation and alignment with the California Air Resources Board (CARB) to ensure a single National Program. The National Program established standards that increase in stringency year-over-year from model year (MY) 2012 through MY2025 for EPA and through MY2021 for NHTSA. California adopted the first in the nation GHG standards for light-duty vehicles in 2004 for MY2009-2016, and in 2012 for MY2017-2025, followed by amendments that allow compliance with the Federal GHG standards as compliance with the California GHG standards, in furtherance of a single National Program. Under the National Program, consumers continue to have a full range of vehicle choices that meet their needs, and, through coordination with the California standards, automakers can build a single fleet of vehicles across the U.S. that satisfies all GHG/CAFE requirements. In the agencies' 2012 final rules establishing the MY2017-2025 standards for EPA and 2017-2021 final and 2022-2025 augural standards for NHTSA, the National Program standards were projected by MY2025 to double fuel economy and cut GHG emissions in half, save 6 billion metric tons of carbon dioxide (CO_2) pollution and 12 billion barrels of oil over the lifetime of MY2012-2025 vehicles, and deliver significant savings for consumers at the gas pump.

The rulemaking establishing the National Program for MY 2017-2025 light-duty vehicles included a regulatory requirement for EPA to conduct a Midterm Evaluation (MTE) of the GHG standards established for MYs 2022-2025.[i] The 2012 final rule preamble also states that "[t]he mid-term evaluation reflects the rules' long time frame, and, for NHTSA, the agency's statutory obligation to conduct a de novo rulemaking in order to establish final standards for MYs 2022-2025." NHTSA will consider information gathered as part of the MTE record, including information submitted through public comments, in the comprehensive *de novo* rulemaking it must undertake to set CAFE standards for MYs 2022-2025.[ii] Through the MTE, EPA must determine no later than April 1, 2018 whether the MY2022-2025 GHG standards, established in 2012, are still appropriate under section 202 (a) of the Clean Air Act, in light of the record then before the Administrator, given the latest available data and information.[iii] EPA's decision could go one of three ways: the standards remain appropriate, the standards should be less stringent, or the standards should be more stringent. EPA and NHTSA also are closely coordinating with CARB in conducting the MTE to better ensure the continuation of the National Program. The MTE will be a collaborative, data-driven, and transparent process and must entail a holistic assessment of all the factors considered in the initial standards setting.[iv]

This Draft Technical Assessment Report (TAR), issued jointly by EPA, NHTSA, and CARB for public comment, is the first formal step in the MTE process.[v] In this Draft TAR, the agencies examine a wide range of technical issues relevant to GHG emissions and augural CAFE standards for MY2022-2025, and share with the public the initial technical analyses of those issues. This is a technical report, not a policy or decision document. The information in this

[1] The agencies finalized the first set of National Program standards covering model years (MYs) 2012-2016 in May 2010[1] and the second set of standards, covering MYs 2017-2025, in October 2012.

report, and in the comments we receive on it, will inform the agencies' subsequent determination and rulemaking actions. The agencies will fully consider public comments on this Draft TAR as they continue to update and refine the analyses for further steps in the MTE process.

In this Draft TAR, EPA provides its initial technical assessment of the technologies available to meet the MY2022-2025 GHG standards and one reasonable compliance pathway, and NHTSA provides its initial assessment of technologies available to meet the augural MY2022-2025 CAFE standards and a different reasonable compliance pathway. Given that there are multiple possible ways that new technologies can be added to the fleet, examining two compliance pathways provides valuable additional information about how compliance may occur. NHTSA and EPA also performed multiple sensitivity analyses which show additional possible compliance pathways. The agencies' independent analyses complement one another and reach similar conclusions:

- A wider range of technologies exist for manufacturers to use to meet the MY2022-2025 standards, and at costs that are similar or lower, than those projected in the 2012 rule;
- Advanced gasoline vehicle technologies will continue to be the predominant technologies, with modest levels of strong hybridization and very low levels of full electrification (plug-in vehicles) needed to meet the standards;
- The car/truck mix reflects updated consumer trends that are informed by a range of factors including economic growth, gasoline prices, and other macro-economic trends. However, as the standards were designed to yield improvements across the light duty vehicle fleet, irrespective of consumer choice, updated trends are fully accommodated by the footprint-based standards.

Additionally, while the Draft TAR analysis focuses on the MY2022-2025 standards, the agencies note that the auto industry, on average, is over-complying with the first several years of the National Program. This has occurred concurrently with a period during which the automotive industry successfully rebounded after a period of economic distress. The industry has now seen six consecutive years of increases and a new all-time sales record in 2015, reflecting positive consumer response to vehicles complying with the standards.

A summary of each chapter of the Draft TAR follows.

Chapter 1: Introduction. This chapter provides a broad discussion of the National Program, explains further the MTE process and timeline, and provides additional background on NHTSA's CAFE program, EPA's GHG program, and California's GHG program. This chapter also includes an update on what the latest science tells us about climate change impacts, and the U.S.'s and California's commitments on actions to address climate change. Chapter 1 also provides a discussion of petroleum consumption and energy security.

Chapter 2: Overview of Agencies' Approach to Draft TAR Analysis. The agencies are committed to conducting the MTE through a collaborative, data-driven, and transparent process. In gathering data and information for this Draft TAR, the agencies drew from a wide range of sources to evaluate how the automotive industry has responded into the early years of the National Program, how technology has developed, and how other factors affecting the light-duty vehicle fleet have changed since the final rule in 2012. The agencies found that there is a wealth of information since the 2012 final rule upon which to inform this Draft TAR, and this information is detailed throughout the document. Chapter 2 describes these sources, including extensive state-of-the-art research projects by experts at the EPA National Vehicle and Fuel Emissions Laboratory, as well as consultants to the agencies, data and input from stakeholders, and information from technical conferences, published literature, and studies published by various organizations. A significant study informing the agencies' analyses is the National Academy of Sciences 2015 report[vi] on fuel economy technologies, which the agencies highlight in Chapter 2, and discuss throughout this document.

The analyses presented in this Draft TAR reflect the new data and information gathered by the agencies thus far, and the agencies will continue to gather and evaluate more up-to-date information, including public comments on this Draft TAR, to inform our future analyses. The agencies have conducted extensive outreach with a wide range of stakeholders – including auto manufacturers, automotive suppliers, non-governmental organizations (NGOs), consumer groups, labor unions, automobile dealers, state and local governments, and others.

Chapter 3: Recent Trends in the Light-Duty Vehicle Fleet since the 2012 Final Rule. This chapter summarizes trends in the light-duty vehicle market in the four years since the 2012 final rule, including changes in fuel economy/GHG emissions, vehicle sales, gasoline prices, car/truck mix, technology penetrations, and vehicle power, weight and footprint. Since the 2012 final rule, vehicle sales have been strong, hitting an all-time high of 17.5 million vehicles in 2015, gas prices have dropped significantly, and truck share has grown. At the same time, fuel economy technologies are entering the market at rapid rates. The agencies provide the latest available projections for vehicle sales, gasoline prices, and fleet mix out to 2025, and compare those to projections made in the 2012 final rule. This chapter also highlights compliance to date with the GHG and CAFE standards, where, for the first three years of the program (MY2012-2014), auto manufacturers have over-complied with the program.

Chapter 4: Baseline and Reference Vehicle Fleets. This chapter describes the agencies' methodologies for developing a baseline fleet of vehicles and future fleet projections out to MY2025. The GHG analysis uses a baseline fleet based on the MY2014 fleet, the latest year available for which there are final GHG compliance data. The CAFE analysis uses a MY2015 baseline fleet based on MY2015 data and sales projections provided by manufacturers in the latter half of MY2015, when production was well underway. These data sets complement one another and each yield important perspective, with the MY2014 data having the benefit of validation through compliance data, and the MY2015 data providing more recent perspective. The GHG and CAFE analysis fleets utilized similar, but separate, purchased projections from IHS-Polk for the future vehicle fleet mix out to 2025, thereby representing some of the uncertainty inherent in all reference case projections. Both analyses used data from the Energy Information Administration's Annual Energy Outlook 2015 (AEO 2015) as the basis for total vehicle sales projections to 2025, as well as for the car and truck volume mix. Although the agencies have relied on different data sources in development of the baseline fleets, we believe this combination of approaches strengthens our results by showing robust results across a range of reference case projections.

Chapter 5: Technology Costs, Effectiveness, and Lead-Time Assessment. This chapter is an in-depth assessment of the state of vehicle technologies to improve fuel economy and reduce GHG emissions, as well as the agencies' assessment of expected future technology developments through MY2025. The technologies evaluated include all those considered for the 2012 final rule, as well as new technologies that have emerged since then. Every technology has been reconsidered with respect to its cost, effectiveness, application, and lead-time considerations, with emphasis on assessing the latest introductions of technologies to determine if and how they have changed since the agencies' assessment in the 2012 final rule. These efforts reflect the significant rate of progress made in automotive technologies over the past four years since the MY2017-2025 standards were established. Technologies considered in this Draft TAR include more efficient engines and transmissions, aerodynamics, light-weighting, improved accessories, low rolling resistance tires, improved air conditioning systems, and others. Beyond the technologies the agencies considered in the 2012 final rule, manufacturers are now employing several technologies, such as higher compression ratio, naturally aspirated gasoline engines, and greater penetration of continuously variable transmissions (CVTs); other new technologies are under active development and are expected to be in the fleet well before MY2025, such as 48-volt mild hybrid systems.

In Chapter 5, the agencies also provide details on the specific technology assumptions used respectively by EPA for the GHG assessment and by NHTSA for the CAFE assessment in this Draft TAR, including the specific assumptions that EPA and NHTSA each made for each technology's cost and effectiveness, and lead-time considerations. The agencies' estimates of technology effectiveness were informed by vehicle simulation modeling approaches; NHTSA utilized the Autonomie model developed by Argonne National Laboratories for the Department of Energy (DOE), and EPA used its Advanced Light-duty Powertrain and Hybrid Analysis (ALPHA) model. The agencies look forward to public comment in this and other areas to help advance collective forecasting of technology effectiveness in the out years of the program.

It is clear that the automotive industry is innovating and bringing new technology to market at a rapid pace and neither of the respective agency analyses reflects all of the latest and emerging technologies that may be available in the 2022-2025 time frame. For example, the agencies were not able for this Draft TAR to evaluate the potential for technologies such as electric turbo-charging, variable compression ratio, skip-fire cylinder deactivation, and P2-configuration mild-hybridization. These technologies may provide further cost-effective reductions in GHG emissions and fuel consumption. The agencies will continue to update their analyses throughout the MTE process as new information becomes available.

Chapter 6: Assessment of Consumer Acceptance of Technologies that Reduce Fuel Consumption and GHG Emissions. This chapter reviews issues surrounding consumer acceptance of the vehicle technologies expected to be used to meet the MY2022-2025 standards. Since the program has been in effect since MY2012, the agencies focus on the evidence to date related to consumer acceptance of vehicles subject to the National Program standards. This evidence includes an analysis of how professional auto reviewers assess fuel-saving technologies. For each technology, positive evaluations exceed negative evaluations, suggesting that it is possible to implement these technologies without significant hidden costs. To date, consumer response to vehicles subject to the standards is positive. Chapter 6 also discusses potential impacts of the standards on vehicle sales and affordability, which are closely interconnected with the effects of macroeconomic and other market forces. Based on the agencies' draft assessments, the reduced operating costs from fuel savings over time are expected to far exceed the increase in up-front vehicle costs, which should mitigate any potential adverse effects on vehicle sales and affordability.

Chapter 7: Employment Impacts. This chapter discusses the effects of employment in the automotive sector to date, and the projected effects of the MY 2022-2025 standards on employment. Employment in the automotive industry dropped sharply during the Great Recession, but has increased steadily since 2009. The primary employment effects of these standards are expected to be found in several key sectors: auto manufacturers, auto parts manufacturing, auto dealers, fuel production and supply, and consumers. The MY2025 standards are likely to have some effect on employment, due to both the effects of the standards on vehicle sales, and the need to produce new technologies to meet the standards. Nevertheless, the net effect of the standards on employment is likely to be small compared to macroeconomic and other factors affecting employment.

Chapter 8: Assessment of Vehicle Safety Effects. This chapter assesses the estimated overall crash safety impacts of the MY 2022-2025 standards. In this chapter, the agencies first review the relationships between mass, size, and fatality risk based on the statistical analysis of historical crash data, which includes the new analysis performed by using the most recent crash data. The updated NHTSA analysis develops five parameters for use in both the NHTSA and EPA assessments to calculate the estimated safety impacts of the modeled mass reductions over the lifetimes of new vehicles in response to MY 2022-2025 GHG standards and augural CAFE standards. Second, to examine the impact of future lightweight vehicle designs on safety, the agencies also reviewed a fleet crash simulation study that examined frontal crashes using existing and future lightweight passenger car and cross-over utility vehicle designs. The study found a relationship between vehicle mass reduction and safety that is directionally consistent with the overall risk for passenger cars from the NHTSA 2016 statistical analysis of historical crash data. Next, the agencies investigate the amount of mass reduction that is affordable and feasible while maintaining overall fleet safety and as well as functionality such as durability, drivability, noise, vibration and handling (NVH), and acceleration performance. Based on those approaches, the agencies further discuss why the real world safety effects might be less than or greater than calculated safety impacts, and what new challenges these lighter vehicles might bring to vehicle safety and potential countermeasures available to manage those challenges effectively.

Chapter 9: Assessment of Alternative Fuel Infrastructure. This chapter assesses the status of infrastructure for alternative fueled vehicles, with emphasis on two technologies the agencies believe will be important for achieving longer-term climate and energy goals – plug-in electric vehicles (PEVs) and fuel cell electric vehicles (FCEVs). The agencies also discuss infrastructure for ethanol (E85) flex-fueled vehicles and natural gas vehicles. The agencies' assessment is that, as we concluded in the 2012 rule, high penetration levels of alternative fueled vehicles will not be needed to meet the MY2025 standards, with the exception of a very small percentage of PEVs, and that infrastructure is progressing sufficiently to support vehicles from those manufacturers choosing to produce alternative fueled vehicles to meet the MY2022-2025 standards. The majority of PEV charging occurs at home, and national PEV infrastructure in public and work locations is progressing appropriately. Hydrogen infrastructure developments are addressing many of the initial challenges of simultaneously launching new vehicle and fueling infrastructure markets, and current efforts in California and the northeast states will facilitate further vehicle and infrastructure rollout at the national level.

Chapter 10: Economic and Other Key Inputs Used in the Agencies' Analyses. This chapter describes many of the economic and other inputs used in the agencies' analyses. This chapter discusses the methodologies used to assess inputs such as the real-world fuel economy/GHG emissions gap, vehicle miles traveled (VMT), vehicle survival rates, the VMT rebound effect, energy security, the social cost of carbon and other GHGs, health benefits, consumer cost of vehicle ownership, and others.

Chapter 11: Credits, Incentives and Flexibilities. The National Program was designed with a wide range of optional compliance flexibilities to allow manufacturers to maintain consumer choice, spur technology development, and reduce compliance costs, while achieving significant GHG and oil reductions. Chapter 11 provides an informational overview of all of these compliance flexibilities, with particular emphasis on those flexibility options likely to be most important in the MY2022-2025 timeframe.

Chapter 12: Analysis of the MY2022-2025 GHG Standards; and **Chapter 13: Analysis of Augural CAFE Standards.** Chapters 12 and 13 provide results, respectively, of EPA's initial technical assessment of the technologies available to meet the MY2022-2025 GHG standards (i.e., the footprint-based standard curves) and their costs, and NHTSA's initial technical assessment of technologies capable of meeting CAFE standards corresponding to the augural standards for MY2022-2025, and these technologies' costs. CARB has not conducted an independent analysis, but has participated in both EPA's and NHTSA's analyses. Although all three agencies have been working collaboratively in an array of areas throughout the development of this Draft TAR, the EPA GHG and NHTSA CAFE assessments were done largely independently. These independent analyses were done in part to recognize differences in the agencies' statutory authorities and to reflect independent choices regarding some of the modeling inputs used at this initial stage of our evaluation. The agencies believe that independent and parallel analyses can provide complementary results. The agencies further believe that, for this Draft TAR which is the first step of the Midterm Evaluation process, it is both reasonable and advantageous to make use of different data sources and modeling tools, and to show multiple pathways for potential compliance with the MY 2022-2025 GHG standards and augural CAFE standards.

As noted above, although CARB did not perform its own modeling assessment of the costs and technologies to meet the 2022-2025 GHG and CAFE requirements, it was integrally involved in analyzing the underlying technology cost and effectiveness inputs to the EPA and NHTSA modeling. CARB believes that the analyses presented in this Draft TAR appropriately present a range of technologies that could be used to meet the requirements. However, as discussed above, there are, and will continue to be, emerging technologies that may well be available in the 2022-2025 timeframe and could perform appreciably better or be lower cost than the technologies modeled in this Draft TAR. Such technologies are exemplified by recent advancements already seen in the marketplace yet not anticipated by the agencies' rule four years ago (e.g., expanded use of higher compression ratio, naturally aspirated gasoline engines). Vehicle manufacturers have historically outpaced agency expectations and CARB believes it is likely that industry will continue to do so.

In this Draft TAR, NHTSA does not present alternatives to the augural standards because, as the first stage of the Midterm Evaluation process, the TAR is principally an exploration of technical issues -- including assumptions about the effectiveness and cost of specific technologies, as well as other inputs, methodologies and approaches for accounting for these issues. The agencies seek comment from stakeholders to further inform the analyses, in advance of the NHTSA rulemaking and the EPA Proposed Determination. For the purposes of clearly reflecting the impacts of updated technology assumptions relative to a familiar point of comparison, both agencies have run their respective models using the stringency levels included in NHTSA's augural standards, and EPA's existing GHG standards through MY2025. However, the technology assumptions and other analyses presented in this Draft TAR, which will be informed by public comment, will support the development of a full range of stringency alternatives in the subsequent CAFE Notice of Proposed Rulemaking.

In this Draft TAR, the EPA GHG and NHTSA CAFE assessments both show that the MY2022-2025 standards can be achieved largely through the use of advanced gasoline vehicle technologies with modest penetrations of lower cost electrification (like 48 volt mild hybrids which include stop/start) and low penetrations of higher cost electrification (like strong hybrids, plug-in hybrid electric vehicles, and all electric vehicles). Given the rapid pace of automotive industry innovation, the agencies may consider effectiveness and cost of additional technologies as new information, including comments on this Draft TAR, becomes available for further steps of the Midterm Evaluation.

Based on various assumptions including the Annual Energy Outlook 2015 (AEO 2015) reference case projections of the car/truck mix out to 2025, the footprint-based GHG standards curves for MY2022-2025 are projected to achieve an industry-wide fleet average CO_2 target of 175 grams/mile (g/mi) in MY2025, and the augural CAFE standards are projected to result in average CAFE requirements increasing from 38.3 mpg in MY2021 to 46.3 mpg in MY2025. The projected fleet average CO_2 target represents a GHG emissions level equivalent to 50.8 mpg (if all reductions were achieved exclusively through fuel economy improvements).[2]

Table ES-1 below compares two additional AEO 2015 scenarios in addition to the AEO 2015 reference case: a low fuel price case and a high fuel price case. As shown, these fuel price cases translate into different projections for the car/truck fleet mix (e.g., with a higher truck share shown in the low fuel price case, and a lower truck share shown in the high fuel price case), which in turn leads to varying projections for the estimated fleet wide CAFE requirements and GHG CO_2 targets and MPG-e levels projected for MY2025, from 169 g/mi (52.6 mpg-e) under the high fuel price case to 178 g/mi (49.9 mpg-e) under the low fuel price case. These estimated GHG target levels and CAFE requirements reflect changes in the latest projections about the MY2025 fleet mix compared to the projections in 2012 when the agencies first established the standards. Under the footprint-based standards, the program is designed to ensure significant GHG reductions/fuel economy improvements across the fleet, and each automaker's standard automatically adjusts based on the mix (size and volume) of vehicles it produces each model year. In the agencies' current analyses for this Draft TAR, we are applying the same footprint-based standards established in the 2012 final rule to the updated fleet projections for MY2025. It is important to keep in mind that the updated MY2025 fleet wide projections reflected in this Draft TAR are still just projections (as were the fleet projections in the 2012 rule) -- based on the latest available information, which may continue to change with future projections -- and that the actual GHG emissions/fuel economy level achieved in MY2025 won't be determined until the

[2] The projected MY 2025 target of 175 g/mi represents an approximate 50% decrease in GHG emissions relative to the fuel economy standards that were in place in 2010. It is clear from current GHG manufacturer performance data that many automakers are earning air conditioner refrigerant GHG credits that reduce GHG emissions, but do not increase fuel economy. Accordingly, the projected MY 2025 target of 175 g/mi represents slightly less than a doubling of fuel economy relative to the standards that were in place in 2010.

manufacturers have completed their MY2025 production. The agencies will continue to assess the latest available projections as we continue the Midterm Evaluation process.

Table ES- 1 Projections for MY2025: Car/Truck Mix, CO2 Target Levels, and MPG-equivalent[1]

		AEO 2015 Fuel Price Case		
	2012 Final Rule	**AEO Low**	**AEO Reference**	**AEO High**
Car/truck mix	67/33%	48/52%	52/48%	62/38%
CAFE (mpg)[2]	48.7	45.7	46.3	47.7
CO_2 (g/mi)	163	178	175	169
MPG-e	54.5	50.0	50.8	52.6

Notes:
[1] The CAFE, CO_2 and MPG-e values shown here are 2-cycle compliance values. Projected real-world values are detailed in Chapter 10.1; for example, for the AEO reference fuel price case, real-world EPA CO_2 emissions performance would be 220 g/mi and real-world fuel economy would be 36 mpg.
[2] Average of estimated CAFE requirements.
[3] Mile per gallon equivalent (MPG-e) is the corresponding fleet average fuel economy value if the entire fleet were to meet the CO2 standard compliance level through tailpipe CO2 improvements that also improve fuel economy. This is provided for illustrative purposes only, as we do not expect the GHG standards to be met only with fuel efficiency technology.

The agencies' updated assessments provide projections for the MY2022-2025 standards for several key metrics, including modeled "low-cost pathway" technology penetrations, per-vehicle average costs (cars, trucks, and fleet, by manufacturer and total industry-wide), industry-wide average costs, GHG and oil reductions, consumer payback, consumer fuel savings, and benefits analysis.

Based on the extensive updated assessments provided in this Draft TAR, the projections for the average per-vehicle costs of meeting the MY2025 standards (incremental to the costs already incurred to meet the MY2021 standard) are, for EPA's analysis of the GHG program, $894 - $1,017, and, for NHTSA's analysis of the CAFE program, $1,245 in the primary analysis using Retail Price Equivalent (RPE), and $1,128 in a sensitivity case analysis using Indirect Cost Multipliers (ICM). In the 2012 final rule, the estimated costs for meeting the MY2022-2025 GHG standards (incremental to the costs for meeting the MY2021 standard in MY2021) was $1,070.[3,vii]

[3] This cost estimate from the 2012 final rule was based on the use of Indirect Cost Multipliers (ICMs) in 2010$.

Table ES- 2 Per-Vehicle Average Costs to Meet MY2025 Standards: Draft TAR Analysis Costs Shown are Incremental to the Costs to Meet the MY2021 Standards

	GHG[1] in MY2025		CAFE in MY 2028	
	Primary Analysis	RPE Sensitivity Case[3]	Primary Analysis[2]	ICM Sensitivity Case[3]
Car	$707	$789	$1,207	$1,156
Truck	$1,099	$1,267	$1,289	$1,096
Combined	$894	$1,017	$1,245	$1,128

Notes:
[1.] The values reported for the GHG analysis to account for indirect costs reflect the use of Indirect Cost Multipliers for the primary analysis, and Retail Price Equivalent for the sensitivity case.
[2] The values reported for CAFE primary analysis reflect the use of RPE and include civil penalties estimated to be incurred by some OEMs as provided by EPCA/EISA. Estimated technology costs (without civil penalties) average $1,111, $1,246, and $1,174, respectively for MY2028 passenger cars, light trucks, and the overall light-duty fleet.
[3] Note that Chapter 12 (GHG) and Chapter 13 (CAFE) include a wide range of additional sensitivity cases.

In Table ES-2, NHTSA's estimates are provided for MY2028 because NHTSA's analysis, which is conducted on a year-by-year basis, indicates that manufacturers could make use of EPCA/EISA's provisions allowing credits to be earned and carried forward to be applied toward ensuing model years. Therefore, NHTSA's analysis indicates that a "stabilized" response to the augural standards might not be achieved until approximately 2028 (see Chapter 13 for additional detail). EPA estimates are provided for MY2025 because EPA's analysis projects that each manufacturer would comply in MY2025 with that year's standards (see Chapter 12 for additional details).

Table ES-3 shows fleet-wide penetration rates for a subset of the technologies the agencies' project could be utilized to comply with the MY2025 standards. While all three agencies have been working collaboratively on an array of issues throughout this initial phase of the Midterm Evaluation, much of the EPA GHG and NHTSA CAFE assessments were done largely independently, as reflected in the different technology pathways shown in Table ES-3 (see Chapter 2.3 for additional detail). The agencies' analyses each project that the MY2022-2025 standards can be met largely through improvements in gasoline vehicle technologies, such as improvements in engines, transmissions, light-weighting, aerodynamics, and accessories. The analyses further indicate that only modest amounts of hybridization, and very little full electrification (plug-in hybrid electric vehicles (PHEV) or electric vehicles (EV)) technology will be needed to meet the standards. This initial assessment of potential technology paths is similar to the agencies' projections made in the 2012 final rule, and is consistent with the findings of the National Academy of Sciences report from June 2015 (discussed in Chapter 2).

Table ES- 3 Selected Technology Penetrations to Meet MY2025 Standards[1]

	GHG	CAFE
Turbocharged and downsized gasoline engines	33%	54%
Higher compression ratio, naturally aspirated gasoline engines	44%	<1%
8 speed and other advanced transmissions[2]	90%	70%
Mass reduction	7%	6%
Stop-start	20%	38%
Mild Hybrid	18%	14%
Full Hybrid	<3%	14%
Plug-in hybrid electric vehicle[3]	<2%	<1%
Electric vehicle[3]	<3%	<2%

Notes:
[1] Percentages shown are absolute rather than incremental. These values reflect both EPA and NHTSA's primary analyses; both agencies present additional sensitivity analyses in Chapter 12 (GHG) and Chapter 13 (CAFE). For EPA this includes a pathway where higher compression ratio naturally aspirated gasoline engines are held at a 10% penetration, and the major changes are turbocharged and downsized gasoline engines increase to 47% and mild hybrids increase to 38% (See Chapter 12.1.2)
[2] Including continuously variable transmissions (CVT)
[3] In EPA's modeling, the California Zero Emission Vehicles (ZEV) program is considered in the reference case fleet; therefore, 3.5% of the fleet is projected to be full EV or PHEV in the 2022-2025 timeframe due to the ZEV program and the adoption of that program by nine additional states.

Although some of the differences in costs are expected as EPA and NHTSA conducted two independent analyses, the consideration of CARB's program also led to one important difference. As noted in the footnote for Table ES-3, EPA's analysis included consideration for compliance with other related state regulations including CARB's ZEV regulation that has also been adopted by nine other states under Section 177 of the Federal Clean Air Act. CARB's ZEV program requires a portion of new light-duty vehicle sales to be ZEVs and collectively, CA and these states represent nearly 30 percent of nationwide sales of light-duty vehicles. CARB worked with EPA to include ZEVs reflecting compliance with California's ZEV program within the reference fleet used by EPA. NHTSA's analysis did not. This accounts for at least part of the cost differences in the two agencies' analyses as well as for some of the difference in technology penetration rates for full hybrids.

EPA's analysis indicates that, compared to the MY2021 standards, the MY2025 standards will result in a net lifetime consumer savings of $1,460 - $1,620 and a payback of about 5 to 5 ½ years.[4] NHTSA's primary analysis indicates that net lifetime consumer savings could average $680 per vehicle, such that increased vehicle purchase costs are paid back within about 6 ½ years, and $800 with payback within about 6 years in a sensitivity case analysis using ICMs.

[4] Based on the AEO 2015 reference case gasoline price projections, 3 percent discount rate, and ICMs.

Table ES- 4 Payback Period and Lifetime Net Consumer Savings for an Average Vehicle Compared to the MY2021 Standards

	GHG MY2025 Vehicle		CAFE MY2028 Vehicle	
	Primary Analysis	**RPE Sensitivity Case**	**Primary Analysis**	**ICM Sensitivity Case**
Payback period (years)	5	5 ½	6 ½	6
Net Lifetime Consumer Savings ($, discounted at 3%)	$1,620	$1,460	$680	$800

* Note that Chapter 12 (GHG) and Chapter 13 (CAFE) include a wide range of additional sensitivity cases.

Over the lifetimes of MY2021-2025 vehicles, EPA estimates that under the GHG standards, GHG emissions would be reduced by about 540 million metric tons (MMT) and oil consumption would be reduced by 1.2 billion barrels. Over the lifetimes of MY2016-2028 vehicles, NHTSA estimates that under the augural MY2022-2025 CAFE standards, GHG emissions would be reduced by about 748 MMT and oil consumption would be reduced by about 1.6 billion barrels. NHTSA's estimates span a wider range of model years for two reasons, as discussed in Chapter 13: first, the NHTSA analysis projects that manufacturers may take some "early action" prior to MY2022; second, as discussed above, the response to the augural standards might not be "stabilized" until after MY2025. Differences in these values also result from differences in the agencies' estimates of annual mileage accumulation by light-duty vehicles.[5]

Table ES- 5 Cumulative GHG and Oil Reductions for Meeting the MY2022-2025 Standards

Lifetime Reductions	**GHG (MYs 2021-2025 vehicles)**	**CAFE (MYs 2016-2028 vehicles)**
CO_2e reduction (million metric tons, MMT)	540	748
Oil reduction (billion barrels)	1.2	1.6

For the EPA GHG analysis, total industry-wide costs of meeting the MY2022-2025 GHG standards are estimated at $34 to $38 billion. Societal monetized benefits of the MY2022-2025 standards (exclusive of fuel savings to consumers) range from $40 to $41 billion. Consumer pre-tax fuel savings are estimated to be $89 billion over the lifetime of vehicles meeting the MY2022-2025 standards. Net benefits (inclusive of fuel savings) are estimated at $90 to $94 billion. These values are all at a 3 percent discount rate; values at a 7 percent discount rate are shown in Table ES-6 below.

[5] The agencies' methods for assessing vehicle mileage accumulation are discussed in Chapter 10.3 for EPA, and Chapter 13 for NHTSA.

Table ES- 6 GHG Analysis of Lifetime Costs & Benefits to Meet the MY2022-2025 Standards (for Vehicles Produced in MY2021-2025)* (Billions of 2013$)

	3 Percent Discount Rate		7 Percent Discount Rate	
	Primary Analysis	RPE Sensitivity Case	Primary Analysis	RPE Sensitivity Case
Vehicle Program	- $34	-$38	-$24	-$27
Maintenance	-$2	-$2	-$1	-$1
Fuel	$89	$89	$49	$49
Benefits*	$41	$40	$30	$30
Net Benefits	$94	$90	$54	$51

Note:
*These values reflect AEO 2015 reference fuel price case. The Primary Analysis reflects ICMs and the Sensitivity Case reflects RPEs. All values are discounted back to 2015; see Chapter 12.3 for details on discounting social cost of GHG and non-GHG benefits. Note that Chapter 12 also includes a number of additional sensitivity cases.

NHTSA's primary analysis shows that compared to the No Action alternative, the augural CAFE standards could entail additional costs totaling $87 billion during MYs 2016-2028 (reasons for this span of MYs are discussed above), and a sensitivity case using ICM shows total costs of $79 billion. The primary analysis shows benefits totaling $175 billion, and the ICM sensitivity case shows $178 billion. Consumer fuel savings are estimated to be $67 billion to $122 billion over the lifetime of vehicles meeting the MY2022-2025 standards. Thus, net benefits (inclusive of fuel savings) could total $88 billion based on the primary analysis and $99 billion for the ICM sensitivity case. These are estimates of the present value (in 2015) of costs and benefits, based on a 3 percent discount rate. NHTSA has also conducted analysis using a 7 percent discount rate, and a broader sensitivity analysis to examine the impact of other key analysis inputs, as discussed in Chapter 13. Below, Table ES-7 provides an overall summary of costs and benefits observed in NHTSA's analysis.

Table ES- 7 CAFE Analysis of Lifetime Costs & Benefits to Meet the MY2022-2025 Standards (for Vehicles Produced in MY2016-2028) (Billions of 2013$)

	3 Percent Discount Rate		7 Percent Discount Rate
	Primary Analysis[2]	ICM Sensitivity Case[3]	Primary Analysis
Vehicle Program[1]*	-$87	-$79	-$60
Benefits (Fuel)	$120	$122	$67
Benefits (Other)	$55	$56	$43
Net Benefits	$88	$99	$50

Notes:
[1] Includes changes in maintenance costs (small relative to cost of additional technology).
[2] The Primary Analysis reflects RPE.
[3] Note that Chapter 13 includes a wide range of additional sensitivity cases.

As noted above, because EPA and NHTSA developed independent assessments of technology cost, effectiveness, and reference case projections, the compliance pathways and associated costs that result are also different. Consideration of these two results provides greater confidence that compliance can be achieved through a number of different technology pathways.

References

[i] See 40 CFR 86.1818-12(h).
[ii] See 40 CFR 86.1818-12(h).
[iii] See 40 CFR section 86.181-12(h).
[iv] See 77 FR 62784 (Oct. 12, 2012).
[v] See 40 CFR 86.1818-12(h)(2)(i).
[vi] National Academy of Sciences, National Research Council to the National Academies, "Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles," June 2015.
[vii] Regulatory Impact Analysis: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards and Corporate Average Fuel Economy Standards, EPA-420-R-12-016, Table 5.1-8, page 5-8.

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Chapter 1: Introduction

1.1 Purpose of this Report

The Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) have conducted two joint rulemakings to establish a coordinated National Program for stringent Federal corporate average fuel economy (CAFE) and greenhouse gas (GHG) emissions standards for light-duty vehicles. The National Program builds on over 35 years of the National Highway Traffic Safety Administration's (NHTSA's) issuance and enforcement of the Nation's fuel economy standards under the Energy Policy and Conservation Act (EPCA), and responds to a 2007 Supreme Court decision determining that greenhouse gases (GHGs) can be regulated under the Clean Air Act (CAA) and EPA's endangerment finding. The agencies finalized the first set of National Program standards covering model years (MYs) 2012-2016 in May 2010[1] and the second set of standards, covering MYs 2017-2025, in October 2012.[2] The National Program establishes standards that increase in stringency year-over-year from MY2012 through MY2025, projected to reach a level by 2025 that nearly doubles fuel economy and cuts GHG emissions in half as compared to MY2008. Through the coordination of the National Program with the California standards, automakers can build one single fleet of vehicles across the U.S. that satisfies all GHG/CAFE requirements, and consumers can continue to have a full range of vehicle choices that meet their needs. In the agencies' October 2012 final rules, the National Program was estimated to save 6 billion metric tons of carbon dioxide (CO_2) pollution and 12 billion barrels of oil over the lifetime of MY2012-2025 vehicles. In addition, the final standards are projected to provide significant savings for consumers due to reduced fuel use.

The rulemaking establishing the National Program for model year MY2017-2025 light-duty vehicles included a regulatory commitment from EPA to conduct a Midterm Evaluation (MTE) of the GHG standards established for MYs 2022-2025.[3] The 2012 final rule states "The mid-term evaluation reflects the rules' long time frame, and, for NHTSA, the agency's statutory obligation to conduct a *de novo* rulemaking in order to establish final standards for MYs 2022-2025. NHTSA will use the MTE as part of the rulemaking it must undertake to set standards for MYs 2022-2025._Through the MTE, EPA will determine whether the GHG standards for model years 2022-2025, established in 2012, are still appropriate, within the meaning of section 202 (a) of the Clean Air Act, in light of the record then before the Administrator, given the latest available data and information. See 40 CFR section 86.181-12(h). EPA’s decision could go one of three ways: the standards remain appropriate, the standards should be less stringent, or the standards should be more stringent. In order to align the agencies' proceedings for MYs 2022-2025 and to maintain a joint national program, EPA and NHTSA will finalize their actions related to MYs 2022-2025 standard concurrently. If the EPA determination is that the standards may change, the agencies will issue a joint NPRM and joint final rules." See 77 FR at 62628 (Oct. 15, 2012).

The MTE is a collaborative, data-driven, and transparent process that will be "a holistic assessment of all of the factors considered in standards setting," and "the expected impact of those factors on manufacturers' ability to comply, without placing decisive weight on any particular factor or projection." See 77 FR 62784 (Oct. 15, 2012). [A] The MTE analysis is intended to be as robust and comprehensive as that in the original setting of the MY2017-2025 standards. *Id.* EPA and NHTSA also are closely coordinating with the California Air Resources Board (CARB) in conducting the MTE to better ensure the continuation of the National Program. *Id*. The agencies fully expect that any adjustments to the standards will be made in consultation with CARB. The details of National Program and the MTE are discussed in Sections 1.2 and 1.3 respectively, below.

The 2012 final rule preamble also states "Prior to beginning NHTSA's rulemaking process and EPA's mid-term evaluation, the agencies plan to jointly prepare a Draft Technical Assessment Report (TAR) to examine afresh the issues and, in doing so, conduct similar analyses and projections as those considered in the current rulemaking, including technical and other analyses and projections relevant to each agency's authority to set standards as well as any relevant new issues that may present themselves." See 77 FR 62965 (Oct. 15, 2012). This Draft Technical Assessment Report (TAR) is the first formal step in the MTE process and is being issued jointly by EPA, NHTSA, and CARB for public comment. EPA is required to prepare and seek public comment on the TAR.[4] The Draft TAR is a technical report, not a decision document. It is an opportunity for all three agencies to share with the public the initial technical analyses of the MY2022-2025 standards. The Draft TAR is a first step in the process that will ultimately inform whether the MY2022-2025 GHG standards adopted by EPA in 2012 should remain in place or should change, and what MY2022-2025 CAFE standards would be maximum feasible for NHTSA. EPA's regulations require it to consider in the Draft TAR a wide range of factors relevant to the MY2022-2025 standards[5] including:

- Powertrain improvements for gasoline and diesel engines
- Battery developments for hybridization, electrified vehicles
- Technology costs
- Vehicle light-weighting and impacts on safety
- Market penetration of fuel efficient technologies
- Fuel prices
- Fleet mix (cars v. trucks)
- Employment impacts
- Infrastructure for electric vehicle charging, alternative fuels
- Consumer acceptance
- Consumer payback periods
- Any other factors deemed relevant

The agencies have conducted extensive research and analyses to support the MTE, as discussed in Chapter 2 and throughout the document. As part of gathering robust data and information to inform the MTE, the agencies also have conducted extensive outreach with a wide range of stakeholders – including auto manufacturers, automotive suppliers, NGOs, consumer

[A] 40 CFR section 86.1818 (h) (1) lists factors which EPA must consider, including "availability and effectiveness of the technology;" "the appropriate lead time for introduction of technology;" the feasibility and practicability of the standards;" "the impact of the standards on reduction of emissions, oil conservation, energy security and fuel savings by consumers;" "the impact of the standards on the automobile industry;" and "the impacts of the standards on automobile safety."

groups, labor unions, state and local governments, the academic and research communities, and others. Among other things, the Draft TAR presents analyses reflecting this research and information obtained during the agencies' outreach, presents updated assessments since the 2012 final rule, including a 2015 assessment by the National Academies of Science, and offers an opportunity for public comments on our work thus far. The agencies will fully consider public comments on this Draft TAR as they continue the MTE process, discussed below.

1.2 Building Blocks of the National Program

The National Program is both needed and possible because the relationship between improving fuel economy and reducing CO_2 tailpipe emissions is very direct and close. The amount of those CO_2 emissions is essentially constant per gallon combusted of a given type of fuel. Thus, the more fuel efficient a vehicle is, the less fuel it burns to travel a given distance. The less fuel it burns, the less CO_2 it emits in traveling that distance. While there are emission control technologies that reduce the pollutants (e.g., carbon monoxide) produced by imperfect combustion of fuel by capturing or converting them to other compounds, there is currently no such technology for CO_2. Further, while some of those pollutants can also be reduced by achieving a more complete combustion of fuel, doing so only increases the tailpipe emissions of CO_2. Thus, there is a single pool of technologies for addressing these twin problems, i.e., those that reduce fuel consumption and thereby reduce CO_2 emissions as well. As noted in the 2012 final rule, the rates of increase in stringency for the CAFE standards are lower than EPA's rates of increase in stringency for GHG standards for purposes of harmonization and in reflection of several statutory constraints on the CAFE program.[6,B]

1.2.1 Background on NHTSA's CAFE Program

The establishment of national fuel economy standards followed directly from passage of the Energy Policy and Conservation Act (EPCA) of 1975. The Act directed the Secretary of Transportation to set standards separately for passenger cars and light trucks at the maximum feasible levels in each model year (with the passenger car standard not to exceed 27.5 mpg), and provided additional direction regarding many aspects of the program. The Secretary has delegated this responsibility to the National Highway Traffic Safety Administration (NHTSA). The first fuel economy standards took effect in MY 1978.

Congress has amended EPCA several times to provide further direction. Through the Energy Independence and Security Act (EISA) of 2007, Congress directed the Secretary to, among other things, define future standards in terms of vehicle attributes related to fuel economy and ensure that those standards cause the overall fleet to achieve an average fuel economy level of at least 35 mpg by 2020. EISA did not otherwise change the requirement that the Department of Transportation (DOT) set standards separately for passenger cars and light trucks at the maximum feasible levels in each model year. NHTSA can only set standards for up to five model years at a time and standards must be set at least eighteen months before the beginning of the model year.[7]

In the late 1970s, NHTSA issued regulations to establish and significantly increase the stringency of fuel economy standards through 1985. In the 1980s, the Department relaxed the

[B] For a fuller discussion of these issues, see 77 FR 62639, October 15, 2012.

passenger car standards for model years 1986-1989 and then increased the standard to 27.5 mpg. In 1994, NHTSA issued a notice proposing to explore higher fuel economy standards for light trucks. However, starting with the fiscal year 1996 and continuing through fiscal year 2001, Congress prohibited NHTSA from using any funds to increase fuel economy standards. In 2003, NHTSA increased light truck standards during model years 2005-2007. In 2006, NHTSA increased light truck standards during model years 2008-2011 and required an attribute-based standard in 2011.

Following EISA and a 2007 decision by the United States Court of Appeals for the Ninth Circuit[8] (requiring that, when issuing CAFE standards, the Department issue Environmental Impact Statements and assign an economic value to avoided CO_2 emissions), the Department proposed in April 2008 to establish more stringent attribute-based standards for both passenger cars and light trucks during model years 2011-2015. The Department subsequently completed work on a rule to finalize these standards; however, with the automobile industry experiencing a steep decline during 2008, the Department withdrew the rule. Under President Obama, the Department promulgated the model year 2011 standards in April 2009, and began work on harmonized DOT fuel economy and EPA GHG standards referred to here as the National Program.

As shown below, as required fuel economy standards have increased, passenger car (PC) and light truck (LT) average fuel economy levels achieved by manufacturers have improved:

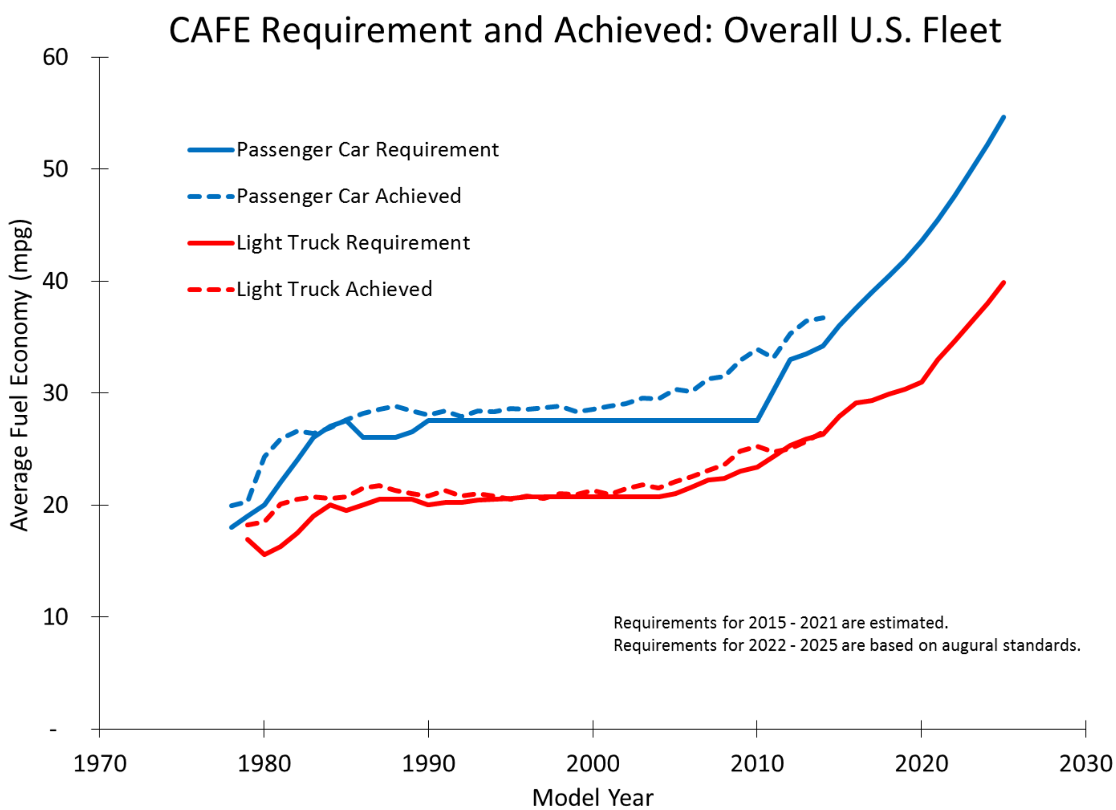

Figure 1.1 Average Required and Achieved Fuel Economy Levels

It is important to note that the CAFE fuel economy values (both the required and the achieved) shown in this chart are based on EPA 2-cycle city and highway tests as required by Congress. Accordingly, these values are a minimum of 25 percent higher than the typical fuel economy values shown on fuel economy labels (which are based on 5-cycle testing that reflects a much broader range of driving conditions) and achieved by consumers in real world driving.

1.2.2 Background on EPA's GHG Program

Under the Clean Air Act, EPA is responsible for addressing emissions of air pollutants from motor vehicles. On April 2, 2007, the U.S. Supreme Court issued its opinion in Massachusetts v. EPA,[9] a case involving EPA's 2003 denial of a petition for rulemaking to regulate GHG emissions from motor vehicles under section 202(a) of the Clean Air Act (CAA).[10] The Court held that GHGs fit within the definition of air pollutant in the Clean Air Act and further held that the Administrator must determine whether or not emissions from new motor vehicles cause or contribute to air pollution which may reasonably be anticipated to endanger public health or welfare, or whether the science is too uncertain to make a reasoned decision. The Court rejected the argument that EPA cannot regulate CO_2 from motor vehicles because to do so would de facto tighten fuel economy standards, authority over which has been assigned by Congress to DOT. The Court stated that "[b]ut that DOT sets mileage standards in no way licenses EPA to shirk its environmental responsibilities. EPA has been charged with protecting the public's 'health' and 'welfare', a statutory obligation wholly independent of DOT's mandate to promote energy efficiency." The Court concluded that "[t]he two obligations may overlap, but there is no reason to think the two agencies cannot both administer their obligations and yet avoid inconsistency."[11] The case was remanded back to the Agency for reconsideration in light of the Court's decision.[12]

On December 15, 2009, EPA published two findings (74 FR 66496): That emissions of GHGs from new motor vehicles and motor vehicle engines contribute to GHG air pollution, and that GHG air pollution may reasonably be anticipated to endanger public health and welfare of current and future generations in the U.S.

1.2.3 Background on CARB's GHG Program

Recognizing the increasing threat of climate change to the well-being of California's citizens and the environment, in 2002 the state legislature passed assembly bill 1493 (AB 1493) which directed CARB to adopt the maximum feasible and cost-effective reductions in GHG emissions from passenger cars and light-duty trucks beginning in the 2009 model year. Accordingly, in 2004, CARB adopted the first in the nation GHG emission requirements for passenger cars and light-duty trucks for model years 2009-2016. In January 2012, CARB adopted additional light-duty vehicle GHG emission requirements for model years 2017-2025. These additional requirements were developed in a joint effort with EPA and NHTSA on the development of corporate fuel economy and federal GHG emission standards for model year 2017 and beyond.

1.3 Background on the National Program

NHTSA and EPA have conducted two joint rulemakings to establish a National Program for corporate average fuel economy (CAFE) and GHG emissions standards. Together, the two rules established strong and coordinated Federal GHG and fuel economy standards for passenger cars, light-duty trucks, and medium-duty passenger vehicles (hereafter light-duty vehicles or LDVs). Each agency adopted standards covering MYs 2012-2016 in May 2010[13] and covering MY2017 and beyond in October 2012.[14] The MYs 2012-2016 rule represented the first time EPA established standards for GHG emissions under its Clean Air Act authority. The Federal GHG and fuel economy standards for MY2017 and beyond were developed in a joint effort with CARB. And, subsequent to the adoption of California-specific GHG standards for MYs 2017-2025 and the adoption of the Federal standards for MY2017 and beyond, CARB adopted a "deemed to comply" provision whereby compliance with the Federal GHG standards would be deemed as compliance with California's GHG program in furtherance of a single National Program. The National Program approach, combined with California standards, helps to better ensure that all manufacturers can build a single fleet of vehicles that satisfy all requirements under both federal programs and under California's program, which helps to reduce costs and regulatory complexity for auto manufacturers. In addition, the National Program provides significant environmental and climate benefits, energy security, and consumer savings to the general public. Most stakeholders strongly supported the National Program, including the auto industry, automotive suppliers, state and local governments, labor unions, NGOs, consumer groups, veterans groups, and others.

Together, light-duty vehicles, which include passenger cars, sport utility vehicles, crossover utility vehicles, minivans, and pickup trucks, are presently responsible for approximately 60 percent of all U.S. transportation-related GHG emissions and fuel consumption.[15] The 2012 final rule projected that combined, the National Program standards, and NHTSA's MY2011 CAFE standards, result in MY2025 light-duty vehicles with nearly double the fuel economy and half the GHG emissions compared to MY2010 vehicles. Collectively, these represented some of the most significant federal actions ever taken to reduce GHG emissions and improve fuel economy in the U.S. In the 2012 final rule, based on future assumptions including car/truck share, EPA projected that its standards would lead to an average industry fleet wide emissions level of 163 grams/mile of carbon dioxide (CO_2) in model year 2025 (compared to 326 g/mile in MY 2011), which is equivalent to 54.5 mpg if this level were achieved solely through improvements in fuel economy.[C,D] In the same notice, NHTSA estimated that, if proposed and subsequently finalized at levels announced on an augural basis for model years 2022-2025, CAFE standards could increase industry-wide fuel economy to 48.7-49.7 mpg by model year 2025, depending on a range of factors.

In the 2012 final rule, the agencies projected that, in meeting the MY2025 standards, a wide range of vehicles would continue to be available, preserving consumer choice. The agencies projected that the MY2025 standards would be met largely through advancements in conventional vehicle technologies, including advances in gasoline engines (such as downsized/turbocharged engines) and transmissions, vehicle weight reduction, improvements in

[C] 163g/mi would be equivalent to 54.5 mpg, if the entire fleet were to meet this CO_2 level through tailpipe CO_2 and fuel economy improvements. However, the agencies projected in the 2012 rulemaking analysis that a portion of these improvements will be made through improvements in air conditioning refrigerant leakage and the use of alternative refrigerants, which would contribute to reduced GHG emissions but would not contribute to fuel economy improvements. This is why NHTSA's 48.7-49.7 mpg range differs from EPA's projected 54.5 mpg standard.

[D] Real-world CO_2 is typically 25 percent higher and real-world fuel economy is typically 20 percent lower than the CO_2 and CAFE compliance values discussed here.

vehicle aerodynamics, more efficient vehicle accessories, and lower rolling resistance tires. The agencies also projected that vehicle air conditioning systems would continue to improve by becoming more efficient and by increasing the use of alternative refrigerants and lower leakage systems. The agencies estimated that some increased electrification of the fleet would occur through the expanded use of stop/start and mild hybrid technologies, but projected that meeting the MY2025 standards would require only about five to nine percent of the fleet to be full hybrid electric vehicles (HEVs) and only about two to three percent of the fleet to be electric vehicles (EV) or plug-in hybrid electric vehicles (PHEVs).[E] All of these technologies were available at the time of the final rule, some on a limited number of vehicles while others were more widespread, and the agencies projected that manufacturers would be able to meet the standards through significant efficiency improvements in the technologies, as well as through increased usage of these and other technologies across the fleet.

In the 2012 final rule, EPA adopted standards through MY2025, with the MY2022-2025 standards subject to the midterm evaluation process established in the EPA regulations. As mentioned above, NHTSA adopted standards only through MY2021, due to a statutory requirement of the Energy Policy and Conservation Act (EPCA) of 1975, as amended by the Energy Independence and Security Act (EISA) of 2007, which allows NHTSA to set CAFE standards for only up to five model years at a time. Due to this statutory requirement, NHTSA must conduct a full *de novo* rulemaking to establish standards for MYs 2022-2025. In the 2012 final rule, NHTSA thus presented MY2022-2025 standards as "augural," reflecting the agency's best judgment of what standards would have been maximum feasible at the time of the final rule, based on the information then available. The future rulemaking to set MY2022-2025 CAFE standards must be based on the best information, data, and analysis available at the time of the new rulemaking.

The MY2012-2016 and MY2017 and beyond CAFE and GHG emissions standards are attribute-based standards,[F] using vehicle footprint as the attribute. Footprint is defined as a vehicle's wheelbase multiplied by its average track width[16]—in other words, the area enclosed by the points at which the wheels meet the ground. The standards are therefore generally based on a vehicle's size: larger vehicles have numerically less stringent fuel economy/GHG emissions targets and smaller vehicles have numerically more stringent fuel economy/GHG emissions targets.

Under the footprint-based standards, the footprint curve defines a GHG or fuel economy performance target for each separate car or truck footprint. Individual vehicles or models, however, are not required to meet the target on the curve. To determine its compliance obligation, a vehicle manufacturer would average the curve targets for a given year for each of its footprints of its vehicle models produced in that year, as weighted by the number of vehicles it produced of each model.[G] Each manufacturer thus will have a GHG and CAFE average

[E] For comparison to vehicles for sale today, an example of a mild HEV is GM's eAssist (Buick Lacrosse), a strong HEV is the Toyota Prius, an EV is the Nissan Leaf, and a PHEV is the Chevrolet Volt.

[F] Attribute-based standards are required by EISA (49 U.S.C. 32902(b)(3)) and allowed by the CAA. NHTSA first used the footprint attribute in its Reformed CAFE program for light trucks for model years 2008-2011 and passenger car CAFE standards in MY2011.

[G] See, e.g., 49 CFR 531.5 for the curve equations for passenger car CAFE standards.

standard that is unique to each of its car and truck fleets, depending on the footprints and production volumes of the vehicle models produced by that manufacturer in a given model year. A manufacturer will have separate footprint-based standards for passenger cars (like sedans, station wagons, and many 2WD sport-utility vehicles and crossovers) and for light trucks (like most 4WD and heavier 2WD sport-utility vehicles, minivans, and pickup trucks)[H]. The curves are mostly sloped, so that generally, vehicles with larger footprints will be subject to higher CO_2 grams/mile targets and lower CAFE mpg targets than vehicles with smaller footprints. This is because, generally speaking, smaller vehicles are more capable of achieving lower levels of CO_2 and higher levels of fuel economy than larger vehicles. Although a manufacturer's fleet average standards could be estimated throughout the model year based on the projected production volume of its vehicle fleet (and are estimated as part of the EPA certification process), the final standards with which each manufacturer must comply are determined by its final model year production figures. A manufacturer's calculation of its fleet average standards as well as its fleets' average performance at the end of the model year will thus be based on the production-weighted average target and performance of each model in its fleet.[I]

The footprint curves for the MY2012-2025 CAFE standards are shown below in Figure 1.1 and Figure 1.2 and GHG standards are shown below in Figure 1.3 and Figure 1.4. As noted above, NHTSA has only adopted standards through MY2021. The CAFE MY2022-2025 curves provided below were presented as augural attribute curves in the MY2017-2025 rule, and will have to be re-evaluated as part of the upcoming rulemaking to establish final CAFE standards for those model years. Although the general model of the target curve equation is the same for each vehicle category and each year, the parameters of the curve equation differ for cars and trucks. Each parameter also changes on a model year basis, resulting in the yearly increases in stringency.[17]

[H] This is required for the CAFE program under 49 U.S.C. § 32902.

[I] A manufacturer may have some models that exceed their target, and some that are below their target. Compliance with a fleet average standard is determined by comparing the fleet average standard (based on the production weighted average of the target levels for each model) with fleet average performance (based on the production weighted average of the performance for each model).

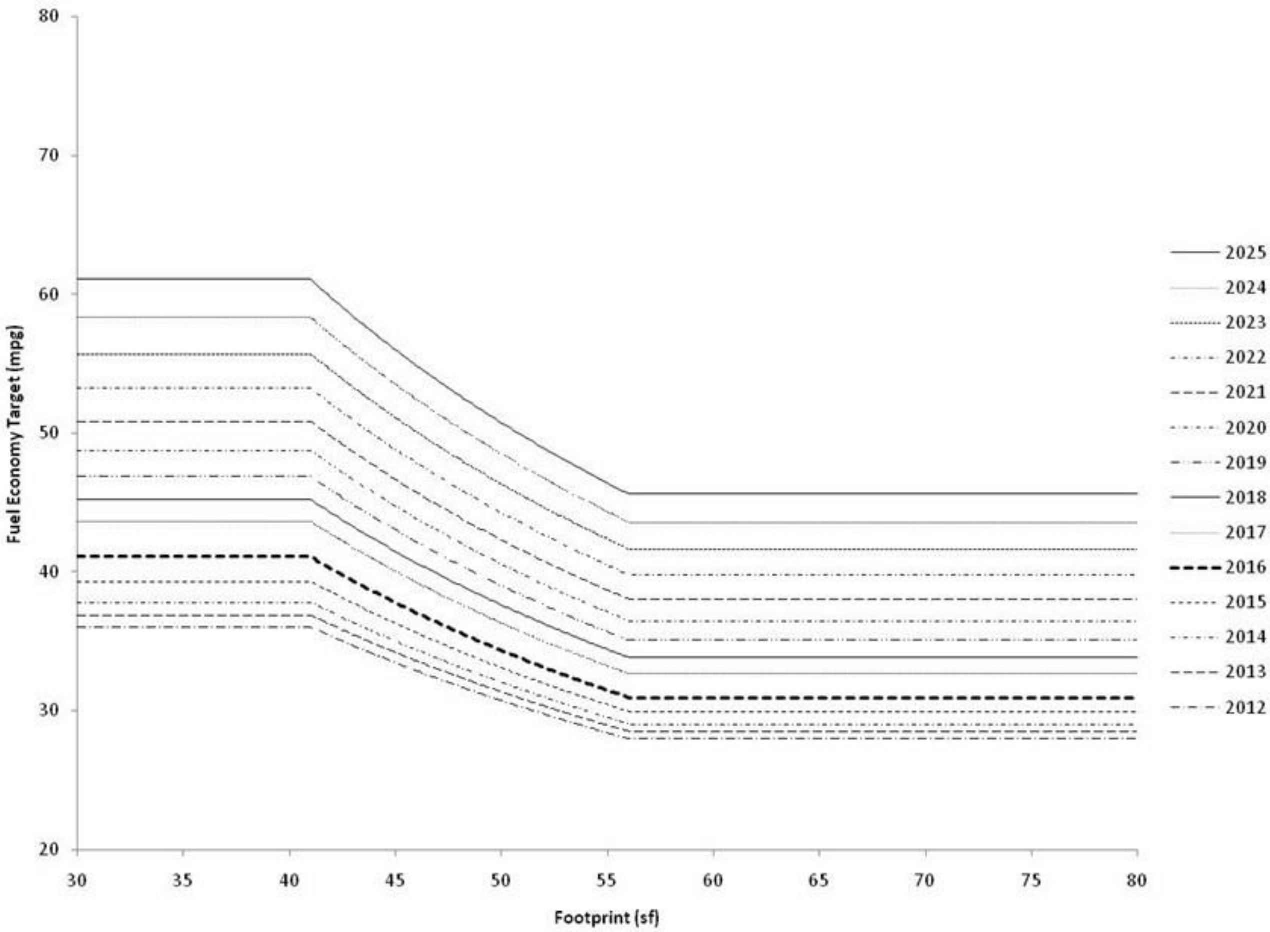

Figure 1.1 CAFE Target Curves for Passenger Cars

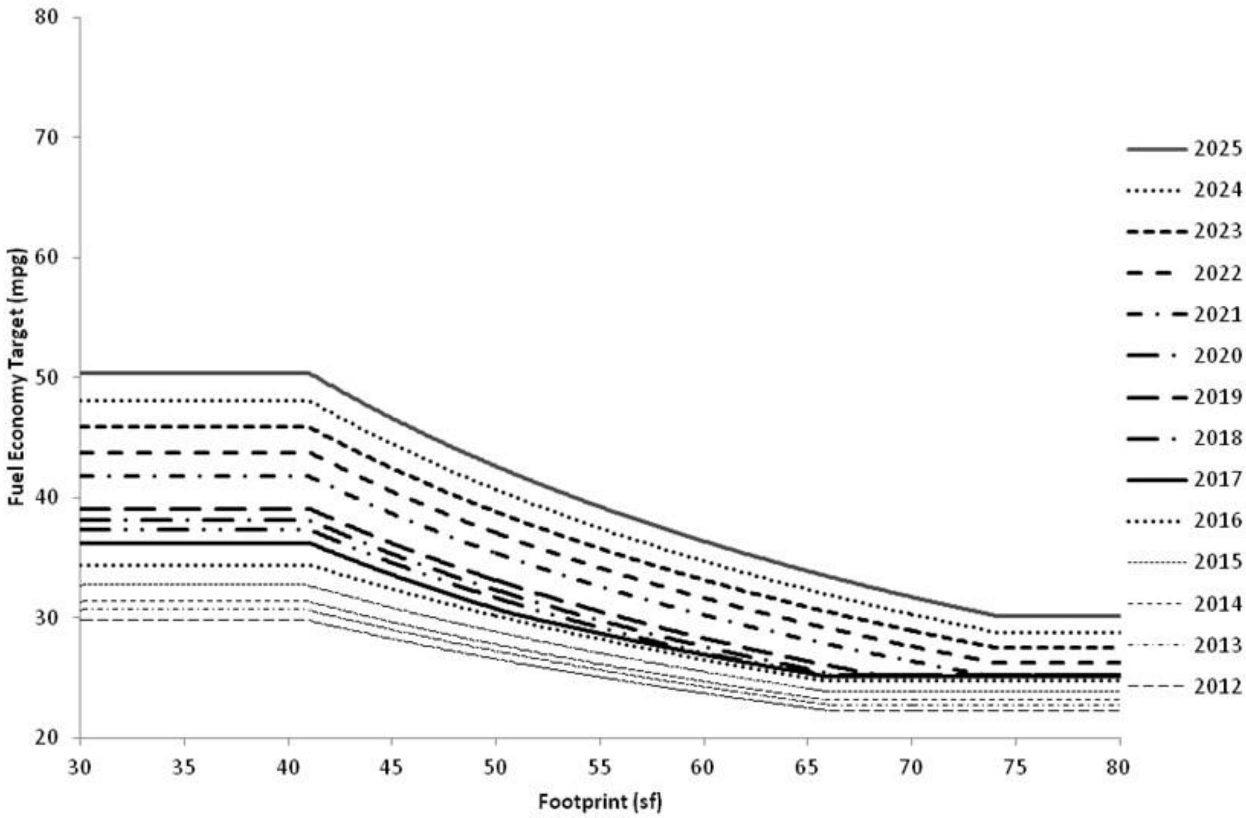

Figure 1.2 CAFE Target Curves for Light Trucks

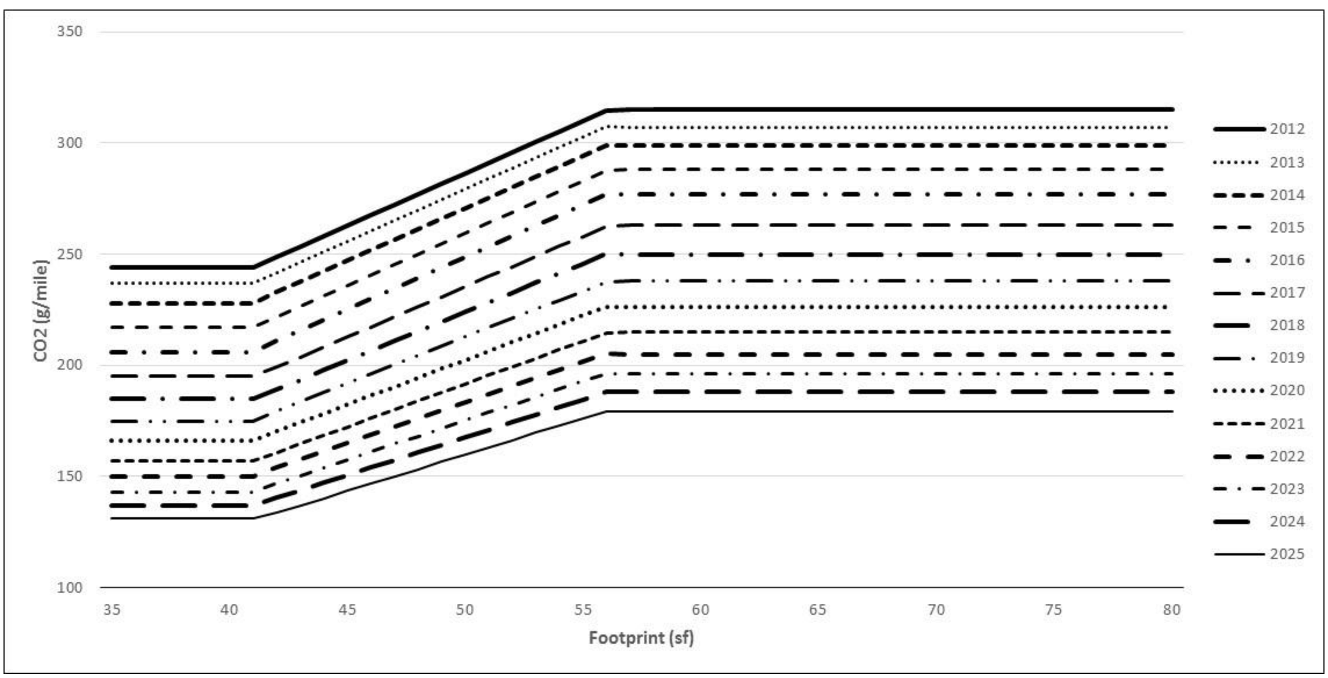

Figure 1.3 CO_2 (g/mile) Passenger Car Standards Curves

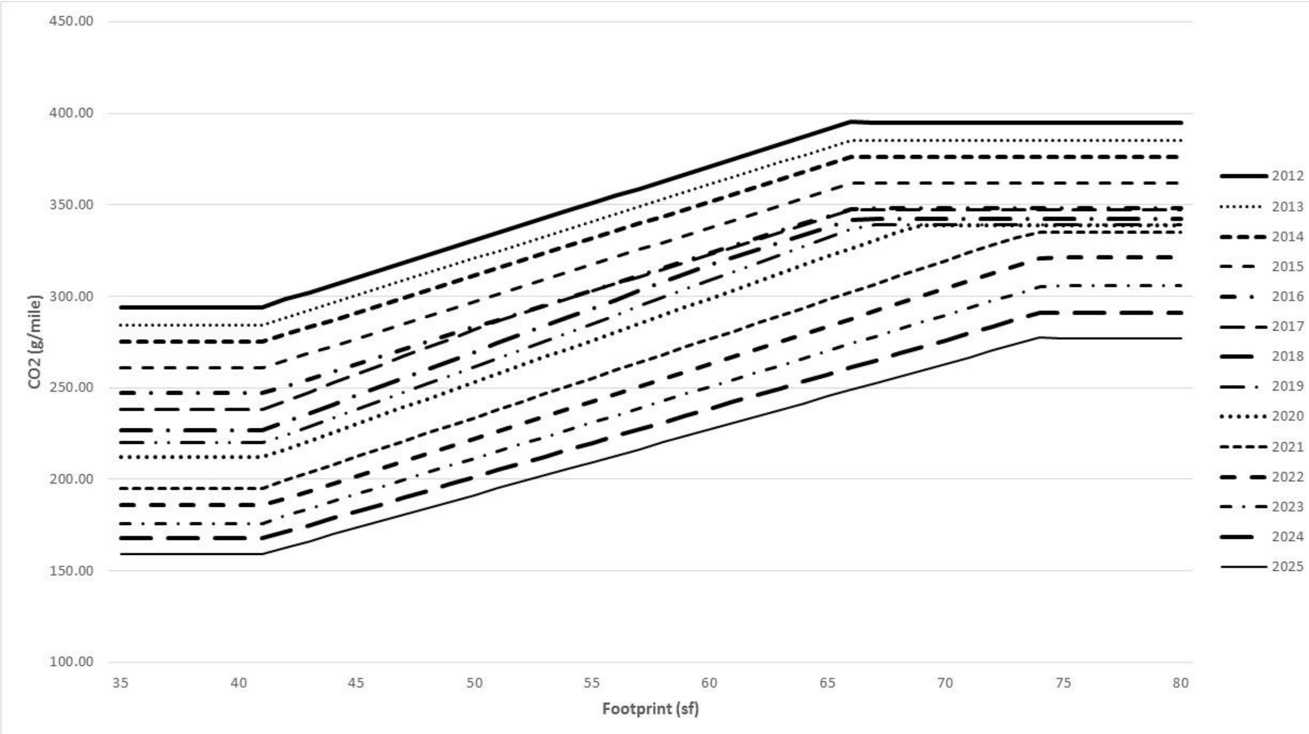

Figure 1.4 CO_2 (g/mile) Light Truck Standards Curves

Footprint-based standards help to distribute the burden of compliance across all vehicle footprints and across all manufacturers. Manufacturers are not compelled to build vehicles of any particular size or type, and each manufacturer has its own fleetwide standard for each fleet in each year that reflects the light-duty vehicles it chooses to produce. This approach also preserves consumer choice, as the standards do not constrain consumers' opportunity to purchase the size of vehicle with the performance, utility and safety features that meet their needs.

1.4 Agencies' Commitment to the Midterm Evaluation (MTE)

Given the long time frame at issue in setting standards for MY2022–2025 light-duty vehicles, and given NHTSA's statutory obligation to conduct a *de novo* rulemaking in order to establish final standards for vehicles for the 2022–2025 model years, the agencies committed in the 2012 final rule to conduct a comprehensive mid-term evaluation for the MY2022–2025 standards. The MY2017-2025 final rule noted that in order to align the agencies' proceedings for MYs 2022–2025 and to maintain a joint national program, EPA and NHTSA will finalize their actions related to MY2022–2025 standards concurrently.

As noted above, through the MTE, EPA will determine whether the GHG standards for model years 2022-2025, established in 2012, are still "appropriate," within the meaning of section 202 (a)(1) of the Clean Air Act, given the latest available data and information. EPA's decision could go one of three ways: the standards remain appropriate, the standards should be less stringent, or the standards should be more stringent. Public input on the Draft TAR, along with any new data and information, will inform the next step in the MTE process -- EPA's Proposed Determination. The Proposed Determination will be the EPA Administrator's proposal on whether the MY2022-2025 standards are appropriate. The Proposed Determination will be available for public comment, as required by EPA's regulations. If the Administrator's proposal is that the standards should change (either more or less stringent), then this action will be a Notice of Proposed Rulemaking. Public input on the Proposed Determination, as well as new data and information available, will inform the next step -- EPA's Final Determination. The Final Determination will be the Administrator's final decision on whether or not the MY2022-2025 standards are appropriate, in light of the record then before the Administrator. EPA is legally bound to make a final determination, by April 1, 2018, on whether the MY2022–2025 GHG standards are appropriate under section 202(a), in light of the record then before the agency. See generally 40 CFR 86.1818-12(h).

As stated above, EPCA limits NHTSA to setting CAFE standards for up to five years at a time, so that the MY2022-2025 CAFE provisions are only "augural," reflecting NHTSA's best judgment of what standards would have been maximum feasible at the time of the final rule, based on the information then available. The MTE is closely coordinated with NHTSA's plan to conduct a CAFE rulemaking to establish MY2022-2025 standards and NHTSA committed to fully participate in the MTE process, including this Draft Technical Assessment Report (TAR). 77 FR 62784. NHTSA's rulemaking will consider all relevant information and fresh balancing of statutory factors in order to determine the maximum feasible CAFE standards for MYs 2022–2025. In order to maintain a joint national program by aligning the agencies' proceedings for MYs 2022–2025, if the EPA determination is that its standards will not change, NHTSA will issue its final rule concurrently with the EPA final determination. If the EPA determination is that standards may change, the agencies will issue a joint NPRM and joint final rule similar to the previous two joint rulemakings. The public input on the research and analysis presented in the Draft TAR will inform NHTSA's proposed rule as well as EPA's MTE determination process.

NHTSA and EPA are conducting this mid-term evaluation in close coordination with the California Air Resources Board (CARB), given our commitment to maintaining a National Program to address GHG emissions and fuel economy. California adopted its own GHG standards for MYs 2017-2025 in 2012 prior to NHTSA and EPA finalizing the GHG and fuel economy standards for the National Program. Through direction from its Board in 2012, CARB both adopted a 'deemed to comply' provision allowing compliance with EPA's GHG standards in lieu of CARB's standards, and committed to participating with NHTSA and EPA in conducting the mid-term evaluation. EPA subsequently granted California's waiver request under the Clean Air Act on January 9, 2013 for its MY2017–2025 GHG standards.[18] To date, CARB has been involved with the preparation of this Draft TAR to inform the mid-term evaluation of the National Program.

Additionally, CARB is scheduled to provide an update to its Board in late 2016 regarding the status of the mid-term evaluation as well as a review of California-specific elements of the CARB Advanced Clean Cars (ACC) program.[19]

1.5 Climate Change and Energy Security Drivers for the National Program

The two primary policy drivers for the National Program are to reduce the U.S. contribution to global climate change (the legal basis for EPA's GHG emissions standards) and to reduce petroleum consumption and improve U.S. energy security (the legal basis for NHTSA's CAFE standards).

1.5.1 Climate Change

1.5.1.1 Overview of Climate Change Science and Global Impacts

According to the National Research Council, "Emissions of CO_2 from the burning of fossil fuels have ushered in a new epoch where human activities will largely determine the evolution of Earth's climate. Because CO_2 in the atmosphere is long lived, it can effectively lock Earth and future generations into a range of impacts, some of which could become very severe. Therefore, emission reduction choices made today matter in determining impacts experienced not just over the next few decades, but in the coming centuries and millennia."[20]

In 2009, based on a large body of robust and compelling scientific evidence, the EPA Administrator issued the Endangerment Finding under CAA section 202(a)(1).[21] In the Endangerment Finding, the Administrator found that the current, elevated concentrations of GHGs in the atmosphere—already at levels unprecedented in human history—may reasonably be anticipated to endanger public health and welfare of current and future generations in the U.S. The D.C. Circuit later upheld the Endangerment Finding from all challenges. *Coalition for Responsible Regulation v. EPA*, 684 F. 3d 102, 116-26 (D.C. Cir. 2012).

Since the administrative record concerning the Endangerment Finding closed following the EPA's 2010 Reconsideration Denial, the climate has continued to change, with new records being set for a number of climate indicators such as global average surface temperatures, Arctic sea ice retreat, CO_2 concentrations, and sea level rise. Additionally, a number of major scientific assessments have been released that improve understanding of the climate system and strengthen the case that GHGs endanger public health and welfare both for current and future generations. These assessments, from the Intergovernmental Panel on Climate Change (IPCC), the U.S. Global Change Research Program (USGCRP), and the National Research Council (NRC), include: IPCC's 2012 Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) and the 2013-2014 Fifth Assessment Report (AR5), the USGCRP's 2014 National Climate Assessment, Climate Change Impacts in the United States (NCA3), and the NRC's 2010 Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean (Ocean Acidification), 2011 Report on Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia (Climate Stabilization Targets), 2011 National Security Implications for U.S. Naval Forces (National Security Implications), 2011 Understanding Earth's Deep Past: Lessons for Our Climate Future (Understanding Earth's Deep Past), 2012 Sea Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future, 2012 Climate and Social Stress: Implications for Security Analysis (Climate and Social Stress), and 2013 Abrupt Impacts of Climate Change (Abrupt Impacts) assessments.

The findings of the recent scientific assessments confirm and strengthen the science that supported the 2009 Endangerment Finding. The NCA3 indicates that climate change "threatens human health and well-being in many ways, including impacts from increased extreme weather events, wildfire, decreased air quality, threats to mental health, and illnesses transmitted by food, water, and disease-carriers such as mosquitoes and ticks."[22] Most recently, the USGCRP released a new assessment, "The Impacts of Climate Change on Human Health in the United

States: A Scientific Assessment" (also known as the USGCRP Climate and Health Assessment). This assessment finds that "climate change impacts endanger our health" and that in the United States we have "observed climate-related increases in our exposure to elevated temperatures; more frequent, severe, or longer lasting extreme events; diseases transmitted through food, water, or disease vectors such as ticks and mosquitoes; and stresses to mental health and well-being." The assessment determines that "[e]very American is vulnerable to the health impacts associated with climate change." Climate warming will also likely "make it harder for any given regulatory approach to reduce ground-level ozone pollution," and, unless offset by reductions of ozone precursors, it is likely that "climate-driven increases in ozone will cause premature deaths, hospital visits, lost school days, and acute respiratory symptoms."[23]

Assessments state that certain populations are particularly vulnerable to climate change. The USGCRP Climate and Health Assessment assesses several disproportionately vulnerable populations, including those with low income, some communities of color, immigrant groups, indigenous peoples, pregnant women, vulnerable occupational groups, persons with disabilities, and persons with preexisting or chronic medical conditions. The Climate and Health Assessment also concludes that children's unique physiology and developing bodies contribute to making them particularly vulnerable to climate change. Children also have unique behaviors and exposure pathways that could increase their exposure to environmental stressors, like contaminants in dust or extreme heat events. Impacts from climate change on children are likely expected from heat waves, air pollution, infectious and waterborne illnesses, disruptions in food safety and security, and mental health effects resulting from extreme weather events. For example, climate change can disrupt food safety and security by significantly reducing food quality, availability and access. Children are more susceptible to this disruption because nutrition is important during critical windows of development and growth. Older people with pre-existing chronic heart or lung disease are at higher risk of mortality and morbidity both as a result of climate warming and during extreme heat events. Pre-existing chronic disease also increases susceptibility to adverse cardiac and respiratory impacts of air pollution and to more severe consequences from infectious and waterborne diseases. Limited mobility among older adults can also increase health risks associated with extreme weather and floods.

The new assessments also confirm and strengthen the science that supported the 2009 Endangerment Finding. The NRC assessment Understanding Earth's Deep Past stated that "[b]y the end of this century, without a reduction in emissions, atmospheric CO_2 is projected to increase to levels that Earth has not experienced for more than 30 million years." In fact, that assessment stated that "the magnitude and rate of the present GHG increase place the climate system in what could be one of the most severe increases in radiative forcing of the global climate system in Earth history."[24] Because of these unprecedented changes in atmospheric concentrations, several assessments state that we may be approaching critical, poorly understood thresholds. The NRC Abrupt Impacts report analyzed the potential for abrupt climate change in the physical climate system and abrupt impacts of ongoing changes that, when thresholds are crossed, could cause abrupt impacts for society and ecosystems. The report considered destabilization of the West Antarctic Ice Sheet (which could cause 3-4 m of potential sea level rise) as an abrupt climate impact with unknown but probably low probability of occurring this century. The report categorized a decrease in ocean oxygen content (with attendant threats to aerobic marine life); increase in intensity, frequency, and duration of heat waves; and increase in frequency and intensity of extreme precipitation events (droughts, floods, hurricanes, and major storms) as climate impacts with moderate risk of an abrupt change within this century. The NRC Abrupt Impacts report also analyzed the threat of rapid state changes in ecosystems and species extinctions as examples of an irreversible impact that is expected to be exacerbated by climate change. Species at most risk include those whose migration potential is limited, whether because they live on mountaintops or fragmented habitats with barriers to movement, or because climatic conditions are changing more rapidly than the species can move or adapt. While some of these abrupt impacts may be of low or moderate probability in this century, the probability for a significant change in many of these processes after 2100 was judged to be higher, with severe impacts likely should the abrupt change occur. Future temperature changes will be influenced by what emissions path the world follows. In its high emission scenario, the IPCC AR5 projects that global temperatures by the end of the century will likely be 2.6°C to 4.8°C (4.7 to 8.6°F) warmer than today. There is very high confidence that temperatures on land and in the Arctic will warm even faster than the global average. However, according to the NCA3, significant reductions in emissions would lead to noticeably less future warming beyond mid-century, and therefore less impact to public health and welfare. According to the NCA3, regions closer to the poles are projected to receive more precipitation, while the dry subtropics expand (colloquially, this has been summarized as wet areas getting wet and dry regions getting drier), while "[t]he widespread trend of increasing heavy downpours is expected to continue, with precipitation becoming less frequent but more intense." Meanwhile, the NRC Climate Stabilization Targets assessment found that the area burned by wildfire in parts of western North America is expected to grow by 2 to 4 times for 1°C (1.8°F) of warming. The NCA also found that "[e]xtrapolation of the present observed trend suggests an essentially ice-free Arctic in summer before mid-century." Retreating snow and ice, and emissions of carbon dioxide and methane released from thawing permafrost, are very likely to amplify future warming.

Since the 2009 Endangerment Finding, the IPCC AR5, the USGCRP NCA3, and three of the new NRC assessments provide estimates of projected global average sea level rise. These estimates, while not always directly comparable as they assume different emissions scenarios and baselines, are at least 40 percent larger than, and in some cases more than twice as large as, the projected rise estimated in the IPCC AR4 assessment, which was referred to in the 2009 Endangerment Finding. The NRC Sea Level Rise assessment projects a global average sea level rise of 0.5 to 1.4 meters by 2100. The NRC National Security Implications assessment suggests that "the Department of the Navy should expect roughly 0.4 to 2 meters global average sea-level rise by 2100." The NRC Climate Stabilization Targets assessment states that a global average temperature increase of 3°C will lead to a global average sea level rise of 0.5 to 1 meter by 2100. These NRC and IPCC assessments continue to recognize and characterize the uncertainty inherent in accounting for melting ice sheets in sea level rise projections.

Carbon dioxide in particular has unique impacts on ocean ecosystems. The NRC Climate Stabilization Targets assessment found that coral bleaching will likely increase due both to warming and ocean acidification. Ocean surface waters have already become 30 percent more acidic over the past 250 years due to absorption of CO_2 from the atmosphere. According to the NCA3, this "ocean acidification makes water more corrosive, reducing the capacity of marine organisms with shells or skeletons made of calcium carbonate (such as corals, krill, oysters, clams, and crabs) to survive, grow, and reproduce, which in turn will affect the marine food chain." The NRC Understanding Earth's Deep Past assessment notes four of the five major coral reef crises of the past 500 million years appear to have been driven by acidification and warming that followed GHG increases of similar magnitude to the emissions increases expected over the next hundred years. The NRC Abrupt Impacts assessment specifically highlighted similarities between the projections for future acidification and warming and the extinction at the end of the Permian which resulted in the loss of an estimated 90 percent of known species.

In addition to future impacts, the NCA3 emphasizes that climate change driven by human emissions of GHGs is already happening now and it is happening in the U.S. According to the IPCC AR5 and the NCA3, there are a number of climate-related changes that have been observed recently, and these changes are projected to accelerate in the future:

- The planet warmed about 0.85°C (1.5°F) from 1880 to 2012. It is extremely likely (>95 percent probability) that human influence was the dominant cause of the observed warming since the mid-20th century, and likely (>66 percent probability) that human influence has more than doubled the probability of occurrence of heat waves in some locations. In the Northern Hemisphere, the last 30 years were likely the warmest 30 year period of the last 1400 years.
- Global sea levels rose 0.19 m (7.5 inches) from 1901 to 2010. Contributing to this rise was the warming of the oceans and melting of land ice. It is likely that 275 gigatons per year of ice melted from land glaciers (not including ice sheets) since 1993, and that the rate of loss of ice from the Greenland and Antarctic ice sheets increased substantially in recent years, to 215 gigatons per year and 147 gigatons per year respectively since 2002. For context, 360 gigatons of ice melt is sufficient to cause global sea levels to rise 1 mm.
- Annual mean Arctic sea ice has been declining at 3.5 to 4.1 percent per decade, and Northern Hemisphere snow cover extent has decreased at about 1.6 percent per decade for March and 11.7 percent per decade for June.
- Permafrost temperatures have increased in most regions since the 1980s, by up to 3°C (5.4°F) in parts of Northern Alaska.
- Winter storm frequency and intensity have both increased in the Northern Hemisphere. The NCA3 states that the increases in the severity or frequency of some types of extreme weather and climate events in recent decades can affect energy production and delivery, causing supply disruptions, and compromise other essential infrastructure such as water and transportation systems.

In addition to the changes documented in the assessment literature, there have been other climate milestones of note. In 2009, the year of the Endangerment Finding, the average concentration of CO_2 as measured on top of Mauna Loa was 387 parts per million, far above preindustrial concentrations of about 280 parts per million.[25] The average concentration in 2015 was 401 parts per million, the first time an annual average concentration has exceeded 400 parts per million since record keeping began at Mauna Loa in 1958, and likely for at least the past 800,000 years.[26] Arctic sea ice has continued to decline, with September of 2012 marking the record low in terms of Arctic sea ice extent, 40 percent below the 1979-2000 median. Sea level has continued to rise at a rate of 3.2 mm per year (1.3 inches/decade) since satellite observations started in 1993, more than twice the average rate of rise in the 20th century prior to 1993.[27] And 2015 was the warmest year globally in the modern global surface temperature record, going back to 1880, breaking the record previously held by 2014; this now means that the last 15 years have been 15 of the 16 warmest years on record.[28]

These assessments and observed changes raise concerns that reducing emissions of GHGs across the globe is necessary in order to avoid the worst impacts of climate change, and underscore the urgency of reducing emissions now. The NRC Committee on America's Climate Choices listed a number of reasons "why it is imprudent to delay actions that at least begin the process of substantially reducing emissions."[29] For example:

- "The faster emissions are reduced, the lower the risks posed by climate change. Delays in reducing emissions could commit the planet to a wide range of adverse impacts, especially if the sensitivity of the climate to GHGs is on the higher end of the estimated range.
- Waiting for unacceptable impacts to occur before taking action is imprudent because the effects of GHG emissions do not fully manifest themselves for decades and, once manifested, many of these changes will persist for hundreds or even thousands of years.
- In the committee's judgment, the risks associated with doing business as usual are a much greater concern than the risks associated with engaging in strong response efforts."

1.5.1.2 Overview of Climate Change Impacts in the United States

The NCA3 assessed the climate impacts in eight regions of the U.S., noting that changes in physical climate parameters such as temperatures, precipitation, and sea ice retreat were already having impacts on forests, water supplies, ecosystems, flooding, heat waves, and air quality. The U.S. average temperatures have similarly increased by 1.3 to 1.9°Fs F since 1895, with most of that increase occurring since 1970, and the most recent decade was the U.S.'s hottest as well as the world's hottest. Moreover, the NCA3 found that future warming is projected to be much larger than recent observed variations in temperature, with 2 to 4°Fs F warming expected in most areas of the U.S. over the next few decades, and up to 10°Fs F possible by the end of the century assuming continued increases in emissions. Extreme heat events will continue to become more common, and extreme cold less common. Additionally, precipitation is considered likely to increase in the northern states, decrease in the southern states, and with the heaviest precipitation events projected to increase everywhere.

In the Northeast, temperatures increased almost 2°F from 1895 to 2011, precipitation increased by about 5 inches (10 percent), and sea level rise of about a foot has led to an increase in coastal flooding. In the future, if emissions continue to increase, the Northeast is projected to experience 4.5 to 10°F of warming by the 2080s. This is expected to lead to more heat waves, coastal and river flooding, and intense precipitation events. Sea levels in the Northeast are expected to increase faster than the global average because of subsidence, and changing ocean currents may further increase the rate of sea level rise.

In the Southeast, average annual temperature during the last century cycled between warm and cool periods. A warm peak occurred during the 1930s and 1940s followed by a cool period and temperatures then increased again from 1970 to the present by an average of 2°F. Louisiana has already lost 1,880 square miles of land in the last 80 years due to sea level rise and other contributing factors. The Southeast is exceptionally vulnerable to sea level rise, extreme heat events, hurricanes, and decreased water availability. Major risks of further warming include significant increases in the number of hot days (95°F or above) and decreases in freezing events, as well as exacerbated ground level ozone in urban areas. Projections suggest that there may be fewer hurricanes in the Atlantic in the future, but they will be more intense, with more Category 4 and 5 storms. The NCA identified New Orleans, Miami, Tampa, Charleston, and Virginia Beach as cities at particular risk of flooding.

In the Northwest, temperatures increased by about 1.3°F between 1895 and 2011. Snowpack in the Northwest is an important freshwater source for the region. More precipitation falling as rain instead of snow has reduced the snowpack, and warmer springs have corresponded to earlier snowpack melting and reduced stream flows during summer months. Drier conditions have increased the extent of wildfires in the region. Average annual temperatures are projected to increase by 3.3°F to 9.7°F by the end of the century (depending on future global GHG emissions), with the greatest warming is expected during the summer. Continued increases in global GHG emissions are projected to result in up to a 30 percent decrease in summer precipitation. Warmer waters are expected to increase disease and mortality in important fish species, including Chinook and sockeye salmon. Ocean acidification also threatens species such as oysters, with the Northwest coastal waters already being some of the most acidified worldwide due to coastal upwelling and other local factors.

In Alaska, temperatures have changed faster than anywhere else in the U.S. Annual temperatures increased by about 3°F in the past 60 years. Warming in the winter has been even greater, rising by an average of 6°F. Glaciers in Alaska are melting at some of the fastest rates on Earth. Permafrost soils are also warming and beginning to thaw. Drier conditions had already contributed to more large wildfires in the 10 years prior to the NCA3 than in any previous decade since the 1940s, when recordkeeping began, and subsequent years have seen even more wildfires. By the end of this century, continued increases in GHG emissions are expected to increase temperatures by 10 to 12°F in the northernmost parts of Alaska, by 8 to 10°F in the interior, and by 6 to 8°F across the rest of the state. These increases will exacerbate ongoing arctic sea ice loss, glacial melt, permafrost thaw and increased wildfire, and threaten humans, ecosystems, and infrastructure.

In the Southwest, temperatures are now about 2°F higher than the past century, and are already the warmest that region has experienced in at least 600 years. The NCA notes that there is evidence that climate-change induced warming on top of recent drought has influenced tree mortality, wildfire frequency and area, and forest insect outbreaks. At the time of publication of the NCA, even before the last 2 years of extreme drought in California, tree ring data was already indicating that the region might be experiencing its driest period in 800 years. The Southwest is projected to warm an additional 5.5 to 9.5°F over the next century if emissions continue to increase. Winter snowpack in the Southwest is projected to decline (consistent with recent record lows), reducing the reliability of surface water supplies for cities, agriculture, cooling for power plants, and ecosystems. Sea level rise along the California coast is projected to worsen coastal erosion, increase flooding risk for coastal highways, bridges, and low-lying airports, and pose a threat to groundwater supplies in coastal cities. Also, "The combination of a longer frost-free season, less frequent cold air outbreaks, and more frequent heat waves accelerates crop ripening and maturity, reduces yields of corn, tree fruit, and wine grapes, stresses livestock, and increases agricultural water consumption." Increased drought, higher temperatures, and bark beetle outbreaks are likely to contribute to continued increases in wildfires.

The rate of warming in the Midwest has markedly accelerated over the past few decades. Temperatures rose by more than 1.5°F from 1900 to 2010, but between 1980 and 2010 the rate of warming was three times faster than from 1900 through 2010. Precipitation generally increased over the last century, with much of the increase driven by intensification of the heaviest rainfalls. Several types of extreme weather events in the Midwest (e.g., heat waves and flooding) have already increased in frequency and/or intensity due to climate change. In the future, if emissions continue increasing, the Midwest is expected to experience 5.6 to 8.5°F of warming by the 2080s, leading to more heat waves. Specific vulnerabilities highlighted by the NCA include long-term decreases in agricultural productivity, changes in the composition of the region's forests, increased public health threats from heat waves and degraded air and water quality, negative impacts on transportation and other infrastructure associated with extreme rainfall events and flooding, and risks to the Great Lakes including shifts in invasive species, increases in harmful algal blooms, and declining beach health.

High temperatures (more than 100°F in the Southern Plains and more than 95°F in the Northern Plains) are projected to occur much more frequently by mid-century. Increases in extreme heat will increase heat stress for residents, energy demand for air conditioning, and water losses. In Hawaii, other Pacific islands, and the Caribbean, rising air and ocean temperatures, shifting rainfall patterns, changing frequencies and intensities of storms and drought, decreasing base flow in streams, rising sea levels, and changing ocean chemistry will affect ecosystems on land and in the oceans, as well as local communities, livelihoods, and cultures. Low islands are particularly at risk.

In Hawaii and the Pacific islands, "Warmer oceans are leading to increased coral bleaching events and disease outbreaks in coral reefs, as well as changed distribution patterns of tuna fisheries. Ocean acidification will reduce coral growth and health. Warming and acidification, combined with existing stresses, will strongly affect coral reef fish communities." For Hawaii and the Pacific islands, future sea surface temperatures are projected to increase 2.3°F by 2055 and 4.7°F by 2090 under a scenario that assumes continued increases in emissions.

1.5.1.3 Recent U.S. Commitments on Climate Change Mitigation

In 2009, President Obama adopted a goal of reducing U.S. GHG emissions by approximately 17 percent below 2005 levels by 2020.[30] The Administration subsequently took several major actions towards this goal under its Climate Action Plan, most notably the historic National Program standards to reduce new car and light truck GHG emissions levels by 50 percent by 2025 (see above for the history of the National Program), promulgating the first standards to reduce GHGs and improve fuel efficiency for medium- and heavy-duty vehicles for model years 2014-2018 (Phase 1) and proposing further Phase 2 standards for this segment, the investment of more than $80 billion in clean energy technologies under the economic recovery program, implementing various energy efficiency measures, and promulgating the Clean Power Plan (i.e. the standards of performance for new and existing electric power plant stationary sources under sections 111 (b) and (d) of the Clean Air Act) to reduce CO_2 emissions from the electric power sector.

In December 2015, the U.S. was one of over 190 signatories to the Paris Climate Agreement, widely regarded as the most ambitious climate change agreement in history. In the Paris agreement, individual countries agreed to commit to putting forward successive and ambitious nationally determined contributions (NDCs) for greenhouse gas emissions reductions to the

United Nations Framework Convention on Climate Change. Further, the countries agreed to revise their NDCs every five years, with the expectation that they will strengthen over time. The Paris agreement reaffirms the goal of limiting global temperature increase to well below 2°Fs Celsius, and for the first time urged efforts to limit the temperature increase to 1.5°Fs Celsius. The U.S. submitted a non-binding intended NDC target of reducing economy-wide GHG emissions by 26-28 percent below its 2005 level in 2025 and to make best efforts to reduce emissions by 28 percent.[31] This pace would keep the U.S. on a trajectory to achieve deep economy-wide reductions on the order of 80 percent by 2050.

1.5.1.4 Recent California Commitments on Climate Change

With climate change threatening California's resources, economy, and quality of life, the State is squarely focused on addressing it and protecting our natural and built environments. Over the past several decades, California has taken a number of innovative actions to cut emissions from the transportation sector. Collectively, the State's set of vehicle, fuels, and land use policies will cut in half emissions from passenger transportation and drivers' fuel costs over the next 20 years. California's Low Carbon Fuel Standard (LCFS) is beginning to drive the production of a broad array of cleaner fuels. Since its launch in 2011, the regulation has generated a multitude of unique approaches for cleaner fuels. The cars on California's roads are also undergoing a transformation. California's vehicle GHG standards-authorized by AB 1493 (Pavley) in 2002, first approved in 2004, and extended in 2012- are delivering both carbon dioxide reductions and savings at the pump. The transition to a fleet of lower-emitting, more-efficient vehicles in California will continue beyond 2020, as these rules cover model years through 2025, and turnover of the fleet will deliver additional benefits from these rules for many more years. California (CARB) is also working with EPA and NHTSA on national GHG standards and corresponding fuel efficiency standards for medium- and heavy-duty trucks. Furthermore, California is making major strides toward reducing the number of miles people drive, through more sustainable local and regional housing, land use, and transportation planning. However, California has recognized these actions will not be sufficient to address deep GHG emission reductions. To begin laying the foundation for further actions, the Governor issued an Executive Order in 2015 establishing new 2030 targets and a revised statewide climate plan is being developed this year. The Governor's 2030 targets include a 40 percent reduction in GHG emissions below 1990 levels, a 50 percent renewable portfolio standard for electricity (now established as law with legislation in late 2015), and a 50 percent reduction in petroleum usage from the state's cars and trucks.

Additionally, reducing emissions of short-lived climate pollutants (SLCPs), such as black carbon (BC), CH_4, and some fluorinated gases (such as a number of hydrofluoroethers and hydrofluorocarbons) may help slow the near-term rate of climate change. This may be particularly important in regions such as the Arctic, where the climate is changing most rapidly, and where BC has additional impacts due to its ability to darken snow and ice. The majority of BC emissions come from mobile sources (predominantly diesel) and open biomass burning. In April 2016, California released a Proposed SLCP Reduction Strategy which is designed to meet planning targets of reducing CH_4 and HFC emissions by 40 percent below 2013 levels by 2030, and reducing BC emissions by 50 percent below 2013 levels by 2030.

1.5.1.5 Contribution of Cars and Light Trucks to the U.S. Greenhouse Gas Emissions Inventory

The most recent U.S. GHG emission inventory[32] includes seven greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3).

Mobile sources, which include cars, light trucks and medium-duty passenger vehicles (the largest sport utility vehicles and full-size passenger vans), heavy-duty trucks and buses, airplanes, railroads, marine vessels, and a variety of smaller sources, are significant contributors of four of the seven GHGs listed above. CO_2, CH_4, and N_2O emissions are present in vehicle tailpipe emissions, and HFCs are used in automotive air conditioning systems. In recent years, the annual GHG emissions inventory due to light-duty vehicles has been slightly more than 1 billion metric tons per year. Currently, HFCs are a small fraction of the total climate forcing emissions, but they are the fastest growing source of GHG emissions in California. Across the US, emissions of HFCs are increasing more quickly than those of any other GHGs, and globally they are increasing 10-15 percent annually.[33] At that rate, emissions are projected to double by 2020 and triple by 2030.[34] The growth is driven both by increased demand for refrigeration and air-conditioning, especially for stationary applications, and because these substances were developed and are being implemented as alternatives to ozone-depleting substances (ODS) under the Montreal Protocol.[35,36]

In 2013, mobile sources emitted 30 percent of all U.S. GHG emissions, the second largest contribution after power plants. Transportation sources, which are largely synonymous with mobile sources but which exclude certain off-highway sources such as farm and construction equipment, account for 27 percent of U.S. GHG emissions. Motor vehicles alone, which include cars, light trucks and medium-duty passenger vehicles, heavy-duty trucks and buses, and motorcycles, are responsible for 23 percent of U.S. GHG emissions. CO_2 emissions represent 96 percent of total mobile source GHG emissions.

Cars, light trucks, and medium-duty passenger vehicles, the motor vehicles covered by the Light-Duty GHG/CAFE National Program, alone account for 16 percent of all U.S. GHG emissions.

1.5.1.6 Importance of the National Program in the U.S. Climate Change Program

The Light-Duty GHG/CAFE National Program is a centerpiece of the U.S. climate change program. The GHG standards that took effect with model year 2012 cars, light trucks, and medium-duty passenger vehicles, promulgated under the Clean Air Act, were the first-ever national GHG emissions standards in the U.S.

The Light-Duty GHG/CAFE National Program is projected to achieve very large GHG emissions reductions. In the analysis for the 2025 rulemaking, EPA projected that the cumulative GHG emissions savings over the lifetimes of the new light duty vehicles sold in model years 2012 through 2025 would be 6 billion metric tons (these reductions would begin in calendar year 2012 and would end in the calendar year when the last model year 2025 vehicles would be retired from the fleet).[37]

Because EPA GHG emissions standards will remain in effect unless and until they are changed, GHG emissions savings will continue to accrue for vehicles sold after model year 2025, and these longer-term GHG emissions (CO_2e) savings are not reflected in the 6 billion metric ton value above. In terms of on-the-ground reductions in specific calendar years, EPA projected, in the 2012 Final Rule analysis, that the National Program would yield GHG (CO_2e) emissions reductions of 180 million metric tons (MMT) in calendar year 2020, 380 MMT in 2025, 580 MMT in 2030, 860 MMT in 2040, and 1100 MMT in calendar year 2050. The cumulative GHG emissions savings over calendar years 2012 through 2050 were projected to be 22 billion metric tons.[38]

Comparing GHG emissions reductions across various countries and policies is complicated, involving many assumptions in order to yield "apples-to-apples" comparisons. In 2014, The Economist published a comparison of global programs that yielded large GHG emissions reductions. [39] In terms of annual GHG emissions reductions, the article concluded that the Light-Duty GHG/CAFE National Program yielded the sixth-greatest rate of GHG emissions reductions among all of the programs evaluated, worldwide.

1.5.2 Petroleum Consumption and Energy Security

1.5.2.1 Overview of Petroleum Consumption and Energy Security

In 1975, Congress enacted the Energy Policy and Conservation Act (EPCA) mandating that NHTSA establish and implement a regulatory program for motor vehicle fuel economy to address "the need of the United States to conserve energy." While the U.S. has plentiful resources for most energy feedstocks, the one source of energy for which the U.S. has been dependent upon imports for many decades is petroleum. Accordingly, NHTSA concluded that the EPCA goal of "the need of the United States to conserve energy" means "the consumer cost, national balance of payments, environmental, and foreign policy implications of our need for large quantities of petroleum, especially imported petroleum."[40] NHTSA first implemented the corporate average fuel economy (CAFE) program in 1978. Congress reaffirmed the CAFE program with the Energy Independence and Security Act (EISA) of 2007.

Dependence on imported petroleum leads to many risks: the potential for oil suppliers to manipulate market mechanisms and thereby raise prices, the threat of supply disruptions which can have significant economic and national security ramifications, and the export of domestic capital to pay for imported petroleum which can have a wide variety of deleterious impacts on domestic economic growth and trade balances. For these reasons, reducing excessive reliance on imported oil has been a national priority since the first oil embargo in 1973-1974. Despite these concerns, net imports of petroleum grew fairly consistently for three decades from around 5 million barrels per day (MBPD) in the early 1970s to over 12 MBPD in 2004-2007, and the import share of U.S. oil consumption over the same period doubled from about 30 percent to about 60 percent.[41] The direct costs of U.S. net oil imports fluctuate with world oil prices, of course, ranging in this century from a little over $100 billion in 2000 to an all-time high of nearly $400 billion in 2008.[42] The U.S. reliance on imported petroleum has decreased significantly in recent years as domestic oil and natural gas liquids production reversed its historical decline and increased from 6.8 MBPD in 2008 to 11.7 MBPD in 2014, at a time when total domestic petroleum demand decreased slightly.[43] Accordingly, net oil imports have declined from a peak of over 12 MBPD a decade ago to 5.0 MBPD in 2014, representing 27 percent of total U.S. oil consumption, with the latter value similar to that in the early 1970s.[44]

While oil imports have declined in recent years, oil prices rose from $15-30 per barrel in the late 1980s through the early 2000s to $50-100 per barrel since, which yields national average gasoline prices of $2.50 to $4.00 per gallon. Accordingly, while payments for imported oil have decreased, payments for total U.S. oil consumption remained at about $600 billion in 2014. These higher oil prices have yielded national average gasoline prices on the order of $3-4 per gallon over much of the last few years, which significantly increased the cost-of-living for American families. Gasoline prices have fallen since late 2014 and averaged about $2.50 per gallon during most of 2015. As of February 2016, the Short-Term Energy Outlook from EIA forecasts the U.S. retail regular gasoline price to average $1.98 per gallon in 2016 and $2.21 per gallon in 2017.[45] U.S. drivers have benefited considerably from these low prices. Nevertheless, DOT must set fuel economy standards considering estimates of future fuel prices.

The history of the oil market over the last few decades has been longer periods of relative stability interrupted by shorter periods of high market volatility. Oil prices dropped significantly in late 2014, and so U.S. payments for both imported oil and total oil are lower today than in the recent past. The Energy Information Administration's AEO 2015 projected a wide range of possible oil prices out to 2040, ranging from a low of $76 per barrel under its Low Oil Price scenario to a high of $252 per barrel in its High Oil Price scenario, with a reference case price of $141 per barrel (all Brent Spot Prices in 2013 dollars).[46] The uncertainty and volatility associated with world oil prices are another risk associated with our dependence on petroleum.

1.5.2.2 Recent U.S. Commitments on Petroleum and Energy Security

Dependence on imported oil has been identified as an important challenge since the first oil embargo in 1973-74.

On March 30, 2011, the U.S. pledged to reduce oil imports by one-third by 2025, or by about 3.6 MBPD.[47] The long-term strategy advanced for achieving this historic reduction in oil imports included several elements: fuel economy/GHG standards for both light-duty and heavy-duty vehicles, expanding domestic oil development, and developing alternative fuels. Due to a combination of factors, primarily increased domestic oil production, but also higher oil prices and the first few years of the CAFE/GHG standards, the one-third reduction in oil imports, or 3.6 MBPD, has already been achieved well in advance of 2025. The broader challenge will be to retain, or even build on, this successful reduction in oil imports over the next decade given the history of volatility in oil markets.

1.5.2.3 Contribution of Cars and Light Trucks to U.S. Petroleum Consumption

In 2014, transportation sources accounted for 70 percent of U.S. petroleum consumption. Cars, light trucks, and medium-duty passenger vehicles, the motor vehicles covered by the National Program, account for about 60 percent of all U.S. transportation oil consumption, about 8 million barrels per day, or about 42 percent of total U.S. petroleum consumption.[48]

1.5.2.4 Importance of National Program to Petroleum Consumption and Energy Security

The CAFE standards have long been regarded as a major reason for the significant increase in average light vehicle fuel economy from the late 1970s through the mid-1980s, and therefore reduced petroleum consumption and improved energy security relative to what would likely have been the case without the CAFE standards.[49] While the CAFE standards were relatively unchanged from the mid-1980s through the mid-2000s, the standards began to be raised for MY2005 for light trucks and then for both cars and light trucks in MY2011.[50] The National Program, which covers new cars, light trucks, and medium-duty passenger vehicles beginning in MY2012, represent the most significant increases in fuel economy standards in over 30 years.

The projected oil savings from the Light-Duty GHG/CAFE National Program are very significant. Fuel economy improvements under U.S. CAFE standards have already helped the Nation to reduce its fuel consumption by more than a trillion gallons of fuel. New standards have the potential to help the Nation to reduce its fuel consumption by a similar amount between now and 2050.

These very large reductions in fuel consumption should dampen world oil prices (see further discussion in Chapter 10) which would further increase consumer fuel savings that are not directly included in our projections.

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[1] 75 FR 25324, May 7, 2010.
[2] 77 FR 62624, October 15, 2012.
[3] See 40 CFR 86.1818-12(h).
[4] See 40 CFR 86.1818-12(h)(2)(i).
[5] 77 FR 62784, October 15, 2012.
[6] 77 FR 62639, October 15, 2012.
[7] 49 U.S.C. 32902.
[8] *Center for Biological Diversity v. NHTSA, 508 F. 3d 508 (9th Cir. 2007).*
[9] 549 U.S. 497 (2007).
[10] 68 FR 52922 (Sept. 8, 2003).
[11] 549 U.S. at 531–32.
[12] For further information on Massachusetts v. EPA see the July 30, 2008 Advance Notice of Proposed Rulemaking, ‘‘Regulating Greenhouse Gas Emissions under the Clean Air Act’’, 73 FR 44354 at 44397. There is a comprehensive discussion of the litigation’s history, the Supreme Court’s findings, and subsequent actions undertaken by the Bush Administration and the EPA from 2007–2008 in response to the Supreme Court remand. Also see 74 FR 18886, at 1888–90 (April 24, 2009).
[13] 75 FR 25324, May 7, 2010.
[14] 77 FR, 62624, October 15, 2012.
[15] Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013, EPA Publication number EPA 430-R-15-004, April 15, 2015.
[16] 49 CFR 523.2.
[17] See 49 CFR 531.5 and 49 CFR 533.5 for the CAFE standards for passenger cars and light trucks, respectively, and 40 CFR 86.1818-12 for the GHG standards.
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[19] http://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/consumer_acc.htm.
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Chapter 2: Overview of the Agencies' Approach to the Draft TAR Analysis

2.1 Factors Considered in this Report

The Midterm Evaluation (MTE) is a comprehensive assessment of all of the factors considered by the agencies in setting the MY 2022-2025 standards. The 2017-2025 final rule (FRM) preamble stated that *"both NHTSA and EPA will develop and compile up-to-date information for the midterm evaluation through a collaborative, robust and transparent process, including public notice and comment. The evaluation will be based on (1) a holistic assessment of all the factors considered by the agencies in setting standards, including those set forth in this final rule and other relevant factors and (2) the expected impact of those factors on the manufacturers' ability to comply, without placing decisive weight on any particular factor or projection*."[A]

The 2017-2025 final rule preamble further provided an outline of what the agencies would consider in the Draft TAR, stating that the *"TAR will examine the same issues and underlying analyses and projections considered in the original rulemaking, including technical and other analyses and projections relevant to each agency's authority to set standards as well as any relevant new issues that may present themselves."*[B] For EPA's part, the EPA regulations state that in making the determination required, the Administrator *"shall consider the information available on the factors relevant to setting greenhouse gas emission standards under section 202(a) of the Clean Air Act for model years 2022 through 2025, including but not limited to:*

- *The availability and effectiveness of technology, and the appropriate lead time for introduction of technology;*
- *The cost on the producers or purchasers of new motor vehicles or new motor vehicle engines;*
- *The feasibility and practicability of the standards;*
- *The impact of the standards on reduction of emissions, oil conservation, energy security, and fuel savings by consumers;*
- *The impact of the standards on the automobile industry;*
- *The impacts of the standards on automobile safety;*
- *The impact of the greenhouse gas emission standards on the Corporate Average Fuel Economy standards and a national harmonized program; and*
- *The impact of the standards on other relevant factors."*[C]

The preamble to the final rule further listed ten relevant factors that the agencies will consider at a minimum during the MTE.[D] These factors are:

- Development of powertrain improvements to gasoline and diesel powered vehicles (Chapter 5)
- Impacts on employment, including the auto sector (Chapter 7)

[A] 77 FR 62652, October 15, 2012.
[B] 77 FR 62784, October 15, 2012.
[C] 40 CFR 86.1818-12(h).
[D] 77 FR 62784, October 15, 2012.

- Availability and implementation of methods to reduce weight, including any impacts on safety (Chapter 5 and 8)
- Actual and projected availability of public and private charging infrastructure for electric vehicles, and fueling infrastructure for alternative fueled vehicles (Chapter 9)
- Costs, availability, and consumer acceptance of technologies to ensure compliance with the standards, such as vehicle batteries and power electronics, mass reduction, and anticipated trends in these costs (Chapters 5, 6, 12, and 13)
- Payback periods for any incremental vehicle costs associated with meeting the standards (Chapter 12 and 13)
- Costs for gasoline, diesel fuel, and alternative fuels (Chapters 10, 12 and 13)
- Total light-duty vehicle sales and projected fleet mix (Chapter 4)
- Market penetration across the fleet of fuel efficient technologies (Chapter 3, 4, 12, and 13)
- Any other factors that may be deemed relevant to the review

Each of the factors listed above is addressed in this Draft TAR, primarily in the chapters indicated above. Among the other factors deemed relevant, EPA's analysis for the Draft TAR examines the potential impact of the California Zero Emission Vehicle (ZEV) program which California has revised since the final rule (Chapter 4) and both EPA and NHTSA also examined the availability and use of credits, including credits for emission reductions from air conditioning improvements and off-cycle technologies (Chapters 5 and 11).

2.2 Gathering Updated Information since the 2012 Final Rule

The agencies' goal is that the midterm evaluation will be conducted through a collaborative, data-driven, and transparent process. In gathering data and information for this Draft TAR, the agencies pulled from a wide range of sources. These sources included research projects initiated by the agencies, input from stakeholders, and information from technical conferences, published literature, and studies published by various organizations. Each of these sources is described further below. The agencies will continue to gather and evaluate more up-to-date information to inform our analyses as we move forward with our respective actions.

2.2.1 Research Projects Initiated by the Agencies

EPA, NHTSA, and CARB have each initiated new research since the 2012 final rule to inform the MTE. This research has been coordinated across the three agencies and, where possible, each agency has made the results of a variety of projects available to the public (e.g., through published papers, presentations at public forums and on agency web sites).[E] This section summarizes each agency's research projects in more detail.

EPA has research projects underway in a wide range of areas. Through the National Vehicle and Fuel Emissions Laboratory (NVFEL) in Ann Arbor, Michigan, starting in 2013 EPA has been conducting a major research benchmarking program for advanced engine and transmission technologies. To date, more than 20 currently available production vehicles have been tested to

[E] For EPA projects, see http://www3.epa.gov/otaq/climate/mte.htm; for NHTSA projects, see http://www.nhtsa.gov/Laws+&+Regulations/CAFE+-+Fuel+Economy/ld-cafe-midterm-evaluation-2022-25 and http://www.nhtsa.gov/Laws+&+Regulations/CAFE+-+Fuel+Economy/nhtsa-epa-carb-workshop-03012016.

assess their engine and/or transmission efficiencies. These data provide inputs and validation for EPA's vehicle simulation model, the Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) model (described further in Chapter 5.3). Thus far, EPA has published more than 15 papers for SAE International describing various aspects of the benchmarking program and ALPHA model validation work.[1]

EPA has continued studies of the costs of fuel economy technologies through state-of-the art cost teardown studies with the engineering firm FEV. EPA has built upon the cost teardown work supporting the FRM with new technologies, including mild hybrid systems, advanced boosted engines, naturally aspirated high compression ratio engines, and diesel engines.[2] In addition, the previous teardown studies have been updated to reflect current costs. In other research related to the costs of the program, EPA commissioned a literature review of the effects of manufacturer "learning by doing."[3]

EPA has built upon previous studies of mass reduction feasibility and costs with the addition of a new study examining the mass reduction potential of full-size light-duty pickup trucks. This study builds upon the mass reduction studies done previously by EPA and NHTSA, respectively, for a mid-size crossover vehicle and mid-size sedan.

EPA has initiated research on consumer issues, including a project exploring automotive reviews of fuel economy technologies,[4] an assessment of consumer satisfaction of new vehicle purchases, a review of literature on consumers' willingness to pay for vehicle attributes, and an updated assessment of vehicle affordability that examines potential impacts on low-income households, low-priced vehicle segments, and the automotive loan market.[5]

In continuing to explore economic impacts of the standards, EPA has completed new research on the vehicle miles travelled (VMT) rebound effect[6], and is currently conducting a literature review of the research on the light-duty vehicle VMT rebound effect.

Finally, EPA has continued the development of modeling tools, including the ALPHA full vehicle simulation model,[7] the Optimization Model for reducing Emissions of Greenhouse gases from Automobiles (OMEGA), and the Lumped Parameter Model (LPM) for assessing vehicle technology package efficiencies. EPA also has continued to explore the potential use of consumer choice modeling by attempting to validate EPA's current working model with actual market impacts.[8]

NHTSA has also sponsored new studies and research to inform the midterm evaluation:

The National Academy of Sciences (NAS) has long had a role in helping to inform NHTSA on issues related to fuel economy. Section 107 of EISA 2007 instructed NHTSA to contract with the NAS to "develop a report evaluating vehicle fuel economy standards, including an assessment of automotive technologies and costs to reflect developments since the [NAS]'s 2002 report (NAS 2002) evaluating the corporate average fuel economy standards was conducted and an assessment of how such technologies may be used to meet the new fuel economy standards." Section 107 also noted that the report should be updated at 5-year intervals through 2025.

In 2011, the first such report in response to this mandate was released, "Assessment of Fuel Economy Technologies for Light-Duty Vehicles" (NAS 2011).[F] This is referred to as the Phase 1 report, which examined categories of near-term technologies important for reducing fuel consumption, their costs, issues associated with estimating costs and price impacts of these technologies, and approaches for estimating the fuel consumption benefits from combinations of these technologies.

In 2015, NAS issued the second report (NAS 2015) in this series titled "Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles."[G] The Phase 2 report was purposely timed to inform the mid-term evaluation by considering technologies applicable in the 2020 to 2030 timeframe. In particular, the committee was asked to include the following in its assessment:

- Methodologies and programs used to develop standards for passenger cars and light trucks under current and proposed CAFE programs;
- Potential for reducing mass by up to 20 percent, including materials substitution and downsizing of existing vehicle designs, systems or components;
- Other vehicle technologies whose benefits may not be captured fully through the federal test procedure, including aerodynamic drag reduction and improved efficiency of accessories;
- Electric powertrain technologies, including the capabilities of hybrids, plug-in hybrids, battery electric vehicles, and fuel cell vehicles;
- Advanced gasoline and diesel engine technologies that will increase fuel economy;
- Assumptions, concepts, and methods used in estimating the costs of fuel economy improvements, including the degree to which time-based cost learning for well-developed existing technologies and/or volume-based cost learning for newer technologies should apply, and the differences between Retail Price Equivalent and Indirect Cost Multipliers;
- Analysis of how fuel economy technologies may be practically integrated into automotive manufacturing processes and how such technologies are likely to be applied;
- Costs and benefits in vehicle value that could accompany the introduction of advanced vehicle technologies;
- Test procedures and calculations used to determine fuel economy values for purposes of determining compliance with CAFE standards; and,
- Assessment of the consumer impacts of factors that may affect changes in vehicle use.

The overall report estimates the cost, potential efficiency improvements, and barriers to commercial deployment of technologies that might be employed from 2020 to 2030. The report describes these promising technologies and makes recommendations for their inclusion on the list of technologies applicable for the 2022-2025 CAFE standards.

[F] Available at http://www.nap.edu/catalog/12924/assessment-of-fuel-economy-technologies-for-light-duty-vehicles (last accessed Feb. 26, 2016).

[G] Available at http://www.nap.edu/catalog/21744/cost-effectiveness-and-deployment-of-fuel-economy-technologies-for-light-duty-vehicles (last accessed Feb. 26, 2016).

NHTSA has funded new work at Argonne National Laboratory (ANL) to conduct large-scale simulation using DOE's Autonomie vehicle simulation tool to estimate the effects of combinations of technologies on fuel economy. Simulation of feasible technology combinations will yield databases that are flexible, account for all technology interactions, and can be fed directly into the CAFE model, which NHTSA uses for fleet-level analysis. Numerous presentations and papers on the new work have been presented at conferences.[9,10,11,12,13,14]

NHTSA conducted a mass reduction and feasibility cost study on a passenger car to determine the maximum feasible weight reduction while maintaining the same vehicle functionalities, such as performance, safety, crash rating etc., as the baseline vehicle. Furthermore, another objective was to maintain retail price of the light-weighted vehicle(s) within +10 percent of the original vehicle. The original report, cost, Computer-Aided Engineering (CAE) models, and peer review report are all publicly available on the NHTSA website.[15,16,17] The mass reduction study is discussed in detail in Chapter 8.

NHTSA has funded a similar mass reduction feasibility and cost study for a full-size pickup (MY 2014 Chevrolet Silverado) that is ongoing. A related study is ongoing on the production costs of changing vehicle attributes (e.g., track width, wheelbase) and determining the effect of these changes on other vehicle characteristics that affect fuel economy.

The FRM also relied on statistical analysis of historical crash data to assess the effects of vehicle mass reduction and size on safety.[18] In addition, Volpe is working to update a 2012 report on the relationship between vehicle mass (represented as curb weight) and societal fatality risk.[19] The updated analysis incorporates data from multiple sources required to represent fatalities, baseline driving risk (i.e., induced exposure), and VMT across distributions of driver-, crash- and vehicle-specific factors. The primary sources applied within the analysis are: the Fatality Analysis Reporting System (FARS), State crash records, R.L. Polk's National Vehicle Population Profiles (NVPP) and odometer readings, and a range of sources of values for curb weight, footprint, track width, wheelbase and other vehicle attributes.

Certain studies used to inform the 2012 final rule continue to inform the safety analysis for the Draft TAR:

- Systems modeling to assess the effects of future lightweight vehicle designs on overall fleet safety. The approach includes estimating the real-world level of safety in a vehicle for its own occupants (self-protection) and for the occupants in vehicles with which it collides (partner protection.[20]

Fuel economy and GHG emissions standards benefit society by reducing fuel and emissions resulting from the operation of motor vehicles, so estimates of the extent to which vehicles will be driven annually are central to the agencies' evaluation of the benefits of new standards. Based on an analysis of more than 70 million odometer readings reported by IHS Automotive (formerly R.L. Polk), NHTSA has developed updated estimates of annual mileage accumulation over vehicles' useful lives. We note that there are many factors that influence how much people drive aside from fuel efficiency.

CARB has also undertaken research since the 2012 rule was finalized. To meet fuel economy and greenhouse gas standards, it is expected that the vast majority of reductions will come from improvements to the vehicle powertrain—specifically, the engine and the transmission.

However, there are other improvements that can increase efficiency and the agencies did assume some reductions from these areas. Notably, items like vehicle aerodynamics, low rolling resistance tires, and making vehicles lighter can have an appreciable contribution by making it easier for the vehicle to overcome resistance from wind and road friction, and thus go farther on the same amount of fuel. To better understand some of the possibilities for these other technologies, CARB commissioned a study with Novation Analytics (formerly known as ControlTec). The study analyzed all available vehicles in the 2014 model year, identified the better performers in class-specific road load characteristics, and then upgraded the entire vehicle fleet to nominally have best-in-class aerodynamics, tire rolling resistance, and mass efficiency. The road load reduction study is discussed in further detail in Appendix A.

2.2.2 Input from Stakeholders

In developing this Draft TAR, the agencies gathered input, data, and information from a wide range of stakeholders. The agencies conducted outreach with numerous stakeholders, including auto manufacturers, automotive suppliers, environmental and other non-governmental organizations (NGOs), consumer groups, labor unions, automobile dealers, state and local governments, fuels and energy providers, and others. Below we characterize the nature of the dialogs conducted with various stakeholders and the kinds of information shared with the agencies.

2.2.2.1 Automobile Manufacturers

The agencies met with nearly all automobile manufacturers individually as well as through their trade associations on numerous occasions. We met with automakers including BMW, Fiat-Chrysler, Ford, General Motors, Honda[H] Jaguar Land Rover, Mazda, Mercedes-Benz, Nissan, Porsche, Subaru, Tesla, Toyota, Volkswagen, and Volvo. Individually, each auto manufacturer generally provided the agencies with information on the company's overall strategy for meeting the 2022-2025 GHG/CAFE standards, the technologies and products they planned to bring to market and the sequence of that product plan, input on the effectiveness, costs, and implementation of those technologies, and challenges in meeting the standards. Several companies also provided feedback on credit provisions contained in the existing GHG and CAFE programs, and offered ideas on additional flexibilities that the companies believed could ease implementation of the program. By its nature, most of the information provided to the agencies was claimed to be confidential business information.

The automobile manufacturer trade associations, the Alliance of Automobile Manufacturers and the Global Automakers, provided the agencies with information on several technical projects they initiated. This work included an assessment of the penetration of GHG/fuel economy technologies in model year 2012-2014 vehicles, an assessment of technology effectiveness, and an assessment of vehicle footprint.

2.2.2.2 Automotive Suppliers

[H] Per Honda's request, EPA has placed in the docket a public version of the company's presentation materials, from a meeting on October 7, 2015. The presentation materials for other auto manufacturers were designated as confidential business information by the manufacturers.

The agencies met with numerous automotive suppliers on several occasions, including Aisin, Borg-Warner, Bosch, Continental, Dana, Delphi, Denso, Eaton, Getrag, Honeywell, Jatco, Mahle, Ricardo, Roechling Automotive, Schaeffler, Tennaco, Valeo, and many others. Automotive suppliers provided the agencies with detailed information on the effectiveness, costs, lead-time and implementation issues surrounding various GHG/fuel economy technologies including powertrain systems, engines, transmissions, accessories, tires, valve trains, axles, active aerodynamics, braking systems, and electrification (stop-start, mild hybrids, 48-volt systems). Much of this information was used directly to inform the agencies' inputs for technology costs, effectiveness, and lead-time, which are described in detail in Chapter 5.

In addition, the agencies met with many trade organizations of various materials used in automotive manufacturing, including the Aluminum Association, American Plastics Council, American Iron and Steel Institute, and others. Much of this discussion related to the potential for various materials, such as high-strength steel, aluminum, and plastics, to contribute to vehicle mass reduction, which is described further in Chapter 5.

2.2.2.3 Environmental Non-governmental Organizations (NGOs) and Consumer Groups

The agencies met with a broad coalition of organizations representing both environmental and consumer advocacy, including the Union of Concerned Scientists, Natural Resources Defense Council, Environmental Defense Fund, Sierra Club, American Council for an Energy Efficient Economy, International Council on Clean Transportation, Environment America, Safe Climate Campaign, Blue Green Alliance, Ceres, Consumer Federation of America, Consumers Union, Pew Charitable Trusts, Better World Group, and Cater Communications. The groups stressed the need to ensure that the environmental benefits expected when the National Program was finalized are actually realized, noting that the Paris international climate agreements will require continued substantial further reductions in GHG emissions across all sectors, including transportation. The organizations pointed to the rapid pace of automotive technology advancements in the marketplace and the important role of the standards in setting long-term targets and stimulating innovation, and encouraged the agencies to ensure the Draft TAR analyses are based on the latest data and projections for technology developments out to the 2025 timeframe. Consumer groups relayed survey information showing that consumers continue to want fuel economy improvements, since they expect gas prices will rise. Consumer groups also noted that gasoline costs are a significant portion of consumers' pocketbook spending, even more so for lower income families. Several NGOs noted research projects they're initiating to address issues relevant to the MTE. The groups also stressed the need for additional GHG reductions beyond 2025, and encouraged the agencies to begin exploring a framework for post-2025 standards.

2.2.2.4 State and Local Governments

The National Association of Clean Air Agencies (NACAA), including many of their state and local government members, met with the agencies to express their support for strong GHG and fuel economy standards. NACAA members expressed their perspective that they are seeing many fuel saving technologies already in today's vehicles and at greater levels than expected when the standards were first set. The state/local government agency representatives believe that the public is concerned about potential rising fuel prices and that, regardless of pump prices, consumers value the fuel savings that come from improved efficiency. NACAA members urged the agencies to conduct a forward-leaning analysis, believing that technologies will develop even faster than the agencies project. The state/local governments want to ensure not only the significant GHG reductions from these standards, but also the co-pollutant benefits that come from reduced fuel consumption. NACAA also encouraged the agencies to begin working toward strong standards for post-2025.

2.2.3 Other Key Data Sources

In addition to relying on research from the agencies' studies and gathering input from stakeholders, the agencies also reviewed relevant studies published by other organizations. One key study informing the agencies' assessment is the National Research Council (NRC) of the National Academies of Sciences (NAS) report, "Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles" issued in June 2015, as discussed above.[21] Throughout this Draft TAR, the agencies discuss specific information provided in the NAS report, as well as address many of the report's recommendations.

The agencies have relied on studies published by other federal government organizations, including the Department of Energy (DOE) studies in areas such as vehicle mass reduction, impacts of mass reduction on vehicle safety, and battery cost modeling. The Energy Information Administration's (EIA) 2015 Annual Energy Outlook formed the basis for the agencies' assumptions about full production, future fuel prices, and the sizes of the future passenger car and light truck markets. Market forecast information from IHS Automotive informed assumptions regarding brand and segment shares of the future light vehicle market.

Beyond our partners in the U.S. government, the Canadian government, including Environment and Climate Change Canada (ECCC) and Transport Canada, has supported significant research in the areas of vehicle light-weighting, aerodynamics, tire efficiency, the effect of mass reduction on vehicle dynamics performance (e.g., braking and handling), and all-wheel drive vehicle technology. These reports are described in more detail in Chapter 5. This work is part of a collaboration under the framework of the Canada-U.S. Air Quality Agreement which includes a commitment for ECCC and EPA to work together toward the alignment of vehicle and engine emission regulations and coordinated implementation. The Canadian government has established light-duty GHG standards aligned with the U.S. standards through 2025, and Canada plans to collaborate with the U.S. on a midterm evaluation of the model year 2022-2025 standards.

The agencies stayed abreast of technology and economic developments by reviewing published literature and attending technical/scientific conferences.[22] For example, since late 2012, there have been hundreds of papers published in the literature (e.g., SAE International) related to GHG/fuel economy technologies, as well as numerous publications presented in other forums. Collectively the agencies' staff attended more than 60 technical conferences. Data gathered from these papers and conferences directly informed the technology inputs described in detail in Chapter 5. Agency staff also reviewed relevant literature on the host of other issues discussed throughout this Draft TAR, including climate science and energy security issues, economic issues (such as rebound, automotive employment, affordability, consumer willingness to pay for vehicle attributes), transportation issues (such as travel demand), and others.

2.3 Agencies' Approach to Independent GHG and CAFE Analyses

NHTSA, CARB, and EPA have made significant updates to the assessment of CAFE and GHG technology readiness, technology effectiveness, and technology costs since the 2012 FRM, including investigating a number of technologies not considered in 2012. These efforts are consistent with the recommendations of the 2015 NAS report[I] and reflect the significant rate of technological progress that has been made in the automotive industry since the FRM.[J] While all three agencies have been working collaboratively on an array of issues throughout this initial phase of the Midterm Evaluation, much of the EPA GHG and DOT CAFE assessments were done largely independently. The independent analyses were done in some part to recognize differences in the agencies' statutory authorities and through independent decisions made in each agency. The agencies all agree that independent and parallel analyses can provide complementary results, and in this Draft TAR the independent NHTSA CAFE assessment and EPA GHG assessment both show that the 2022-2025 standards can largely be achieved through the use of advanced gasoline vehicle technologies with modest penetration of lower cost electrification (like 12-volt start/stop and 48-volt mild hybrids) and low penetrations of higher cost electrification (like strong hybrids, plug-in hybrids, and all electric vehicles). The CAFE and GHG assessments show just two of a number of potential pathways for meeting the MY2022-2025 standards.

It is clear that the automotive industry is innovating and bringing new technology to market at a brisk pace and neither of the respective agency analyses reflect all of the latest and emerging technologies that may be available in the 2022-2025 time frame. For example, the agencies were not able for this Draft TAR to evaluate the potential for technologies such as electric turbo-charging, variable compression ratio, skip-fire cylinder deactivation, and P2-configuration mild-hybridization. These technologies may provide further cost effective reductions in fuel consumption and the agencies will continue to update their respective analyses throughout the MTE process as new information becomes available.

Both agencies have made broad use of the application of full-vehicle simulation. This is consistent with the NAS's conclusions in its 2015 report: "Full system simulation is acknowledged to be the most reliable method for estimating fuel consumption reductions for technologies before prototype or production hardware becomes available for testing." In addition, the NAS also concluded that: "For spark ignition engines, these simulations should be directed toward the most effective technologies that could be applied in 2025 MY to support the midterm review of the CAFE standards." There are many readily available options for full-vehicle simulation software. Many vehicle manufacturers use their own, internally developed simulation software to estimate the effectiveness of technologies. In addition, full-vehicle simulation software packages are also available through engineering consulting firms, such as Southwest Research Institute, FEV, Ricardo, AVL, and through academia.

For the 2012 FRM, both NHTSA and EPA relied on simulation results produced by Ricardo using Ricardo's proprietary Easy 5 model. Both agencies agreed that greater transparency would

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[I] See Chapter 2.2.1 for further discussion of the NAS report.

[J] See for example Finding 2.4 from the 2015 NAS Study - "Other Technologies by 2025 Not Considered by EPA/NHTSA," in which the Committee recommends that NHTSA and EPA consider evaluating a number of gasoline engine technologies not evaluated in the 2012 Final Rule.

improve the robustness of the regulatory process and both agencies made independent decisions as to how best to meet this goal. For this Draft TAR, NHTSA contracted with the Department of Energy's Argonne National Lab (ANL) to employ the use of the Autonomie model. Autonomie was developed by ANL and has been largely informed by benchmarking work performed in ANL's Advanced Powertrain Research Facility and by engine technology analysis performed by IAV Automotive Engineering. For light-duty, the EPA vehicle simulation model is referred to as ALPHA - Advanced Light-duty Powertrain and Hybrid Analysis tool.[K] The supporting benchmarking and development of ALPHA has been completed by EPA's National Center for Advanced Technology (NCAT). In addition, both agencies have applied information regarding technology effectiveness from sources other than full-vehicle simulation modeling. These sources include, for example, stakeholder meetings, the 2015 NAS report, and information from the technical literature and publications from technical conferences.

As in past greenhouse gas and fuel economy rulemakings, NHTSA and EPA have utilized unique program analysis models. This difference in methodology ensures that the respective analyses produced by the agencies recognize their respective statutory authorities. EPA has continued to use its Optimization Model for Reducing Emissions of Greenhouse Gases from Automobiles (OMEGA). NHTSA has continued to use its Volpe CAFE Model.

In addition to the decision to use two different full-vehicle simulation models, NHTSA and EPA have also made independent decisions regarding some modeling inputs. Many of the modeling methodologies and inputs are common.[L] Each of the individual inputs that are different is described in its respective section. The primary differences include engine and transmission effectiveness, model year baseline fleet, and mass reduction inputs for both the baseline assessment and for the overall cost.

The agencies believe that, for this first step of the Draft TAR, it is reasonable to show multiple pathways for potential compliance with the MY 2022-2025 standards, and to make use of different data sources and modeling tools. We welcome public comment on the various sources of information and analytical approaches. As stated previously, given the rapid pace of automotive industry innovation, the agencies may consider adding additional technologies as new information becomes available in the next step of the MTE, in addition to the comments we receive on this Draft TAR.

[K] See Chapter 5.3.2 for further discussion of EPA's ALPHA model.
[L] Where inputs to the analysis are consistent with the FRM, the input has been assessed with respect to the latest available information and found to be appropriate.

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Chapter 3: Recent Trends in the Light-Duty Vehicle Fleet Since the 2012 Final Rule

In support of the GHG/fuel economy rules for MY2017-2025 light duty vehicles, EPA and NHTSA[A] performed an extensive analysis of the light-duty automobile marketplace and the projected impacts of the GHG/fuel economy rules. Those analyses were performed in 2012 and were based on then-available historical data, market forecasts from commercial sources, and projections based on the work published in the U.S. Energy Information Administration's (EIA) Annual Energy Outlook 2011 (AEO 2011) and 2012 Early Release (AEO 2012ER) report.[1,2]

Since the publication of the 2012 final rule, the agencies have continued to collect and evaluate an extensive amount of light-duty automobile data through the GHG, CAFE, and other regulatory programs. In December 2015, EPA published two reports based on analysis of the data provided by manufacturers. The first report is "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975-2015"[3] which analyzes the GHG emissions, fuel economy, and technology trends of new vehicles in the United States since 1975. The second report is "GHG Emission Standards for Light-Duty Vehicles: Manufacturer Performance Report for the 2014 Model Year."[4] This report, which is EPA's third annual report, documents the compliance status of every manufacturer under the GHG program for MY2012-2014. Combined, these reports provide an extensive review of the current status of the automotive industry under the light-duty GHG program.

NHTSA provides information about manufacturer compliance with CAFE on the CAFE Public Information Center (PIC) website.[5] The PIC website was launched in July 2015 as a public interface for NHTSA's new CAFE database. This database was developed to simplify data submissions between EPA and NHTSA, improve the quality of the agency's data, expedite public reporting, improve audit verifications and testing, and enable more efficient tracking of manufacturers' CAFE credits with greater transparency. NHTSA provides the following CAFE related reporting exclusively available through its PIC: fleet and manufacturers' fuel economy performance reporting; reporting on manufacturers' CAFE credit balances; reporting on civil penalties collected; flexed-fuel vehicle reporting; pre and mid-model year early projections of CAFE data.

This chapter is intended to give the reader an overarching summary of the changes in the light-duty market in the last four years. The reports issued by EPA and NHTSA document the progress in the industry, and this section will rely heavily on those reports. In addition to the updated EPA and NHTSA analysis, this section will compare industry trends and projections from the 2012 FRM to updated AEO 2015 projections.[6] These data, and continuing updates to them, will ultimately influence much of the underlying analysis throughout the midterm evaluation. Throughout the midterm evaluation process, the agencies will continue to rely on the most up-to-date data.

[A] EPA finalized GHG standards for model years 2017-2025 under the Clean Air Act. NHTSA finalized Corporate Average Fuel Economy (CAFE) standards for model years 2017-2021 and issued augural standards for model years 2022-2025 under the Energy Policy and Conservation Act.

3.1 Changes in the Automotive Market

Since the promulgation of the 2017-2025 final rulemaking (FRM) in 2012, the automotive marketplace has undergone many changes. New vehicle sales, fuel economy, and horsepower are all at record highs. Many new technologies have been quickly gaining market share, gasoline prices have dropped by more than a third, and truck share has been increasing.

3.1.1 Fuel Economy and GHG Emissions

Average new vehicle fuel economy has increased in 8 of the last 10 years, and currently stands at a record high. Over that span, average new vehicle fuel economy has increased 5 mpg (a 26 percent increase). For MY2014, the average new vehicle fuel economy[B] is 30.7 miles per gallon (35.6 mpg for cars and 25.5 mpg for trucks) as tested on EPA's 2-cycle city and highway tests. This 2-cycle (or unadjusted) fuel economy is used as the basis for EPA and NHTSA's regulatory programs, as required by law, and is generally about 25 percent higher than fuel economy values that are published for new vehicle labels (also referred to as adjusted fuel economy).

In MY2014, average new vehicle fuel economy was unchanged from MY2013, largely due to an increasing percentage of truck sales. However, truck fuel economy in MY2014 increased by 0.8 mpg over the previous year, which was the second largest increase in the last 30 years. Truck fuel economy has increased for 10 years in a row and is now at a record 25.5 mpg. Overall, in MY2014 the improved fuel economy in trucks offset the market shift towards trucks to result in no change to the overall average fuel economy of new vehicles.

The trends for new vehicle GHG emissions have also been favorable, with new 2-cycle vehicle GHG emissions at a record low of 290 grams of CO_2 per mile on average. Overall GHG emissions for new light duty vehicles are down 21 percent in the ten years since MY2004. EPA projected GHG emissions year-by-year in the 2012 FRM, and although EPA does not expect that actual emissions will match projections made in 2012, for MY2014 the actual vehicle GHG emissions of 290 g/mile did match the level projected in the 2012 FRM. For a detailed year-by-year comparison of achieved GHG emissions compared to the FRM projections, see EPA's GHG Manufacturer Performance Report.

Projected data for MY2015, provided to EPA by manufacturers as part of the vehicle labeling process, suggests that fuel economy and GHG emissions will improve once again. Average new vehicle fuel economy is projected to increase to 31.2 miles per gallon, and GHG emissions are projected to decrease to 284 grams per mile. However, gas prices dropped significantly at the beginning of MY2015, after these projections were provided to EPA by manufacturers, so these estimates could change. Figure 3.1 shows the trends in fuel economy and GHG emissions from 1975 to 2015.

[B] "Average vehicle fuel economy" is the production weighted average for all new light-duty vehicles produced for sale in the United States for a given model year.

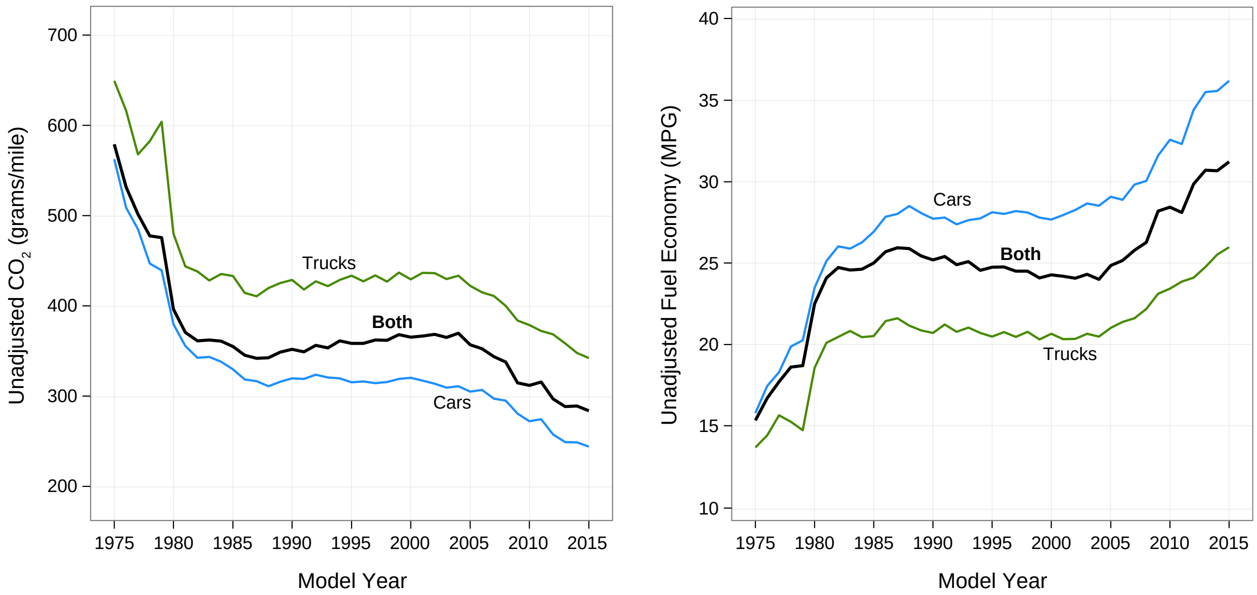


Figure 3.1 Average New Vehicle CO_2 and Fuel Economy for Model Years 1975-2015 (production weighted) [4]

3.1.2 Vehicle Sales

Vehicle sales in the United States are currently at record levels. The number of new light-duty vehicles sold in the United States reached a new all-time high of 17.5 million vehicles in calendar year 2015[7] and sales through the first four months of calendar year 2016 are up by another 3.4 percent.[8] The current state of the auto industry is an impressive turnaround from only a few years ago. Vehicle sales dropped precipitously to 10.4 million vehicles in calendar year 2009 due to the Great Recession. The domestic automakers underwent their own well documented financial turmoil with GM and Chrysler declaring bankruptcy, and the subsequent purchase of Chrysler by Fiat. Manufacturers have increased sales to record highs and returned to profitability while meeting the first three years of the national program CAFE and GHG standards.

EPA and NHTSA track vehicle production by model year,[C] as opposed to vehicles sales in a calendar year. These two metrics are slightly different, however they are highly correlated and trend similarly over time. Figure 3.2 shows historic vehicle production per model year, as tracked by EPA and NHTSA. It also includes AEO 2015 new vehicle sales projections, which provide a forecast to 2040. In AEO 2015, EIA projects relatively flat, but slightly increasing number of vehicle sales per year. Also included in Figure 3.2 are the projected model year production values that were used in the 2012 final rulemaking, based on AEO 2011. Actual vehicle sales in 2015 exceeded the final rule's projected values for 2017, by about a million vehicles. However the AEO 2015 projections predict a slower growth rate going into the future,

[C] Vehicle production data represent production volumes delivered for sale in the U.S. market, rather than actual sales data. They include vehicles built overseas imported for sale in the U.S., and exclude vehicles built in the U.S. for export.

which is slightly lower than the final rule's projected vehicle sales towards the end of the 2017-2025 rule timeframe.

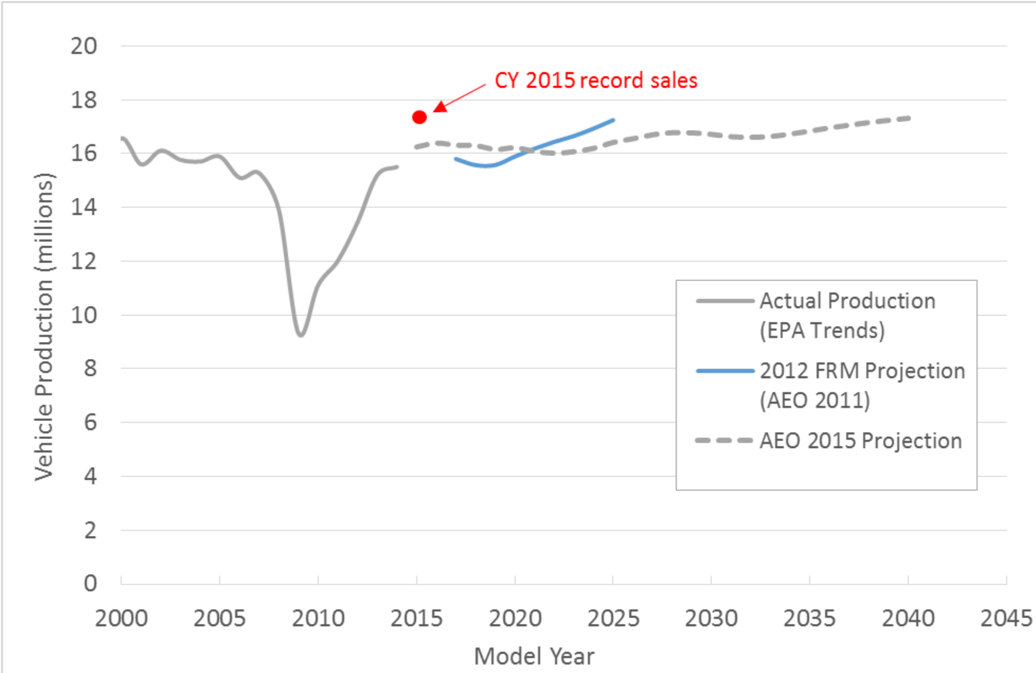


Figure 3.2 Actual and Projected Vehicle Production

3.1.3 Gasoline Prices

One recent, unexpected, and significant development in the automotive market has been the volatility in gasoline prices. In October 2012 when the 2017-2025 rule was finalized, U.S. average gasoline prices were at $3.87 per gallon. The agencies, based on AEO 2011, projected in the 2012 FRM that gasoline prices would climb slowly over time. Instead, gasoline prices dropped more than 40 percent in the United States, and ended 2015 at about $2.15 per gallon.[9]

Historically, the price of gasoline has been volatile and difficult to predict accurately. The price of gasoline, which generally reflects crude oil prices, fluctuates based on the world supply of and demand for oil. Many factors, including growing demand from developing countries, natural disasters, economic conditions, geo-political events, and introduction of new technology, can all have large impacts on the supply and demand for crude oil. In particular, U.S. production of crude oil increased more than 70 percent between 2010 and 2015[10] which undoubtedly affected domestic oil prices. The combination of many unpredictable factors has led to sometimes unanticipated shocks in the short-term price of oil and a long-term trend of oscillation between high and low prices (as seen in Figure 3.3).

In AEO 2015, the U.S. Energy Information Administration (EIA) provides three projections for gasoline prices out to the year 2040. The use of reference, high, and low projections is meant to capture the broad band of uncertainty for key variables that affect gasoline prices to 2040. In the reference case, AEO 2015 assumes a continuation of the long-term trend of rising gasoline prices and estimates gasoline prices to increase to $3.90 by 2040. The primary factor influencing the long term increase in price is increased world oil demand, especially by non-OECD (Organization for Economic Cooperation and Development) countries like China and India as they continue to experience strong economic growth, which offsets any decrease in oil and gasoline prices due to increased production. In the high oil price scenario, AEO 2015 projects gasoline prices 62 percent greater than the reference case, due to higher global oil demand, again driven by non-OECD nations, as well as lower oil production by the Organization of the Petroleum Exporting Countries (OPEC), and higher costs of production and development from non-OPEC countries. For the low oil price scenario, just the opposite is projected, and gasoline prices fall 33 percent below the reference case by 2040.

The uncertainty in projecting gasoline prices is reflected in the wide range of gasoline prices projected in the high and low scenarios. In the high scenario, gasoline prices reach $6.33 per gallon in 2040. In the low scenario, gasoline prices fall through 2017, then increase incrementally to $2.60 in 2040. AEO 2015 high and low projections vary by a factor of 2.5, which reinforces the uncertainty of these projections.

Historical gasoline prices[11] and future AEO 2015 projections are shown in Figure 3.3. Gasoline prices were at an all-time high in 2012, although in terms of constant dollars were only slightly above gasoline prices in 1981. The gasoline prices used in the 2012 final rulemaking are also included in Figure 3.3, and show that the prices used in the rule, which were based on AEO 2011, are well above current gasoline prices. The AEO 2015 reference projections predict lower gasoline prices than the rule projections through 2040; however, the rule projections for gasoline prices are well below the high AEO 2015 scenario. The volatility in oil prices and the wide range of AEO projections serve to reinforce the problem of predicting future gasoline prices with any accuracy.

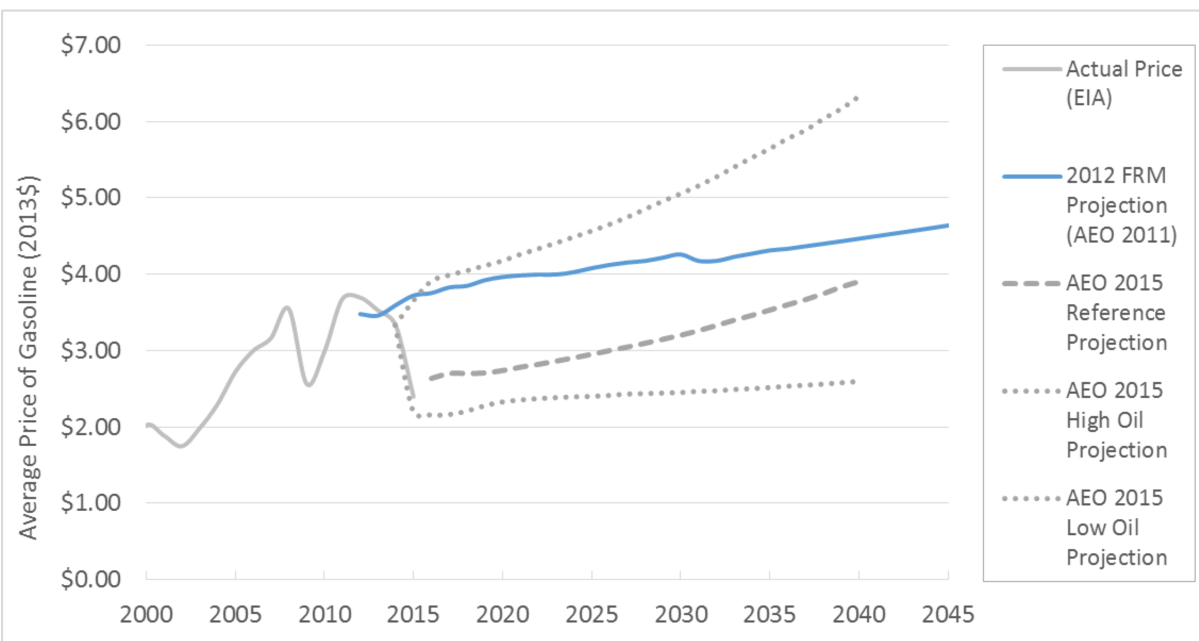


Figure 3.3 Gasoline Prices in the United States

3.1.4 Car and Truck Mix

The 2012 FRM finalized footprint-based standards designed to spur improvements in all types of vehicles and maintain consumer choice. EPA and NHTSA used AEO 2011 car and truck fleet mix projections in the 2012 FRM to evaluate the overall impacts of the rule. Since the 2012 FRM, the light duty vehicle market has moved more towards trucks than projected.

The overall percentage of trucks sold in the United States increased in MY2014 but has been somewhat volatile in recent years. The percentage of trucks sold increased 4.8 percentage points to 40.7 percent of all sales in MY2014, the last year for which EPA has final data. This is still well below the all-time record of 48 percent of all sales, set in MY2004. Truck market share increased steadily in all but four years between MY1980 and MY2004, then quickly fell 15 percentage points to 33 percent of all sales in MY2009. Since MY2009, truck market share has bounced around between 33 percent and 42.2 percent of all sales. Projected sales (based on preliminary automaker projections) for MY2015 predict a slight drop in the percentage of trucks sold; however, lower than expected gasoline prices may alter the final sales data.

In MY2014, pickups captured 12.4 percent of new vehicle sales, while truck SUVs captured 23.9 percent of sales. Smaller 2WD SUVs and 2WD crossovers are generally considered cars under the regulations, and those car SUVs captured 10.1 percent of vehicle sales. Sales of SUVs (including "crossover" vehicles) are continuing to grow and have increased from 20 percent of total sales in 2004 to 34 percent in MY2014. The growth of SUVs looks to continue, especially as the market for small SUVs continues to develop. Vehicles like the Jeep Renegade, Honda HR-V, and Chevy Trax represent a relatively new market segment of "subcompact SUVs." These vehicles can be classified as either cars (for the 2WD versions) or as trucks (for 4WD versions meeting several requirements, such as ground clearance) and are further blurring the line between cars and trucks.

Figure 3.4 shows the recent trend in truck production share by year, the projections from the 2012 FRM, and AEO 2015 projections looking forward. In MY2014, the 2012 FRM projected 38 percent of new vehicles produced would be trucks. The actual percentage of trucks produced was just under 41 percent, so truck were about 3 percent more of the market than projected. EPA does not have final data for MY2015 or MY2016 data, but industry reports suggest a strong demand for trucks. The AEO 2015 projections account for a significant increase in truck production share, but also project that truck share will peak in 2015 before slowly drifting back to lower levels[D]. Under the AEO 2015 high oil price scenario, truck production slowly falls to 39 percent of production in MY2025 and in the low oil price scenario truck production is 53 percent in MY2025. Many factors could influence the future direction of car and truck sales, most notably the volatile gasoline prices of recent years. For additional analysis of light-duty vehicle sales by class, see EPA's Light Duty Automotive Technology, Carbon Dioxide Emissions and Fuel Economy Trends report (Figure 3.4).

[D] The historical data in AEO 2015 for 2011-2014 show a higher percentage of trucks than what actually occurred. The AEO historical data does not impact the analysis in this report, nor does it impact AEOs long term projections. The data will be updated in AEO 2016.

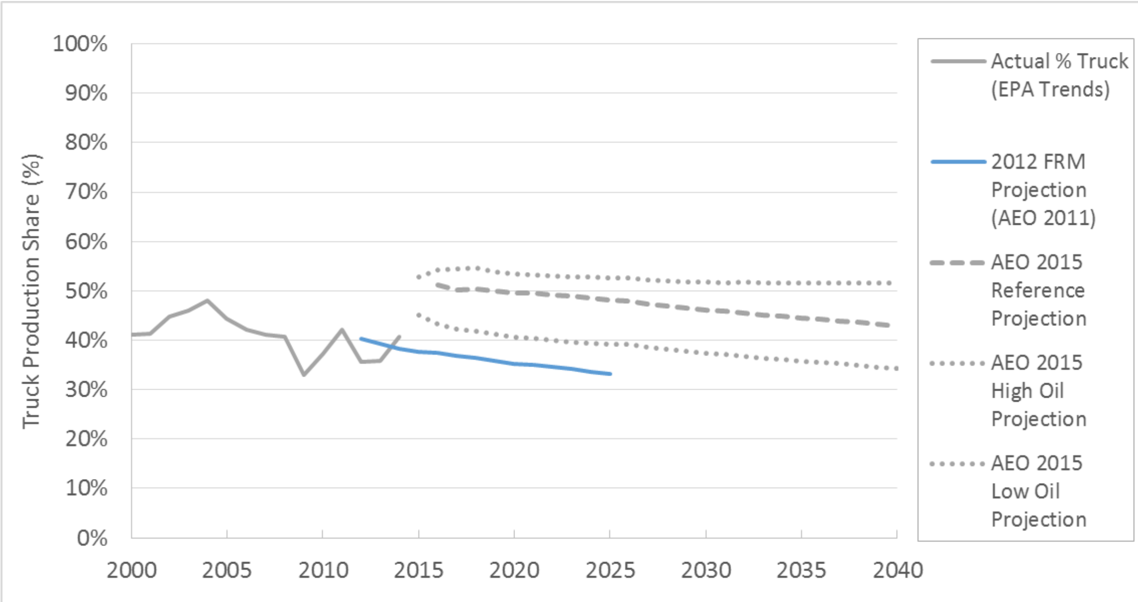


Figure 3.4 Truck Production Share by Year

3.1.5 Vehicle Power, Weight, and Footprint

The automotive industry is continuously innovating and improving vehicles offered to consumers. However, innovations in the automotive industry have not always been used for the same purposes. For example, from the early 1980s to 2004, vehicles grew steadily larger and more powerful but fuel economy decreased (Chapter 4.1.4.3 discusses the role of innovation and how it has been applied in the automotive industry). Vehicle weight, horsepower, and footprint are correlated to vehicle fuel economy and GHG emissions. The relationship between fuel economy, weight, and horsepower is shown in Figure 3.5.

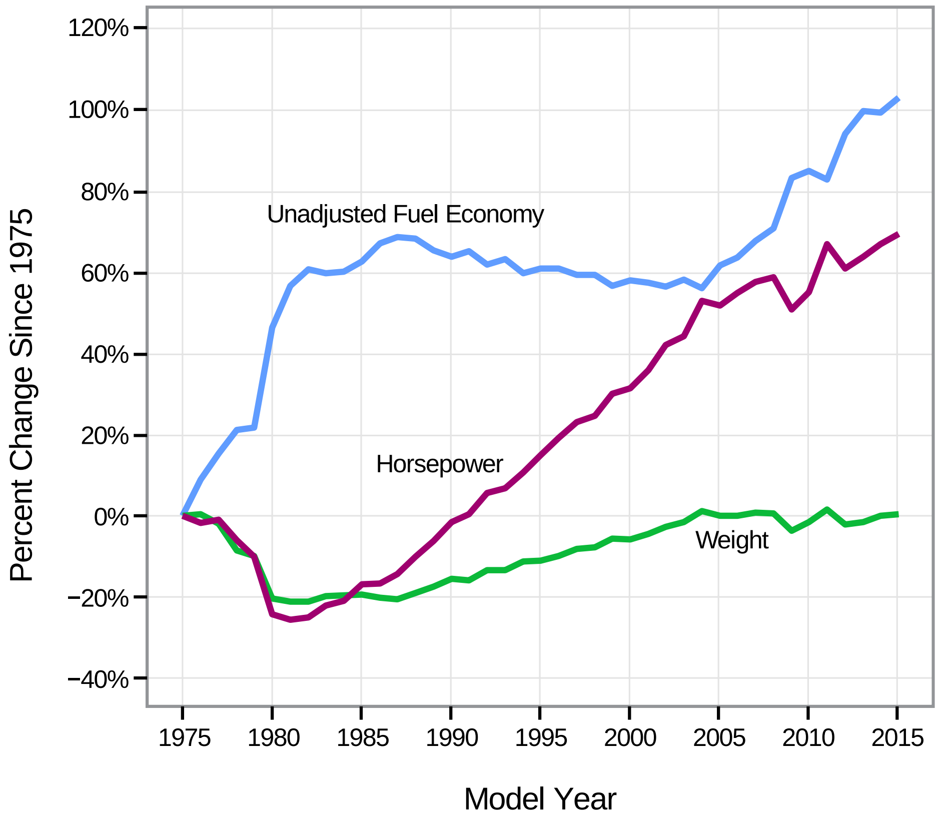


Figure 3.5 Average New Vehicle Fuel Economy, Weight, and Power (production weighted) [4]

The baseline analysis presented in the 2012 FRM was based on MY2008. Since then, average new vehicle sales weighted horsepower has increased 14 horsepower to a projected record high 233 horsepower in MY2015. Horsepower did decrease in MY2009, but that was the first dip in horsepower in 28 years. With the exception of MY2009 and MY2012, horsepower has increased every year since MY 1981. Both cars and trucks are projected to reach record average horsepower numbers in MY2015. Since MY2008, car horsepower is up 6 horsepower on average to 200 horsepower, and trucks are up 29 horsepower on average to 283 horsepower. Increases in horsepower have been a little more volatile the last few years than the very steady increases seen for more than 25 years, but clearly manufacturers have continued to increase average vehicle power in the past several years while also significantly reducing GHG emissions and increasing fuel economy. Examining horsepower by vehicle type clearly shows that pickup trucks have experienced the largest increase in horsepower, as shown in Figure 3.6.[E]

[E] The five vehicle type categories are those used by EPA in the report "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 to 2014." Cars are subdivided into Cars and Car SUVs, and trucks are subdivided into Pickups, Truck SUVs, and Vans.

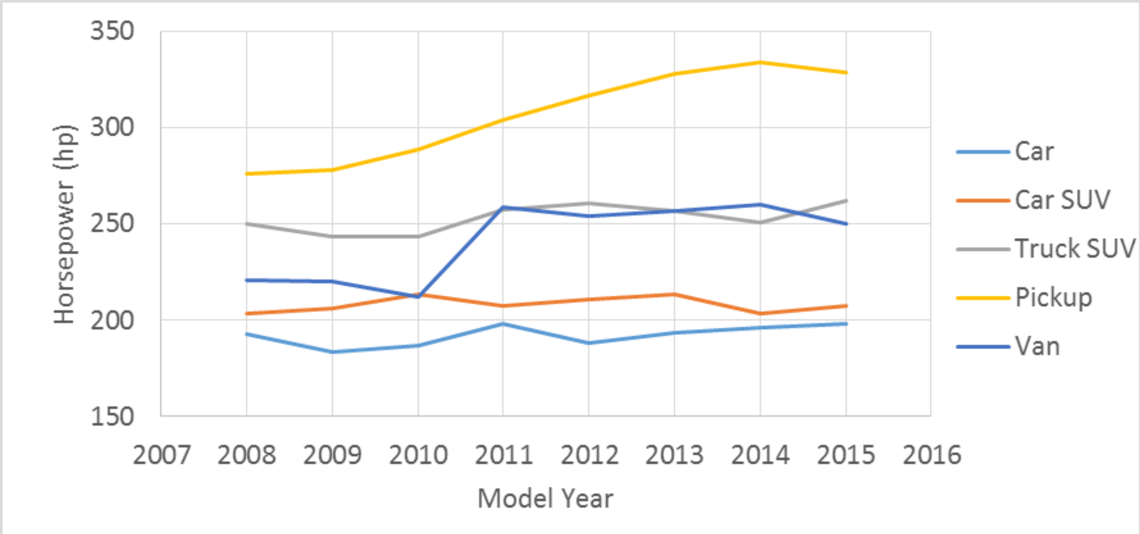


Figure 3.6 Horsepower by Vehicle Class, MY2008-MY2015

New vehicle weight has been relatively constant for the last decade, based on the sales-weighted average of all new vehicles for each year. New vehicles in MY2004 had the highest recorded average weight, at 4,111 lbs. The projected new vehicle average weight for vehicles in MY2015 is 4,076 lbs, which is less than a 1 percent difference from MY2004.

Since MY2014, the weight of an average new car has held relatively constant (within 2.5 percent), again based on the sales-weighted average of all new vehicles for each year. Over that same time pickup trucks increased weight by about 10 percent, adding 546 lbs by MY2014 to reach an all-time high of 5,485 lbs. Projected data for MY2015 shows a significant weight reduction for new pickup trucks of 222 lbs, compared to MY2014, which would be a 4 percent reduction if realized. The weight of truck SUVs, or of those SUVs that are considered trucks for regulatory purposes, has been much more constant and is projected to be down about 147 lbs in MY2015 compared to MY2004. Vehicle weight by class is shown in Figure 3.7.

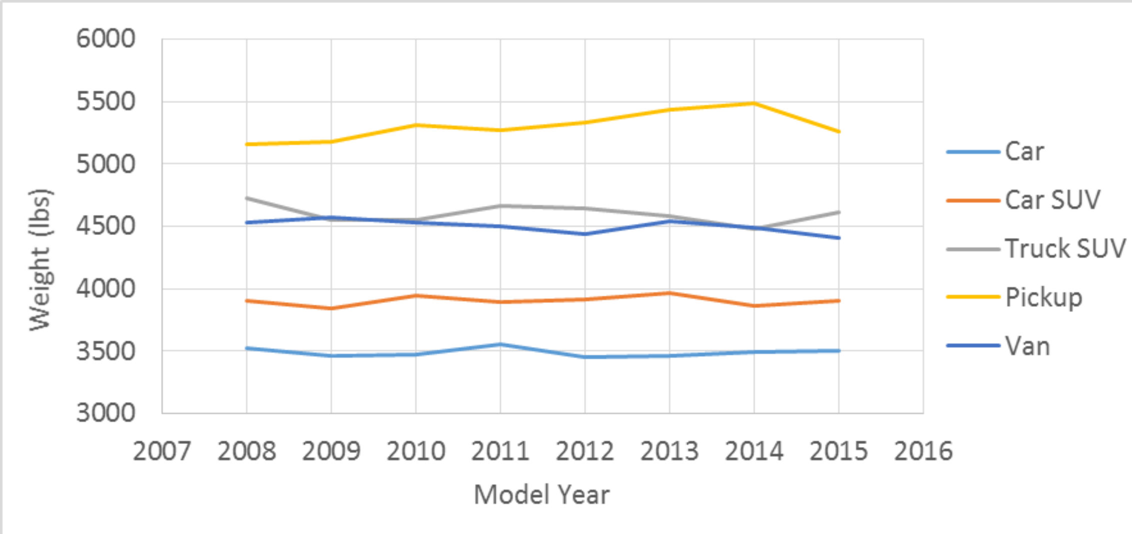


Figure 3.7 Weight by Vehicle Class, MY2008-MY2015

The GHG/fuel economy standards are based on vehicle footprint, where footprint is defined as the area where the centers of the four tires touch the ground. EPA began tracking footprint in MY2008 and since that time, the average new vehicle footprint has increased to the highest level on record. New vehicle production weighted footprint is projected to be at 49.9 square feet in MY2015, which is a small increase of one square foot, or about 2 percent, since MY2008. The average new car footprint is up 0.8 square feet since MY2008, and the average new truck footprint is up 1.5 square feet. The increase in truck footprint is driven largely by pickup trucks, which are up almost 3.2 square feet, or 5 percent, since MY2008. In addition, the recent shift towards trucks is driving up the overall fleet-wide average footprint of new vehicles. While pickup truck footprint has increased, other vehicle segments have been relatively constant since MY2008, as shown in Figure 3.8.

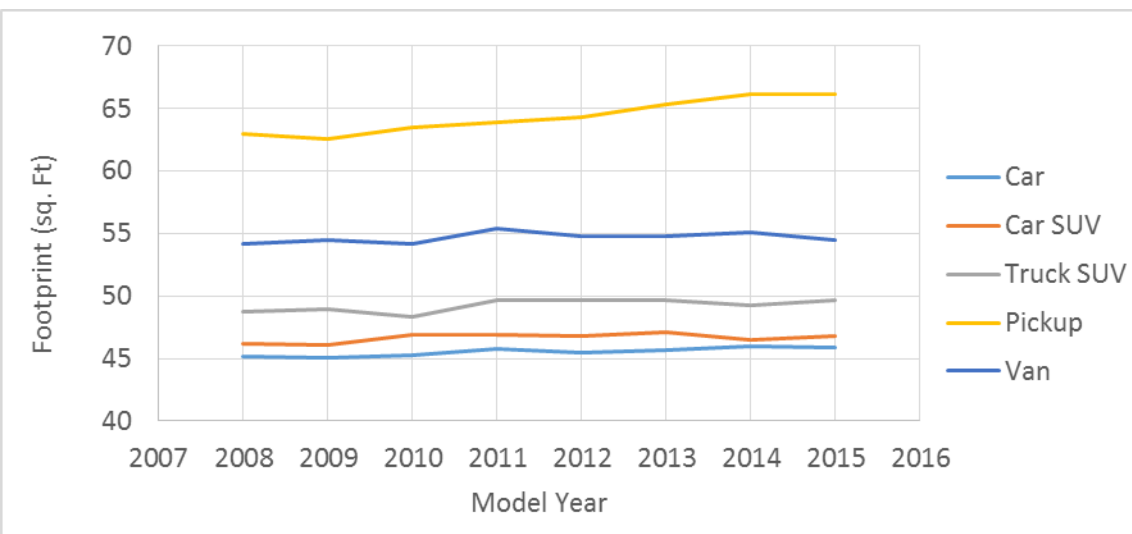


Figure 3.8 Footprint by Vehicle Class, MY2008-MY2015

The average footprint for new cars and trucks is higher than the 2012 FRM projections. For MY2014, cars are 1.5 square feet larger, and trucks are 1.1 square feet larger. Overall, the average new vehicle in MY2014 had a footprint of 1.6 square feet more than projected, due to the increasing percentage of trucks sold. The footprint trends for cars and trucks are shown in Figure 3.9.

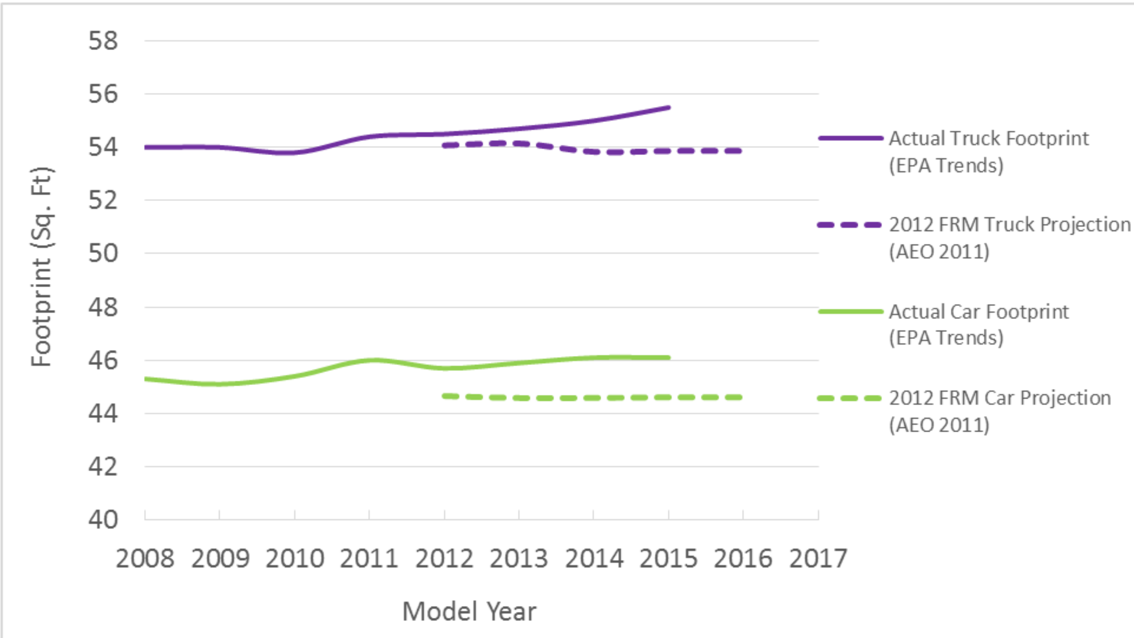


Figure 3.9 Car and Truck Footprint

Overall, the general trend since the 2012 FRM continues towards slightly larger vehicles with more power, particularly for pickup trucks. However, overall new vehicle weight has remained nearly constant even given the continuing trend towards larger vehicles, and overall fuel economy has improved. For additional analysis of light-duty vehicle footprint, weight, and horsepower by vehicle class, see EPA's Light Duty Automotive Technology, Carbon Dioxide Emissions and Fuel Economy Trends report (Figure 3.5).

3.1.6 Technology Penetration

In the 2012 FRM, the agencies discussed many technologies that were available to the industry to improve fuel economy and to reduce GHG emissions. These technologies largely included continual improvements to the gasoline internal combustion engine, such as more advanced engines and transmissions, vehicle light-weighting, aerodynamics, and more efficient accessories. Many of these technologies were already available on vehicles for sale back in 2012, and meeting future standards would require manufacturers to adopt the technologies on a more widespread basis across their fleets. This is, in fact, exactly what is happening, as discussed below.

Based on the technologies discussed in the 2012 FRM, EPA presented a feasible, least cost pathway to illustrate that manufacturers could comply with the standards. The pathway reflected in the 2012 FRM was meant to illustrate one possible path that manufacturers could use to meet the standards, based on the OMEGA model's projection of the least-cost set of technologies to meet the 2025 standards. EPA recognized that each manufacturer could chose a pathway based on many factors, but most manufacturers are beginning to widely use the technologies outlined in the 2012 FRM. Several of the major technologies that were discussed in the FRM are tracked by EPA as part of the GHG compliance program, and are documented in the Fuel Economy Trends report. For these technologies, EPA can compare the penetration rate of these technologies at the time of the 2012 FRM and for current models.

Figure 3.10 shows the change in production for several emerging fuel economy related technologies between MY2008, which was the baseline in the 2012 FRM, and MY2015. The MY2015 data are based on projected production volumes from the manufacturers and are the most current data available. All of the technologies in Figure 3.10 are technologies that were discussed in the FRM as possible options for manufacturers to use to increase fuel economy, reduce GHG emissions, and comply with the standards. The pathway presented in the 2012 FRM included many of the technologies that are included in Figure 3.10. Chapter 5 discusses these technologies in more depth.

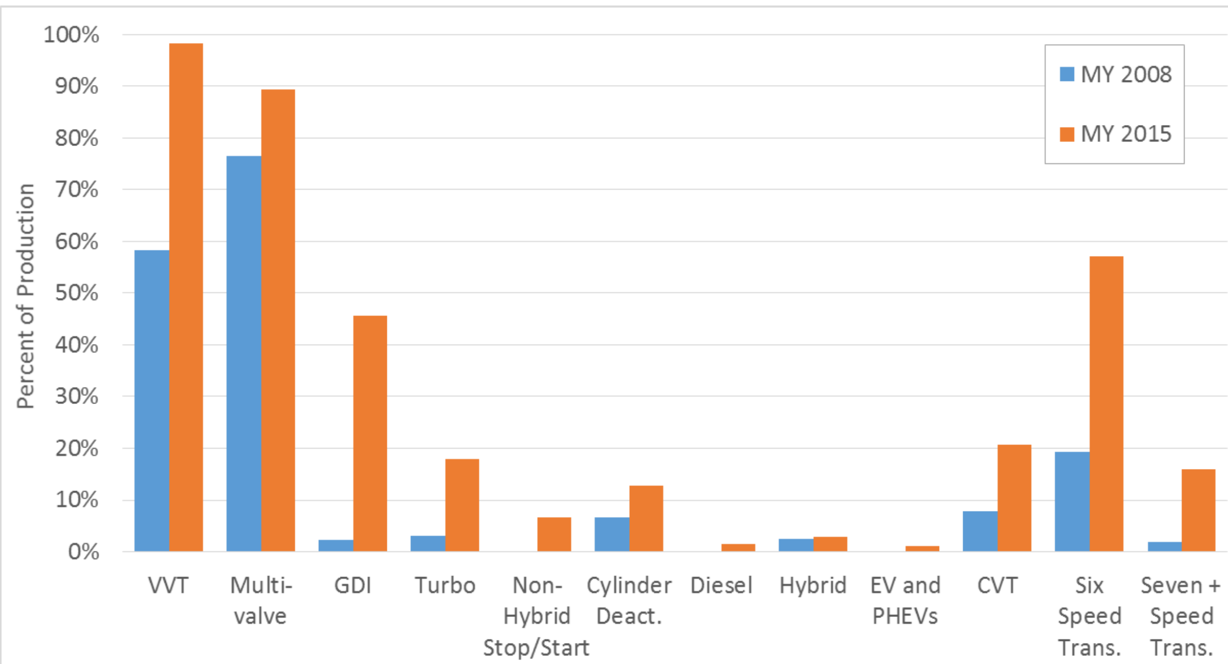


Figure 3.10 Light Duty Vehicle Technology Penetration Share since the 2012 Final Rule

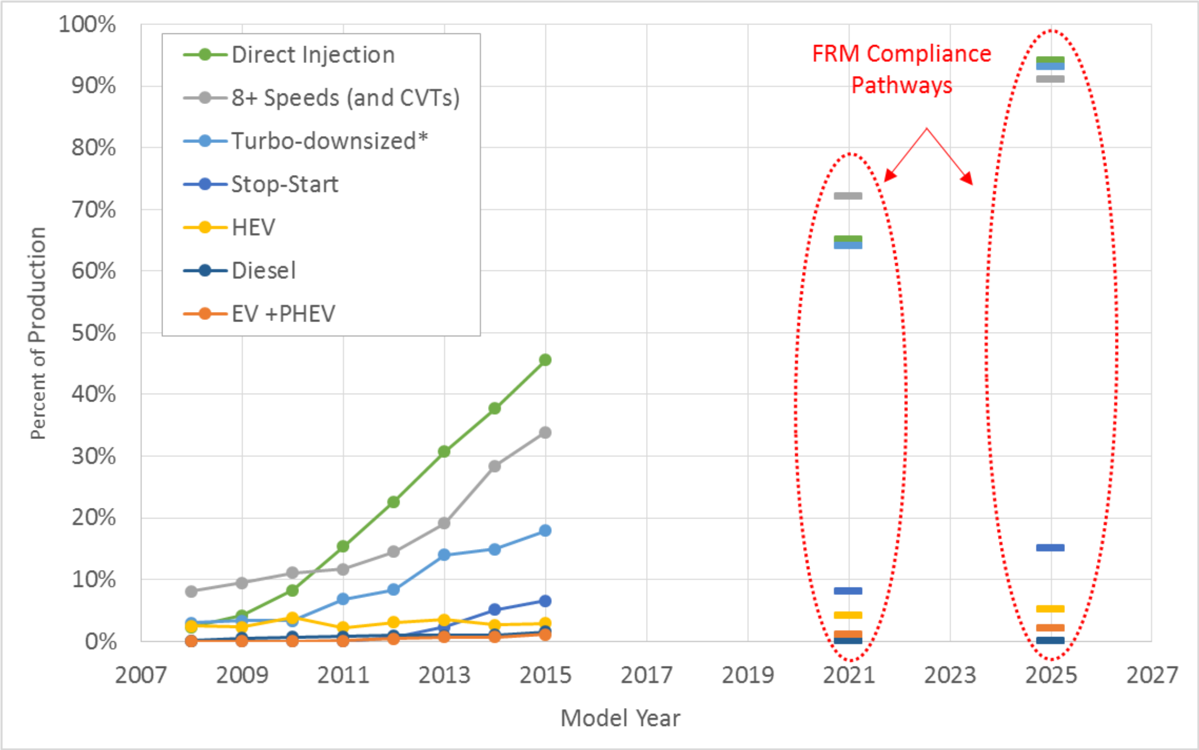
In particular, vehicles utilizing gasoline direct injection engines (GDI) have been entering the market at a very rapid pace. In MY2008, GDI engines represented 2.3 percent of production. That number has grown to just over 45 percent of expected production in MY2015. Turbocharged engines have also seen a swift increase in market share. These two technologies are often employed together as a downsized, turbocharged, GDI engine package that many manufacturers have released to improve fuel economy and reduce GHG emissions. Stop-start systems (excluding hybrids) and cylinder deactivation have also increased market share significantly.

Transmission technology has also been changing rapidly. Six-speed transmissions increased from 19 percent in MY2008 to a projected market share of 57 percent in MY2015. Continuously variable transmissions (CVTs), which were not projected to increase market share in the 2012 FRM, have increased from 8 percent in MY2008 to capture just over 20 percent of the market for MY2015. An additional 16 percent of new vehicles expected to be produced in MY2015 will have transmissions with 7 or more speeds, up from 2 percent of all new vehicles in MY2008. Transmissions with 5 or less speeds, which made up over 70 percent of the market in MY2008, now account for only just over 5 percent of vehicle production.

Hybrid electric vehicles (HEVs) were 2.5 percent of production for MY2008, and reached their peak market penetration in MY2010 at 3.8 percent of all new vehicles produced. Since then, they have fallen back slightly, to a projected 2.9 percent in MY2015. There are several possible reasons that HEV sales have been flat. First, non-hybrid vehicles continue to improve fuel economy at a faster rate than hybrids. Between MY2004 and MY 2014, the difference in fuel economy between the average hybrid midsize car and the average non-hybrid midsize car has fallen from 24 mpg to about 13 mpg. Second, some HEV buyers may also be looking to all electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) instead of HEVs. Third, recent low gas prices may make hybrids less appealing to consumers.

Plug-in hybrids and electric vehicles continue to enter the market. There are now 12 battery EVs and 13 PHEVs available, and more are scheduled to be released in the coming years. There are also 2 fuel cell electric vehicles (FCEVs) available to consumers. Overall, sales of these vehicles are still low, but appear to be slowly growing. Sales of EVs increased 9 percent in 2015 to about 69,000 vehicles, and EV sales in the first quarter of 2016 are up 22 percent from the first quarter of 2015. PHEV sales were down 24 percent in 2015 (largely due to limited supply of one vehicle early in the year), but are up over 80 percent in the first quarter of 2016 compared to the first quarter of 2015. Both EVs and PHEVs had first quarter sales in 2016 that were higher than any other year.[12] While overall national sales are low, the 2012 FRM assumed only small numbers of EVs and PHEVs (2 percent of all vehicles) would be needed to meet the standards in MY2025. Further, some regions of the nation (most notably California) already have EV and PHEV sales in excess of 2 percent of new car sales today.

Many of the major technologies analyzed in the 2012 FRM appear to be on trend for reaching relatively high penetration levels, similar to what EPA projected for 2021 and 2025 in its analysis of least cost compliance pathways. Figure 3.10 shows the technology penetration for several major technologies from MY2008 to MY2015. The MY2021 and the MY2025 projected technology penetration levels for each of these technologies, from the 2012 FRM, is also included in Figure 3.11 for comparison. Chapter 5 of this report examines these technologies in much more detail, and Chapter 12 evaluates and update the projected technology penetrations.



* Data through 2015 includes all turbocharged vehicles, not specifically turbo-downsized engines

Figure 3.11 Technology Changes since MY2009

3.2 Compliance with the GHG Program

Three model years, MY2012–2014, have been completed under the new footprint based GHG regulations. In all three model years, manufacturers have outperformed the standards by a wide margin even as the standards have become more stringent. In MY2014, the industry compliance was 13 g/mile better than required by the standards. In model years 2012 and 2013, industry compliance was 11 and 12 g/mile respectively, better than required. This industry-wide performance means that, across the fleet, consumers continue to buy vehicles with lower GHG emissions than required by the EPA standards. The standards decreased 12 g/mile from MY2012 to 2014, and manufacturers more than kept pace by reducing compliance values by 14 g/mile. A summary of industry compliance values versus the standards is shown in Figure 3.12.

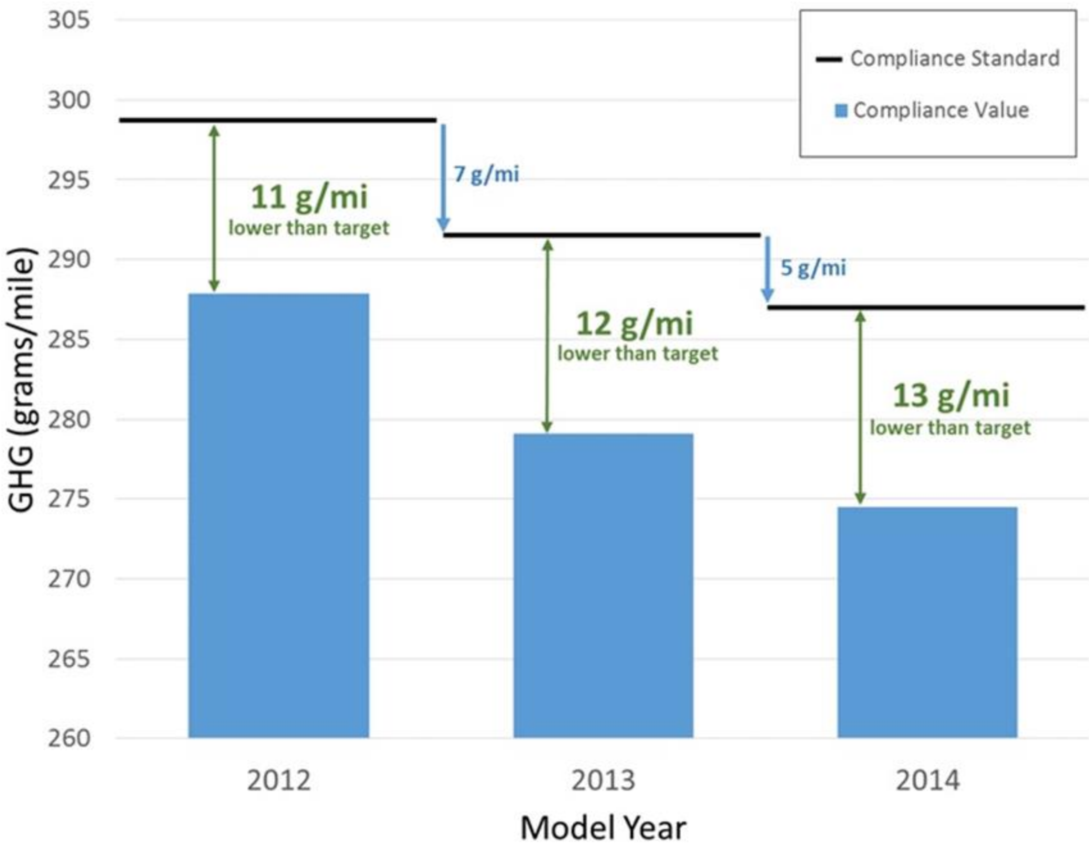


Figure 3.12 Industry GHG Compliance Values versus Standards in 2012-2014 Model Years[F]

The majority of manufacturers, representing more than 99 percent of U.S. production, are in compliance with the standards for the 2012-2014 model years. In fact, 20 of 24 manufacturers[G] are carrying a positive credit balance into the 2015 model year, meaning that these manufacturers have met the standards in all of the 2012-2014 model years (credits cannot be carried forward if a deficit exists in a prior model year). The manufacturers currently with deficits in any or all of the 2012-2014 model years are allowed to carry those deficits forward for three model years, giving them time to generate or purchase credits to demonstrate compliance with the 2012-2014 model year standards. Thus, a manufacturer with a deficit remaining from the 2012 model year has until the end of the 2015 model year to offset that deficit. The current status of manufacturers carrying a deficit into the 2015 model year is neither compliance nor non-compliance, rather, they have not yet fully demonstrated compliance. The makeup of these credit and deficit balances is tracked by model year.

[F] The "Compliance Standard" is the effective overall GHG g/mile standard for all light duty vehicles in a given model year, based on the production volumes and footprints of the vehicles produced. The "Compliance Value" is the effective overall GHG g/mile emission rate actually achieved by the industry in a given model year, based on the production volumes and footprints of the vehicles produced.

[G] Volkswagen is excluded due to an ongoing investigation.

Table 3.1 Credit Balances at Conclusion of the 2014 Model Year (Mg)

Credit Balances at Conclusion of the 2014 Model Year (Mg) (including credit transfers & trades)			
Manufacturer	**Credits Carried to 2015**	**Manufacturer**	**Credits Carried to 2015**
Toyota	81,271,823	Suzuki*	428,242
Honda	39,410,925	Mercedes†	228.172
GM	30,380,022	Ferrari	107,613
Ford	27,514,195	Volvo	74,291
Hyundai	19,727,364	Fisker*	46,694
Nissan	17,810,733	Coda*	7,251
Fiat Chrysler	13,890,014	BYD Motors	4,824
Subaru	10,236,711	Tesla	1,965
Kia	9,819,076	Lotus†	(2,841)
Mazda	7,160,086	McLaren†	(6,507)
BMW	1,532,564	Aston Martin†	(35,844)
Mitsubishi	1,333,267	Jaguar Land Rover†	(509,745)
All Manufacturers			**265,182,108**

Note: Volkswagen is not included in this table due to an ongoing investigation. Based on the original compliance data, Volkswagen has a credit balance of 4,751,213 Mg.
†These companies are using a temporary program for limited-volume manufacturers that allows some vehicles to be subject to less stringent standards. See Section 3.B.
*Although these companies produced no vehicles for the U.S. in the most recent model year, the credits generated in previous model years continue to exist.

The 2012 FRM also introduced the options for manufacturers to trade credits between companies. EPA included this provision because it will allow for greater GHG reductions, lower compliance costs, and greater consumer choice. Manufacturers have been actively trading credits, with almost 10 million Megagrams of CO_2 credits changing hands by the close of the 2014 model year reporting period.

The credit transactions reported by manufacturers through the 2014 model year are shown in Table 3.2. Credit distributions are shown as negative values, in that a disbursement represents a deduction of credits of the specified model year for the selling manufacturer. Credit acquisitions are indicated as positive values because acquiring credits represents an increase in credits for the purchasing manufacturer. The model year represents the “vintage” of the credits that were sold, i.e., the model year from which the credits originated. Note that each value in the table is simply an indication of the quantity of credits from a given model year that has been acquired or disbursed by a manufacturer, and thus may represent multiple transactions with multiple buyers or sellers. The total credit balances shown in Table 3.1 include the credits transactions reported in Table 3.2.

Table 3.2 Reported Credits Sold and Purchased as of the 2014 Model Year (Mg)

	Manufacturer	Model Year "Vintage" 2010	2011	2012	2013	2014	Total
Credits Sold	Honda	(3,609,383)	-	-	-	-	(3,609,383)
	Nissan	(200,000)	(1,000,000)	(250,000)	-	-	(1,450,000)
	Tesla	(35,580)	(14,192)	(177,941)	(1,048,689)	(1,019,602)	(2,296,004)
	Toyota	(2,507,000)	-	-	-	-	(2,507,000)
Credits Purchaed	Ferrari	265,000	-	-	-	-	265,000
	Fiat Chrysler	5,651,383	500,000	-	1,048,689	1,019,602	8,219,674
	Mercedes	435,580	514,192	427,941	-	-	1,377,713

In the first three years of the GHG compliance program, the industry has outperformed the standards each year, all large manufacturers are carrying forward credits, and there has been active trading of credits between manufacturers. The specific details of the compliance program, including tailpipe emissions, earned credits, credit trading, and comparisons to the 2012 FRM projections, are all detailed in the EPA report titled, "GHG Emission Standards for Light-Duty Vehicles: Manufacturer Performance Report for the 2014 Model Year."

3.3 Compliance with the CAFE Program

An overview of how manufacturers complied with the CAFE program is provided for model years 2011 to 2014.[H,I] On average, manufacturers showed significant strides complying with the CAFE program for model years 2011 and later in improving the total fleet fuel economy performance for passenger cars and trucks despite increasingly more stringent standards over the period. Manufacturers were able to successfully execute compliance strategies for both the NHTSA and EPA programs that accommodated the differences in compliance flexibilities and credit balances between the programs.

As directed by Congress, the total light duty vehicle fleet is divided into three compliance categories, domestic and import passenger cars and light trucks, for meeting CAFE standards and distinct statutory differences exist in the compliance flexibilities for each category. Figure 3.13 and Table 3.3 provide the total fleet standards and actual fleet fuel economy performance for each vehicle category. As shown in the figure, for each model year from 2011 through 2014, manufacturers far exceeded standards for their combined domestic and import passenger cars but fell short in meeting standards for their combined light truck fleets for model years 2012 and

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[H] Model year 2011 is an important year in the CAFE programs because it signifies the first year EISA amended EPCA mandating the first stage of combined footprint-based CAFE standards and established a credit trading program that supplemented previous existing credit flexibilities for all passenger cars and light trucks. EISA and EPCA also required CAFE standards that would increase annually and set sufficiently high enough levels to ensure that the total fleet average of all new passenger cars and light trucks, combined, was not less than 35 miles per gallon by model year 2020.

[I] Model year 2014 is the last year manufacturers, NHTSA and EPA have completed production, testing and reporting for all vehicles complying with CAFE standards.

2013. Consumers will save an estimated 16.6 billion gallons of fuel over the lifetime of model year 2011 to 2014 vehicles due to the manufacturers exceeding the CAFE standards in those years.

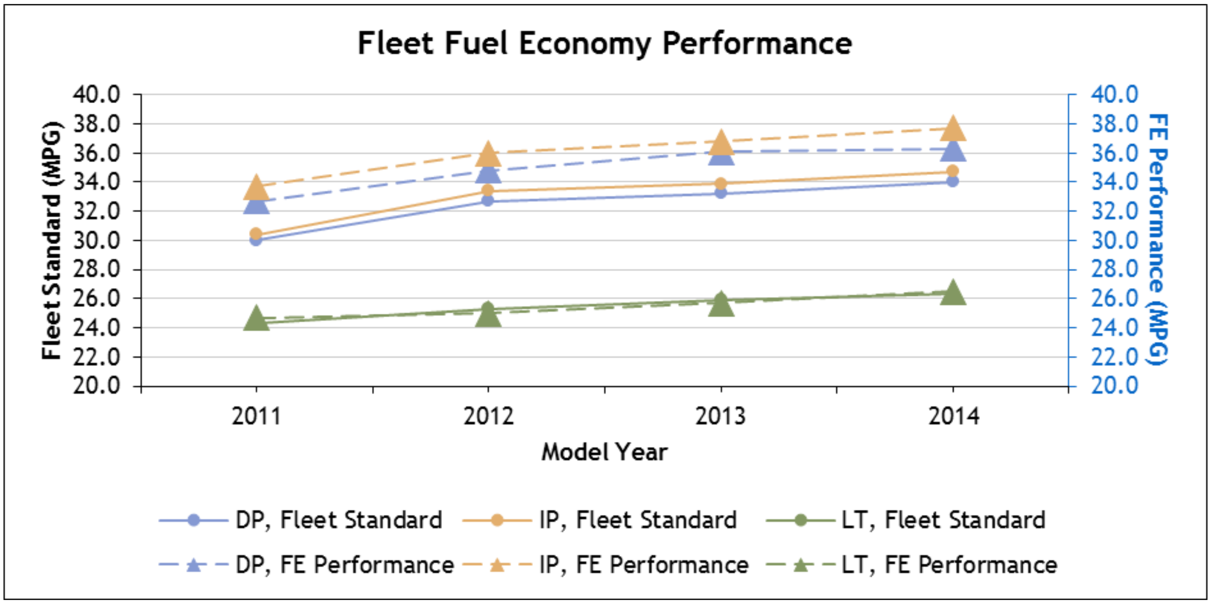

Figure 3.13 Industry CAFE Compliance Values versus Standards in Model Years 2011-2014

Table 3.3 Industry CAFE Compliance Values versus Standards in Model Years 2011-2014

Model Year	Domestic Passenger Car			Import Passenger Car			Light Truck		
	FE Performance (MPG)	Fleet Standard (MPG)	Sales Production Volume	FE Performance (MPG)	Fleet Standard (MPG)	Sales Production Volume	FE Performance (MPG)	Fleet Standard (MPG)	Sales Production Volume
2014	36.3	34.0	5,563,657	36.9	34.6	3,641,470	26.5	26.3	6,306,647
2013	36.1	33.2	5,566,615	36.8	33.9	4,172,770	25.7	25.9	5,457,777
2012	34.8	32.7	5,260,200	36.0	33.4	3,396,020	25.0	25.3	4,788,574
2011	32.7	30.0	3,986,385	33.7	30.4	2,965,213	24.7	24.3	5,069,696

The design of the CAFE program, as instructed by Congress, anticipates that not all manufacturers' compliance fleets will meet CAFE standards for each model year. Fleets not meeting CAFE standard represented 44 percent of all fleets on average but represented only 33 percent of the total industry production volume for model years 2012 through 2014. The majority of these manufacturers failed to meet the standard for their light truck fleets for these model years but have rebounded for the 2014 compliance period.

Therefore, to compensate for shifts in production markets and to allow NHTSA to set CAFE standards at the maximum feasible levels, the CAFE program was designed to allow manufacturers to comply by exercising one or more program flexibilities to leverage compliance over multiple model years or by eliminating the deficiencies of under complying fleets using the benefits gained by over performing fleets.[J] There are three basic flexibilities outlined by EPCA/EISA that manufacturers can currently use to achieve compliance with CAFE standards beyond applying fuel economy-improving technologies: (1) building dual- and alternative-fueled vehicles[K]; (2) banking (carry-forward and carry-back), trading, and transferring credits earned for exceeding fuel economy standards; and (3) paying civil penalties.[L]

Using program flexibilities, all manufacturers not beating the standard have either complied or will be able to comply with CAFE standards through model year 2014. As the first compliance pathway, manufacturers are building advanced technology vehicles and eleven manufacturers are incentivizing the performance of their fleets by building flexible fueled vehicles. Building flexible fueled vehicles is a major incentive established by Congress for the CAFE program.[M] Figure 3.14 shows the increase in each compliance category for those manufacturers building flexible fuel vehicles for the applicable model years. On average, these manufacturers raised the fleet performance of domestic passenger cars by 1.9 percent, import passenger cars less than 1 percent and light trucks by 3.4 percent over these model years.

For the remaining compliance pathways, under-complying manufacturers have offset their compliance shortfall (credit shortfalls) by carrying forward, backward, transferring or trading credits. While some manufacturers are also still paying civil penalty payments for noncompliance, the amount has significantly decreased mainly due to an active credit trading market. An overview of the compliance credit flexibilities used by manufacturers from model year 2011 through 2014 is shown in Figure 3.15.

NHTSA anticipates that credit trading will continue to be a major incentive for manufacturers in the upcoming model years as credit trading was the primary flexibility in model year 2014. NHTSA predicts that the CAFE credit market moving into model year 2015 for each compliance fleet is robust enough to allow manufacturers not meeting standards to continue to comply for the next several model years. A summary of the CAFE credits carrying into model year 2015 is shown in Table 3.4.

[J] EPCA, as amended by EISA, is very prescriptive with regard to the number of flexibilities that are available to manufacturers to help them comply with the CAFE standards but intentionally placed some limits on certain flexibilities and incentives for the purpose of balancing energy-savings.

[K] Incentives are allowed for building advanced technology vehicles such as hybrids and electric vehicles, compressed natural gas vehicles and building vehicles able to run on dual fuels such as E85 and gasoline.

[L] We note that while these flexibility mechanisms will reduce compliance costs to some degree for most manufacturers, although 49 U.S.C. 32902(h) expressly prohibits NHTSA from considering the availability of statutorily-established credits (either for building dual- or alternative-fueled vehicles or from accumulated transfers or trades) in determining the level of the standards. Thus, NHTSA may not raise CAFE standards because manufacturers have enough of those credits to meet higher standards. This is an important difference from EPA’s authority under the CAA, which does not contain such a restriction, and which would allow EPA to set more stringent standards as a result.

[M] Congress established the Alternative Motor Fuels Act (AMFA) which allows manufacturers to increase fleet Fuel Economy Performance values by producing dual fueled vehicles. For model years 1993 through 2014, the maximum increase in CAFE performance for a manufacturer attributable to dual fueled vehicles is 1.2 miles per gallon for each model year and thereafter decreases by 0.2 miles per gallon each model year until ending in 2019 (see 49 U.S.C. 32906).

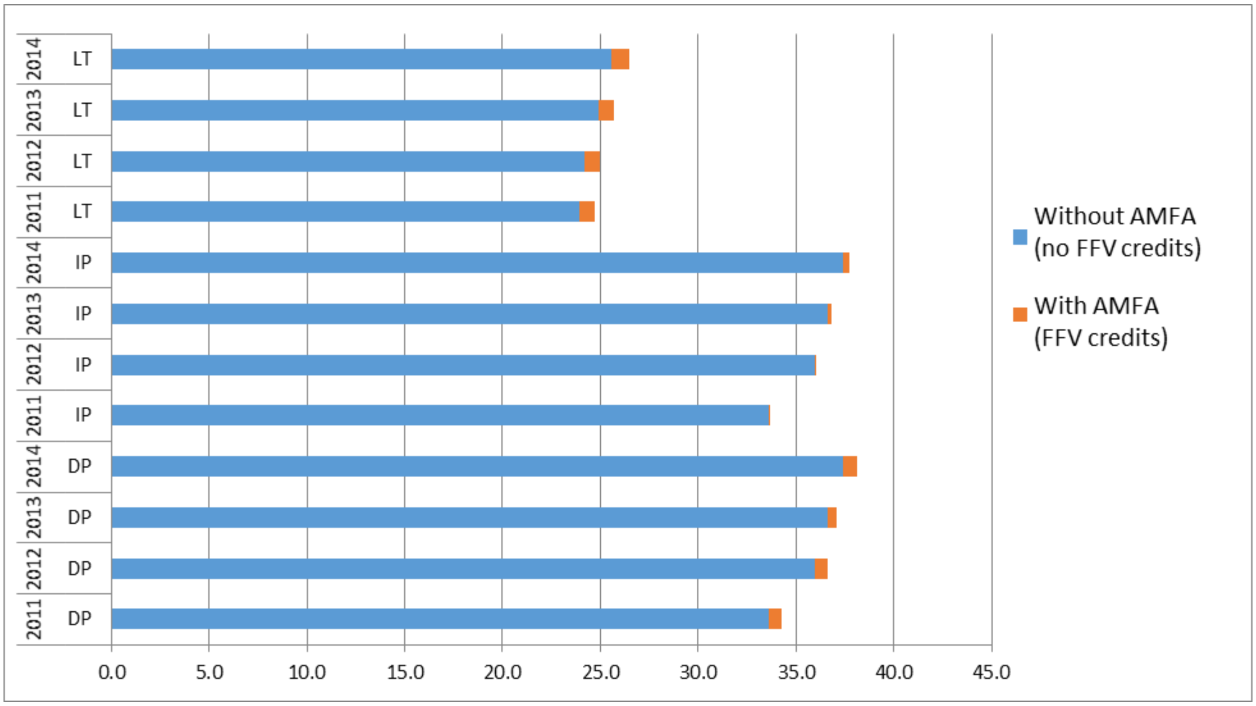

Figure 3.14 Increase due to Flexible Fuel Vehicles on CAFE Fleet Performance in Model Years 2011-2014

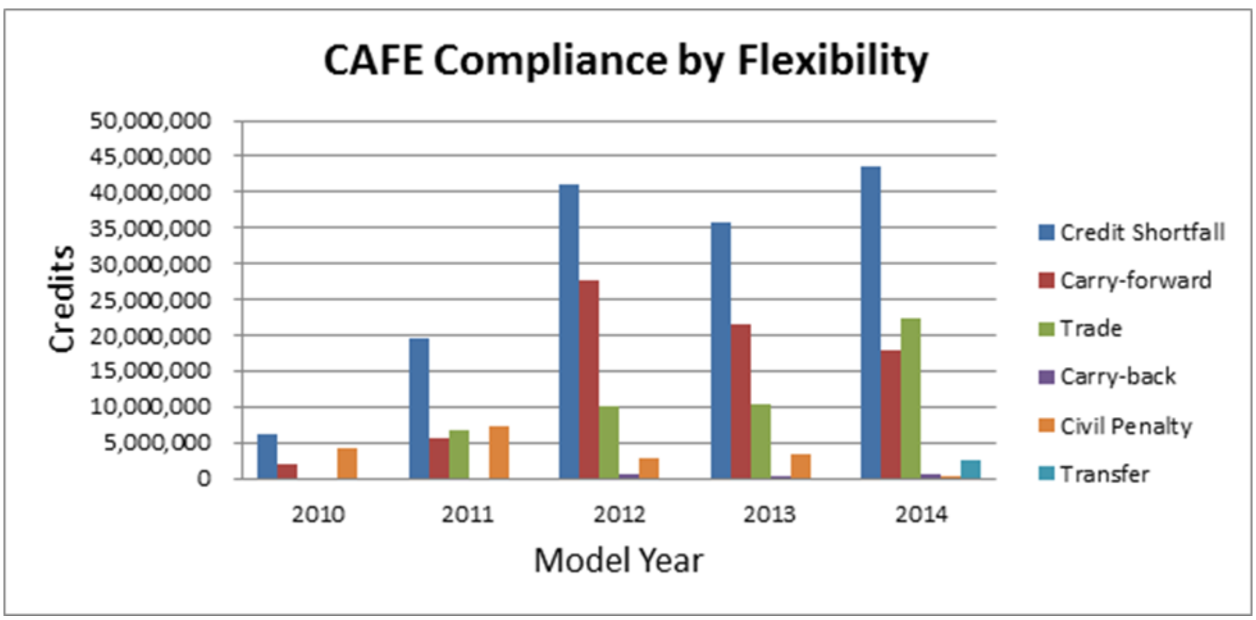

Figure 3.15 CAFE Credit Flexibilities Used and Civil Penalty Payments for Model Years 2010-2014

Table 3.4 CAFE Credit Balances at Conclusion of the 2014 Model Year

Manufacturer	Credits Carried to 2015		
	DP	IP	LT
Aston Martin [1]		0	
BMW		6,030,713	235,952
BYD Motors		177,951	
Coda		331,750	
Daimler	0	0	0
Fiat Chrysler	99,987,234	284,321	-4,174,892
Ford	157,373,701	1,175,577	17,818,347
General Motors	65,229,249	10,617,792	38,007,715
Honda	133,012,923	35,237,193	32,427,500
Hyundai [2]		127,023,114	7,060,784
Jaguar Land Rover		0	0
Kia [3]		54,652,961	3,838,194
Lotus		0	
Mazda	15,526	49,341,062	6,525,997
McLaren [4]		0	
Mitsubishi		6,067,098	2,574,682
Nissan [5]	116,007,703	3,014,623	5,399,372
Pagani [6]		0	
Spyker [7]		0	
Subaru	2,256,442	4,528,333	50,901,342
Suzuki		2,016,752	244,384
Tesla [8]	8,020,132		
Toyota	167,007,230	342,032,536	29,446,815
Volkswagen [9]	8,756,755	24,505,396	2,921,482
Volvo	37,435	-247,890	-315,044
All Manufacturers	**757,704,330**	**666,789,282**	**192,912,630**

[1] Aston Martin has submitted a petition for an alternative standard for MYs 2008 - 2014. This petition for an alternate standard is pending.

[2] MY 2014 EPA report is pending

[3] MY 2014 EPA report is pending

[4] McLaren has submitted a petition for an alternative standard for MYs 2012 - 2014. This petition for an alternate standard is pending.

[5] Nissan IP and DP fleets were exempt from two-fleet rule for model years 2006 – 2010

[6] Pagani has submitted a petition for an alternative standard for MY 2014.

[7] Spyker has submitted a petition for an alternative standard for MYs 2008 - 2010. This petition for an alternate standard is pending.

[8] Prior to MY 2012, per 40 CFR 600.001(b)(1), manufacturers that produced only electric vehicles were exempt from submitting CAFE information . EPA did not test vehicles and confirm compliance values of manufacturers who produce only electric vehicles from this time period.

[9] Volkswagen is included in an ongoing investigation. Data provided is based on original compliance data.

3.4 Emerging Transportation Developments

The automotive industry of today is rapidly evolving, and the pace of change is only increasing. Major automotive CEOs are not just talking about horsepower, but about becoming "mobility" companies[13] and "disrupting" the industry.[14] Technology companies that have not previously been associated with the automotive industry are further challenging and changing the industry as connectivity, autonomous driving, and infotainment systems continue to become a more prominent part of automotive design.

Autonomous vehicle developments are regularly in the headlines, with most manufacturers, many suppliers, and several technology companies actively developing and testing autonomous systems. Semi-autonomous systems are already available in some luxury vehicles today, and many more are promised in the next several years. The race to develop fully autonomous vehicles is clearly a high priority across the industry. Emerging in parallel with vehicle automation is vehicle connectivity. Vehicle connectivity, in conjunction with automated systems, has the potential benefit of allowing vehicles to communicate with each other and with infrastructure to optimize vehicle driving behavior to current conditions, and to interact with other vehicles and infrastructure to reduce congestion. And of course, connectivity can also mean more access to high speed data, entertainment, and productivity applications.

In addition to connected and automated vehicles, new companies based on the idea of the sharing economy are already upending how some people think about transportation and mobility in general. Ride hailing services continue to grow quickly and are already disrupting rental car and taxi business models. The largest ride hailing service is already valued more than several major OEMs after only a few years of existence.[15,16] The rapidly expanding list of transportation related apps for everything from finding a parking spot more efficiently, sharing rides, or finding public transit options also point to an industry that is facing rapid change.

Autonomous vehicles, shared mobility, parking apps, and other innovations were not considered by the agencies in the GHG rules, but their net impact on GHGs and fuel economy is yet unknown. They could ultimately have a very profound impact on the efficiency of our future transportation system. Preliminary research suggests that connected and automated vehicles could lead to dramatically reduced GHG emissions through more efficient driving, better traffic flow, shared mobility, and by enabling greater use of electrification. However, the same research acknowledges that the technology could also lead to increased vehicle miles traveled, higher speeds, and more vehicle content which could result in a large increase in emissions instead.[17,18,19,20] These emerging technologies and transportation changes will pose considerable future challenges and uncertainties. At the present time and probably even over the next several years, there will continue to be much uncertainty around the impacts of these changes on the transportation system. It is likely that many of these transformational changes will have impacts for the longer-term, and it will be difficult to assess any specific impacts in the 2022-2025 timeframe. While the agencies will continue to keep abreast of data and analyses surrounding transportation impacts of these transformations, it is likely that such uncertainty will remain throughout the timeframe of the midterm evaluation. EPA, NHTSA, and CARB are beginning to explore research on the potential emissions and fuel economy impacts of emerging transformational technologies and transportation trends. The agencies will continue to stay abreast of future research and partner with stakeholders to evaluate these emerging technologies and transportation trends, which may help to inform any regulatory development beyond model year 2025.

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Chapter 4: Baseline and Reference Vehicle Fleets

4.1 EPA's Baseline and Reference Vehicle Fleets

The passenger cars and light trucks sold currently in the United States, and those that are anticipated to be sold in the MYs 2021-2025 timeframe, are highly varied and satisfy a wide range of consumer needs. From two-seater miniature cars to 11-seater passenger vans to large extended cab pickup trucks, American consumers have a great number of vehicle options to accommodate their needs and preferences. The recent decline in oil prices and the improved state of the economy have demonstrated that consumer demand and choice of vehicles within this wide range can be sensitive to these factors. Although it is impossible to precisely predict the future, the agencies need to characterize and quantify the future fleet in order to assess the impacts of the 2022-2025 GHG standards that would affect that future fleet. The EPA has examined various publicly-available sources (some require purchase), and then used inputs from those sources in a series of models to project the composition of baseline and reference fleets for purposes of this analysis. This chapter describes this process, and the characteristics of the baseline and reference fleets.

The EPA has made every effort to make this analysis transparent and duplicable. Because both the input and output sheets from our modeling are public,[1] stakeholders can verify and check EPA's modeling results, and perform their own analyses with these.

4.1.1 Why does the EPA Establish Baseline and Reference Vehicle Fleets?

In order to calculate the impacts of the final 2022-2025 GHG standards, it is necessary to estimate the composition of the future vehicle fleet absent the 2022-2025 standards. EPA has developed a baseline/reference fleet in two parts. The first step was to develop a "baseline" fleet. The baseline fleet represents data from a single model year of actual vehicles sales. The EPA creates a baseline fleet in order to track the volumes and types of fuel economy-improving and CO_2-reducing technologies that are already present in the existing vehicle fleet. Creating a baseline fleet prevents the OMEGA model from adding technologies to vehicles that already have these technologies, which would result in "double counting" of technologies' costs and benefits. The second step was to project the baseline fleet sales into MYs 2022-2025. This is called the "reference" fleet volumes, and it represents the fleet volumes (but, until later steps, not additional levels of technology) that the EPA believes would exist in MYs 2022-2025 absent the application of the 2022-2025 GHG standards. For this Draft TAR, the EPA also projected the fleet from MYs 2026-2030 though we are only showing the result out to 2025.

After determining the reference fleet volumes, the third step is to account for technologies (and corresponding increases in cost and reductions in CO_2 emissions) that could be added to the baseline technology vehicles in the future, taking into account previously-promulgated standards, and assuming MY2021 standards apply at the same levels through MY2025. This step uses the OMEGA model to add technologies to vehicles in each of the baseline market forecasts such that each manufacturer's car and truck average CO_2 levels reflect MY2021 standards. The models' output, the "reference case," is the light-duty fleet estimated to exist in MYs 2022-2025 without new GHG standards. All of the EPA's estimates of emission reductions improvements, costs, and societal impacts for purposes of this Draft TAR are developed in relation to the EPA reference case. This chapter describes the first two steps of the development of the baseline and reference fleets volumes. The third step of technology addition is developed as the outputs of the OMEGA model (see Chapter 12 for an explanation of how the models apply technologies to vehicles in order to evaluate potential paths to compliance).

4.1.2 EPA's 2014 MY Baseline Fleet

EPA has chosen to use the final 2014 MY fleet GHG data as the basis for the baseline fleet used in its analysis. The 2014 MY fleet GHG data is the most recent complete set of final U.S. vehicle data that has actual manufacturer volumes and CO_2 values that is available to use in this Draft TAR. The 2014 MY volumes and CO_2 values comes from the EPA Verify[A] database. The data contained in the Verify system is quite robust since it under goes a complex number of quality checks done by the manufacturer, the Verify database software, and finally EPA's certification staff. Figure 4.1 shows the quality steps that are completed before data is available for use in the Verify system. The finalized 2014 GHG certification data is an accurate representation of vehicle and technology mix for the 2014 model year. Estimated volumes are also available for the 2015 model year (CAFE midyear report data), however, EPA chose to use the final 2014 MY data in lieu of the 2015 MY midyear estimates because the final 2014 MY was the latest data set which had completed the entire Verify quality assurance process. EPA's rationale for not using the 2015 MY data is explained in more detail at the end of this section.

The information used by EPA to develop the 2014 MY baseline fleet includes final MY2014 GHG certification data for MY2014 model volumes, some valve train information from Wards Automotive Group [B,C], and some technology from a 2014 fleet file that was created for the California Air Review Board (CARB) by Novation Analytics[2] (formerly known as Control Tec).

EPA will update the baseline fleet for future assessments in the MTE process to the most recent MY for which final data is available for the U.S. fleet.

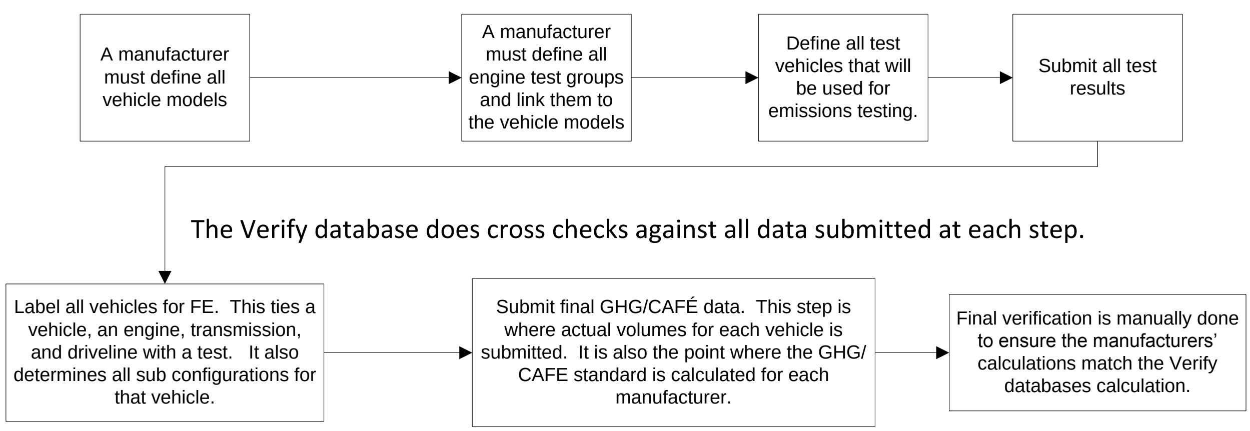

Figure 4.1 The Verify Process for the Data EPA's MY2014 Baseline Vehicle Fleet is Based

[A] The EPA Verify Database is the electronic system by which vehicle manufacturers provide their compliance data to the EPA. There are several built-in quality assurance provisions.
[B] WardsAuto.com: Used as a source for engine specifications shown in Figure 4.2.
[C] Note that WardsAuto.com, where this information was obtained, is a fee-based service, but all information is public to subscribers.

Similar to the 2008 baseline used in the 2017-2025 GHG FRM, most of the information about the vehicles that make up the 2014 fleet was gathered from EPA's emission certification and fuel economy database, most of which is available to the public. (Note that a 2010 baseline was created for the 2017-2025 GHG FRM, but it was only used for a sensitivity analysis and will not be used for analysis in this Draft TAR).[3] The 2014 GHG certification data included, by individual vehicle model produced in MY2014, vehicle production volume, carbon dioxide emissions rating for GHG certification, fuel type, fuel injection type, EGR, number of engine cylinders, displacement, intake valves per cylinder, exhaust valves per cylinder, variable valve timing, variable valve lift, engine cycle, cylinder deactivation, transmission type, drive (rear-wheel, all-wheel, etc.), hybrid type (if applicable), and aspiration (naturally-aspirated, turbocharged, etc.). In addition, the EPA augmented the 2014 GHG certification and fuel economy database (the EPA "Verify" database) with publicly-available data which includes valve information from Ward's Automotive Group, and data from Novation Analytics. Novation Analytics did an analysis of the 2014 fleet for CARB. In the process of doing their analysis they created a detailed fleet file from publicly available sources such as manufacturer's website. Novation Analytics" source for knowing which vehicles existed in MY2014 is EPA's certification test car list.[D]

The process for creating the 2014 baseline fleet Excel file was more complicated than in the 2012 FRM analysis. EPA created the baseline using 2014 GHG certification data from EPA's Verify database. In the past the data in Verify did not include vehicle footprint data. Verify now includes a complete set of footprint data for each vehicle, however it is separate from the GHG information. Manufacturers are required to report the number of each vehicle produced with a given footprint so the CO_2 target for that vehicle can be calculated. Separately, manufacturers are required to report the number of each unique combination of vehicle, engine, transmission, and driveline (2 wheel drive vs. 4 wheel drive) that is produced along with its measured GHG information. The combination of the two sets of data are used to determine if a manufacturer is complying with the GHG standards. These two data sets along with a data set from Wards Automotive, which contains engine cam information, the set from Novation Analytics, and volume projections from both EIA's Annual Energy Outlook (AEO) 2015 and IHS-Polk were used to create the 2014 baseline with the reference fleet volumes. These different sets of data had to be mapped into a single data set. Figure 4.2 shows the process for combining the six data sets with the result being the completed baseline with reference fleet projections.

[D] The test car list is available at http:://epa.gov/otaq/tcldata.htm.

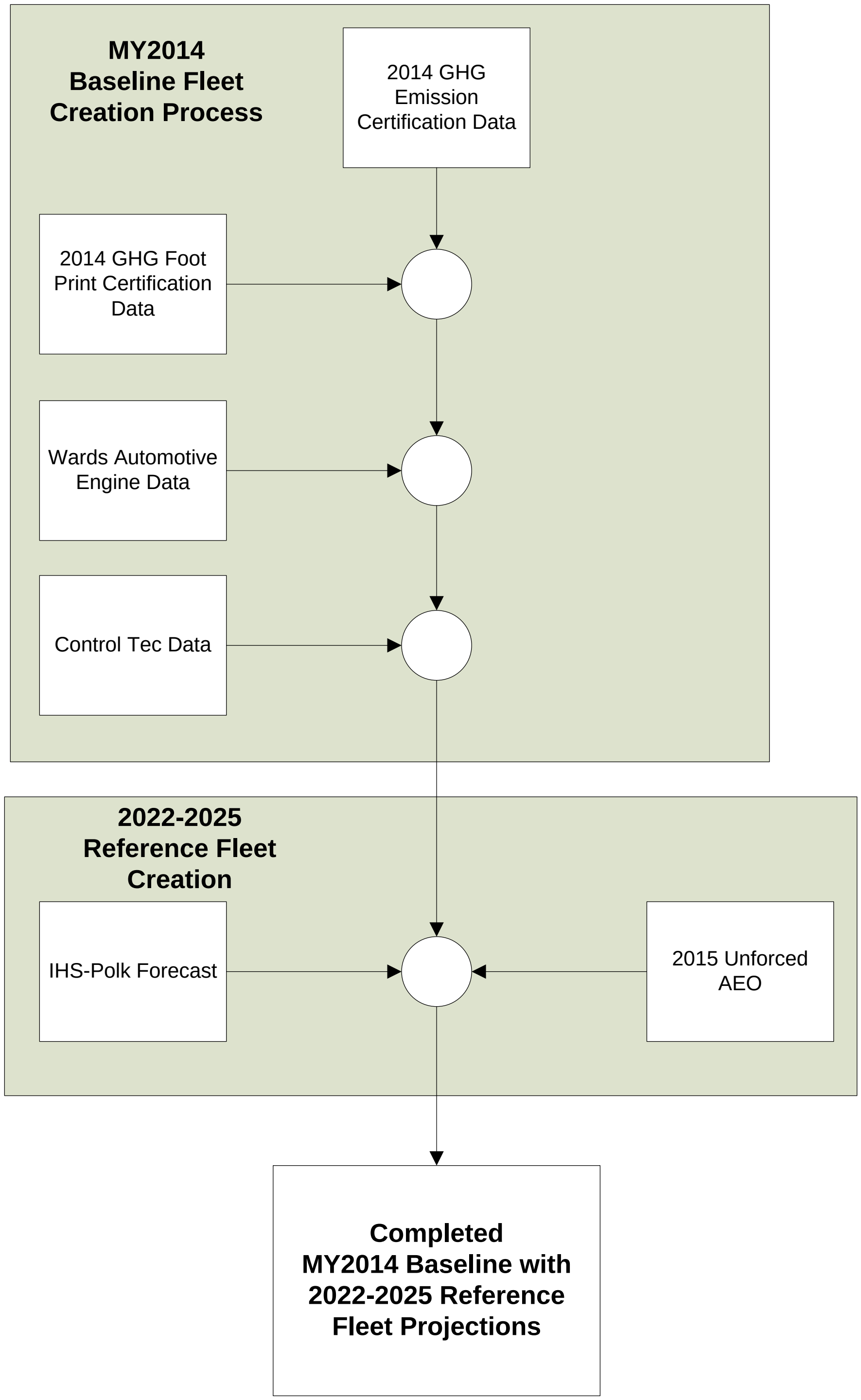

Figure 4.2 Process Flow for Creating the Baseline and Reference Fleet.

EPA contracted IHS-Polk to produce an updated long range forecast of volumes for the future fleet. A detailed discussion of the method used to project the future fleet volumes is in 4.1.2.1.1 of this chapter.

EPA used the previously mentioned data to populate input files for the OMEGA model. The baseline Excel file is available in the docket.[4] The Data Definitions tab of the Excel file has a list of the columns of data page with the units, definition, and source for each item that was compiled for the baseline data.

Table 4.1 displays the engine technologies present in the MY2014 baseline fleet. Most of the information came from certification data with Wards' data only being used for information regarding utilization of cam technology.

Table 4.1 MY2014 Engine Technology Penetration

Manufacturers	Vehicle Type	Turbo Charged	Super Charged	Single Overhead Cam	Dual Over Head Cam	Over Head Cam	Variable Valve Timing Continuous Intake Only	Variable Valve Timing Discrete	Variable Valve Discrete Lift Only	Variable Valve Lift and Timing Discrete	Vehicles without Variable Valve Timing or Lift	Cylinder Deactivation	Direct Injection
All	Both	15%	1%	6%	85%	8%	8%	74%	0%	16%	2%	11%	38%
All	Cars	18%	1%	5%	93%	1%	1%	78%	0%	18%	2%	2%	44%
All	Trucks	10%	1%	7%	75%	18%	18%	68%	0%	13%	1%	23%	30%
Aston Martin	Cars	0%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%
Aston Martin	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
BMW	Cars	93%	0%	2%	97%	0%	0%	1%	0%	91%	8%	0%	93%
BMW	Trucks	100%	0%	0%	100%	0%	0%	6%	0%	89%	5%	0%	100%
FCA	Cars	7%	0%	6%	84%	9%	9%	70%	0%	20%	1%	8%	2%
FCA	Trucks	2%	0%	0%	77%	23%	22%	73%	0%	3%	2%	23%	0%
Ferrari	Cars	0%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	100%
Ferrari	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Ford	Cars	29%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	54%
Ford	Trucks	34%	0%	7%	93%	0%	0%	100%	0%	0%	0%	0%	34%
GM	Cars	24%	0%	0%	96%	4%	3%	83%	0%	12%	2%	3%	64%
GM	Trucks	2%	0%	0%	30%	70%	69%	30%	0%	0%	1%	68%	88%
Honda	Trucks	0%	0%	57%	43%	0%	0%	0%	0%	100%	0%	55%	12%
Honda	Cars	0%	0%	43%	57%	0%	0%	0%	0%	100%	0%	11%	38%
Hyundai/Kia	Trucks	3%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	79%
Hyundai/Kia	Cars	6%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	81%
JLR	Cars	9%	85%	0%	100%	0%	0%	94%	0%	6%	0%	0%	100%
JLR	Trucks	17%	83%	0%	100%	0%	0%	42%	0%	58%	0%	0%	100%
Lotus	Cars	0%	67%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%
Lotus	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mazda	Cars	0%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	91%
Mazda	Trucks	0%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	61%
McLaren	Cars	100%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%
McLaren	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mercedes	Cars	46%	0%	0%	99%	0%	0%	97%	0%	0%	3%	0%	92%
Mercedes	Trucks	42%	0%	2%	98%	0%	0%	85%	0%	0%	15%	0%	98%
Mitsubishi	Cars	7%	0%	65%	35%	0%	0%	100%	0%	0%	0%	0%	0%
Mitsubishi	Trucks	0%	0%	100%	0%	0%	0%	38%	11%	51%	0%	0%	0%
Nissan	Cars	4%	0%	0%	99%	0%	0%	92%	0%	7%	1%	0%	0%
Nissan	Trucks	0%	2%	0%	100%	0%	0%	95%	0%	5%	0%	0%	4%
Subaru	Cars	11%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%
Subaru	Trucks	3%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	3%
Tesla	Cars	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%
Tesla	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Toyota	Cars	0%	0%	0%	100%	0%	0%	98%	0%	1%	0%	0%	3%

Toyota	Trucks	0%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%
Volkswagen	Cars	73%	6%	9%	91%	0%	0%	47%	0%	25%	27%	1%	84%
Volkswagen	Trucks	54%	28%	0%	100%	0%	0%	34%	0%	49%	17%	0%	100%
Volvo	Cars	79%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%
Volvo	Trucks	45%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%

The data in Table 4.1 indicate that manufacturers have added a significant amount of engine technology to the vehicles in the baseline (2014) fleet (as also discussed in Chapter 3.1.6). For example, BMW stands out as having a significant number of gasoline turbocharged direct injection engines. Most of the fleet's engines are using DOHC (dual overhead cam), and have discrete variable valve timing (VVT). Over half of Honda's vehicles have engines with cylinder deactivation.

The data in Table 4.2 shows the changes between the 2014 engine technology penetrations and the 2008 engine technology penetrations. To increase fuel economy, manufacturers applied considerable technology between 2008 and 2014. Manufacturers increased the use of direct injection 37 percent on cars and 28 percent on trucks. Manufacturers also increased the use of turbo chargers 14 percent on cars and 9 percent on trucks.

Table 4.2 Change (2014-2008) in Engine Technology Penetration

Manufacturers	Vehicle Type	Turbo Charged	Super Charged	Single Overhead Cam	Dual Over Head Cam	Over Head Cam	Variable Valve Timing Continuous Intake Only	Variable Valve Timing Discrete	Variable Valve Discrete Lift Only	Variable Valve Lift and Timing Discrete	Vehicles without Variable Valve Timing or Lift	Cylinder Deactivation	Direct Injection
All	Both	12%	1%	-14%	23%	-9%	0%	54%	-9%	13%	-59%	4%	33%
All	Cars	14%	0%	-12%	20%	-8%	-8%	58%	-9%	14%	-55%	0%	37%
All	Trucks	9%	1%	-17%	28%	-11%	12%	50%	-9%	11%	-64%	11%	28%
Aston Martin	Cars	0%	0%	0%	0%	0%	0%	24%	0%	-24%	0%	0%	0%
Aston Martin	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
BMW	Cars	60%	-1%	-12%	11%	0%	-2%	-84%	0%	77%	8%	0%	60%
BMW	Trucks	95%	0%	0%	0%	0%	0%	-94%	0%	89%	5%	0%	94%
FCA	Cars	6%	0%	-15%	13%	2%	9%	28%	0%	20%	-57%	3%	2%
FCA	Trucks	2%	0%	-39%	73%	-34%	22%	69%	0%	3%	-94%	18%	0%
Ferrari	Cars	0%	0%	0%	0%	0%	0%	29%	0%	-29%	0%	0%	100%
Ferrari	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Ford	Cars	29%	-1%	-15%	15%	0%	-4%	100%	0%	0%	-96%	0%	54%
Ford	Trucks	34%	0%	-59%	62%	-3%	-28%	99%	0%	0%	-71%	0%	34%
GM	Cars	23%	0%	0%	40%	-40%	-26%	52%	0%	12%	-38%	-1%	58%
GM	Trucks	2%	0%	0%	-1%	1%	64%	13%	0%	0%	-76%	28%	88%
Honda	Trucks	-4%	0%	-7%	7%	0%	0%	0%	-96%	96%	0%	55%	8%
Honda	Cars	0%	0%	-14%	14%	0%	0%	0%	-73%	72%	0%	0%	38%
Hyundai/Kia	Trucks	3%	0%	0%	0%	0%	0%	100%	0%	0%	-100%	0%	79%
Hyundai/Kia	Cars	6%	0%	0%	0%	0%	0%	100%	0%	0%	-100%	0%	81%
JLR	Cars	9%	85%	0%	0%	0%	0%	18%	0%	6%	-24%	0%	100%
JLR	Trucks	17%	63%	0%	0%	0%	0%	42%	0%	58%	-100%	0%	100%
Lotus	Cars	0%	-11%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Lotus	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mazda	Cars	-11%	0%	0%	1%	0%	0%	93%	0%	0%	-93%	0%	80%
Mazda	Trucks	-24%	0%	-1%	1%	0%	0%	87%	0%	0%	-87%	0%	38%
McLaren	Cars	100%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%
McLaren	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mercedes	Cars	44%	0%	-55%	53%	0%	-72%	93%	0%	0%	-21%	0%	91%
Mercedes	Trucks	26%	-1%	-35%	35%	0%	-35%	67%	0%	0%	-33%	0%	83%
Mitsubishi	Cars	1%	0%	-35%	35%	0%	-100%	100%	0%	0%	0%	0%	0%
Mitsubishi	Trucks	0%	0%	0%	0%	0%	-38%	38%	11%	51%	-62%	0%	0%
Nissan	Cars	4%	0%	0%	-1%	0%	0%	88%	0%	7%	-95%	0%	0%
Nissan	Trucks	0%	2%	0%	0%	0%	0%	95%	0%	5%	-100%	0%	4%
Subaru	Cars	-4%	0%	-69%	69%	0%	0%	100%	-1%	0%	-99%	0%	0%
Subaru	Trucks	0%	0%	-70%	70%	0%	0%	100%	-5%	-23%	-73%	0%	3%
Tesla	Cars	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Tesla	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Toyota	Cars	0%	0%	0%	0%	0%	0%	70%	0%	1%	-71%	0%	-5%
Toyota	Trucks	0%	0%	0%	0%	0%	0%	39%	0%	0%	-39%	0%	-6%

Volkswagen	Cars	32%	6%	-70%	70%	0%	0%	-2%	0%	24%	-22%	1%	0%
Volkswagen	Trucks	48%	28%	0%	0%	0%	0%	22%	0%	-39%	17%	0%	0%
Volvo	Cars	31%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Volvo	Trucks	45%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Finally, the decision to not use the mid-year report data for 2015 MY was based on several factors. For mid-year reports manufacturers must estimate volumes for every vehicle they can produce instead of accounting for the vehicles they actually produce. These include powertrain and other options that may never ultimately be produced or may be produced at significantly different volumes than those the manufacturers initially estimated. Manufacturers may certify these extra configurations (and estimate them as part of certification) in order to ensure they can continuously produce at plants no matter which components are available. This practice provides the manufacturers with a high degree of manufacturing flexibility. Table 4.3 shows the differences between the 2015 midyear estimates and the preliminary final submission (this data has been entered into the Verify database by Ford and marked final, but has not gone through the manual verification process) for Ford's vehicles. The difference between estimated and actual penetration rates are significant enough to impact EPA's compliance pathway projections. In addition to estimated vs. actual sales volume projections, mid-year estimates may also affect individual vehicle fuel economy and greenhouse gas emissions performance. Label testing is done based on a manufacturer's high volume seller for a model. Manufacturers often do additional emissions testing between the initial labeling for vehicles and when final data is submitted due to regulatory requirements for meeting CAFE and GHG standards. Compliance solutions that are compromised by significant differences in sales volumes can be exacerbated by changes in individual vehicle emissions. A different mix of vehicles will end up changing the reported GHG for a model since GHG is production weighted based on the vehicles within each model. These differences make using the midyear data a soft basis for projecting the future verse the solid foundation of exact volumes and exact CO_2 that final reported data gives.

Table 4.3 MY2015 Ford Engine Technology Penetration

	Penetration of Turbo's and Supercharged Engines	
	Mid-Year Data	Final Data
Trucks	49.6%	40.4%
Cars	33.2%	28.7%
All	43.1%	35.2%

4.1.2.1 EPA's MY2014 Based MY2022-2025 Reference Fleet

This section provides further detail on the projection of the MY2014 baseline volumes into the MYs 2022-2025 reference fleet. It also describes more of the data contained in the baseline spreadsheet.

The reference fleet aims to reflect our latest projections about the market and fleet characteristics during the model years 2022 to 2025. Fundamentally, constructing this fleet involved projecting the MY2014 baseline fleet volumes out to the MYs 2022-2025. It also included the assumption that none of the vehicle models changed during this period. As with the MY2008-based MY2022-2025 reference fleet used in the 2012 FRM, EPA relied on many sources of reputable information to make these projections, yet any future fleet projections are inherently uncertain.

4.1.2.1.1 On What Data Are EPA's Reference Vehicle Fleet Volumes Based?

EPA has based the projection of total car and light truck sales on the Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2015, which was the most recent projection available by at the time our Draft TAR analysis was underway. EIA's AEO 2015 also projects future energy production, consumption and prices.[5] EIA issued the AEO 2015 on April 14, 2015. Similar to the analyses supporting the MYs 2017-2025 rulemaking and for the 2008 based fleet projection, the EPA used the EIA's National Energy Modeling System (NEMS) to estimate the future relative market shares of passenger cars and light trucks. However, in NEMS, EIA models the light-duty fleet to comply with CAFE and GHG standards from 2012 through 2025 (along with the car/truck mix). In order to create a reference fleet absent the 2022-2025 standards, we only wanted NEMS to modify the fleet up to MY2021. Therefore, for the current analysis, EPA and NHTSA developed a new projection of passenger car and light truck sales shares by using NEMS to run scenarios from AEO 2015 cases (reference, high, low), holding post-2021 CAFE and GHG standards constant at MY2021 levels. The output of the NEMS model is consistent with AEO 2015 since it has the same inputs as AEO 2015. As with the comparable exercise for the 2012 FRM baseline fleet, this case is referred to as the "Unforced Reference Case," and the values are shown below in Table 4.4. The "unforced reference case" will be referred to as "unforced AEO 2015" for the rest of Chapter 4.1. Table 4.5 shows the originally published AEO 2015 fleet projections.

Table 4.4 AEO 2015 Unforced Reference Case Values used in the 2014 Market Fleet Projection

Model Year	Cars	Trucks	Total Vehicles
2021	8,136,376	7,960,213	16,096,589
2022	8,143,641	7,884,714	16,028,354
2023	8,269,894	7,820,048	16,089,941
2024	8,410,497	7,798,752	16,209,249
2025	8,597,413	7,827,599	16,425,012

Table 4.5 AEO 2015 Reference Case Values

Model Year	Cars	Trucks	Total Vehicles
2021	8,132,575	7,964,258	16,096,833
2022	8,140,457	7,889,725	16,030,182
2023	8,224,600	7,864,634	16,089,233
2024	8,323,431	7,886,273	16,209,704
2025	8,517,159	7,911,763	16,428,922

In 2021, car and light truck sales are projected to be 8.1 and 7.9 million units, respectively. While the total level of sales of 16 million units is similar to pre-2008 levels, the fraction of car sales in 2021 and beyond is projected to be lower than some of the previous AEO projections.

In addition, sales of segments within both the car and truck markets have also been changing and are expected to continue to change in the future. In order to reflect these changes in fleet makeup, EPA used a custom long range forecast purchased from IHS-Polk Automotive (IHS bought CSM from whom we previously purchased a long range forecast). IHS also purchased Polk automotive which has registration data for all the vehicles in the United States. IHS-Polk is a well-known industry analysis source for forecasting casting and other data. EPA decided to use the forecast from IHS-Polk for MY2014-based market forecast for several reasons. First, IHS-Polk Automotive continues to use CSM's bottom-up approach (e.g., looking at the number of plants and capacity for specific engines, transmissions, vehicles, and now registration data from Polk) for their forecast, which we believe is a robust forecasting approach. Second, IHS-Polk agreed to allow EPA to publish their entire forecast in the public domain. Third, the IHS-Polk forecast covered the timeframe of greatest relevance to this analysis (2022-2025 model years). Fourth, it provided projections of vehicle sales both by manufacturer and by market segment. Fifth, it utilized market segments similar to those used in the EPA emission certification program and fuel economy guide, such that the EPA could include only the segments types covered by the light-duty vehicle standards.

IHS-Polk created a custom forecast for EPA that covered model years 2012-2030. Since the EPA is using this forecast to generate the reference fleet volumes for this Draft TAR (i.e., the fleet expected to be sold absent any increases in the stringency regulations after the 2021 model year), it is important for the forecast to be independent of increases during 2022-2025 in the stringency of CAFE/ GHG standards. IHS-Polk does not normally use the CAFE or GHG standards as an input to their model, and EPA specified that they assume that the stringencies of the two programs would stay constant at 2021 levels in the 2022-2025 time frame for our forecast. This was done to eliminate the effects of the current EPA standards on the 2022 to 2025 MY fleet. In addition, EPA specified that the IHS-Polk forecast use EIA's AEO 2015 fuel prices and economic indicators to create the forecast. IHS-Polk uses many additional inputs in their model including GDP growth, interest rates, the unemployment Rate, and crude oil prices to determine overall demand. They then use vehicle size, price, and function to forecast with enough resolution to predict brand and fleet segmentation. Additional details regarding the IHS-Polk forecast can be found in a methodology description provided by IHS-Polk to EPA is available in the docket EPA-HQ-OAR-2015-0827.

The EPA combined the IHS-Polk forecast with data from other sources to create the 2014 baseline reference fleet projections. This process is discussed in sections that follow.

4.1.2.1.2 *<u>How did the EPA develop the 2014 Baseline and 2022-2025 Reference Vehicle Fleet Volumes?</u>*

The process of producing the MY2014 baseline 2022-2025 reference fleet volumes involved combining the baseline fleet with the projection data described above. This was a complex multistep procedure, which is described in this section. The procedure is new and some of the steps are different than those used with the MY2008 baseline fleet projection used in the FRM.

4.1.2.1.3 *<u>How was the 2014 Baseline Data Merged with the IHS-Polk Data?</u>*

EPA employed a method similar to the method used in the FRM for mapping certification vehicles to IHS-Polk vehicles. Merging the 2014 baseline data with the 2022-2025 IHS-Polk data required a thorough mapping of certification vehicles to IHS-Polk vehicles by individual make and model. One challenge that the EPA faced when determining a reference case fleet was that the sales data projected by IHS-Polk has similar but different market segmentation than the data contained in EPA's internal database. In order to create a common segmentation between the two databases, the EPA performed a side-by-side comparison of each vehicle model in both datasets, and created an additional "IHS-Polk Class" modifier in the baseline spreadsheet to map the two datasets. The reference fleet volumes based on the "IHS-Polk Class" was then projected.

The baseline data and reference fleet volumes are available to the public. The baseline Excel spreadsheet in the docket is the result of the merged files.[6] The spreadsheet provides specific details on the sources and definitions for the data. The Excel file contains several tabs. They are: "Final Data," "Data Tech Definitions, "Platforms," "VehType," "VehType(2)," "Lookups," "Metrics," "Machine," "MarketFile2021," and "MarketFile2025," "Final Data" is the tab with the raw data. "Data Tech Definitions" is the tab where each column is defined and its data source named.

In the combined EPA certification and IHS-Polk data, all 2014 vehicle models were assumed to continue out to 2025, though their volumes changed in proportion to IHS-Polk projections. This methodology is used to provide surrogate greenhouse gas performance data for new emerging models. As a result, new models expected to be introduced within the 2015-2025 timeframe are mapped to existing models. Remapping the volumes from these new vehicles to the existing models via manufacturer segments preserves the overall fleet volume. All MYs 2022-2025 vehicles are mapped from the existing vehicles to the manufacturer's future segment volumes. The mappings are discussed in the next section. Further discussion of this limitation is discussed below in Section 4.1.2.1.4. The statistics of this fleet will be presented below since further volume modifications were required.

4.1.2.1.4 <u>How were the IHS-Polk Forecast and the Unforced AEO 2015 Forecast Used to Project the Future Fleet Volumes?</u>

As with the comparable step in the MY2008 baseline 2022-2025 reference fleet process, the next step in the EPA's generation of the reference fleet is one of the more complicated steps to explain. First, each vehicle in the 2014 data had an IHS-Polk segment mapped to it. Second, the breakdown of segment volumes by manufacturer was compared between the IHS-Polk and 2014 data set. Third, a correction was applied for Class 2B vehicles in the IHS-Polk data. Fourth, the individual manufacturer segment multipliers were created by year. And finally, the absolute volumes of cars and trucks were normalized (set equal) to the total sales estimates of the unforced AEO 2015. This final step is required to create a fleet forecast that reflects the official government forecast for future vehicle sales. The unforced AEO 2015 forecast alone does not have the necessary resolution, down to the vehicle segment level, for EPA to perform its analysis. Therefore EPA applies both a purchased forecast from IHS-Polk and the unforced AEO 2105 forecast to create a complete fleet forecast.

The process started with mapping the IHS-Polk segments to each vehicle in the baseline data. The mapping required determination of the IHS-Polk segment by lookup at each of the 2,160 baseline vehicles in the IHS-Polk forecast (which has only 617 vehicles since they do not forecast powertrain or footprint differences), and labeling it in the "IHS-Polk Class" column of the baseline data. The IHS-Polk data has 52 segments. Table 4.6 has the IHS-Polk segments for reference. Table 4.7 shows some of the Honda vehicles in the CAFE data with their "IHS-Polk Segment" identified.

Table 4.6 List of IHS-Polk Segments

IHS-Polk Segments		
Micro Non-premium Car	Compact Non-premium Car	Mid-Size Premium Van
Micro Non-premium Sporty	Compact Non-premium MPV	Mid-Size Super Premium Car
Mini Non-premium Car	Compact Non-premium Sporty	Mid-Size Super Premium Sporty
Mini Non-premium MPV	Compact Non-premium SUV	Mid-Size Super Premium SUV
Mini Non-premium Sporty	Compact Non-premium Van	Full-Size Non-premium Car
Mini Non-premium SUV	Compact Premium Car	Full-Size Non-premium Pickup
Mini Premium Car	Compact Premium Sporty	Full-Size Non-premium Sporty
Mini Premium Sporty	Compact Premium SUV	Full-Size Non-premium SUV
Subcompact Non-premium Car	Compact Super Premium Sporty	Full-Size Non-premium Van
Subcompact Non-premium MPV	Compact Super Premium SUV	Full-Size Premium Car
Subcompact Non-premium Pickup	Mid-Size Non-premium Car	Full-Size Premium Sporty
Subcompact Non-premium Sporty	Mid-Size Non-premium MPV	Full-Size Premium SUV
Subcompact Non-premium SUV	Mid-Size Non-premium Pickup	Full-Size Premium Van
Subcompact Premium Car	Mid-Size Non-premium Sporty	Full-Size Super Premium Car
Subcompact Premium MPV	Mid-Size Non-premium SUV	Full-Size Super Premium Sporty
Subcompact Premium Sporty	Mid-Size Premium Car	Full-Size Super Premium SUV
Subcompact Premium SUV	Mid-Size Premium Sporty	
Subcompact Super Premium Sporty	Mid-Size Premium SUV	

Table 4.7 Example of Honda Vehicles Being Mapped to Segments Based On the IHS-Polk Forecast

Manufacturer	Name Plate	Model	IHS-Polk Segment
Honda	Acura	ILX	Compact Premium Car
Honda	Acura	MDX	Mid-Size Premium SUV
Honda	Acura	RDX	Compact Premium SUV
Honda	Acura	RLX	Mid-Size Premium Car
Honda	Acura	TSX	Mid-Size Premium Car
Honda	Honda	ACCORD	Mid-Size Non-Premium Sporty
Honda	Honda	ACCORD	Mid-Size Non-Premium Car
Honda	Honda	CIVIC	Compact Non-Premium Car
Honda	Honda	CIVIC	Compact Non-Premium Sporty
Honda	Honda	FCX	Compact Non-Premium Car
Honda	Honda	CR-V	Compact Non-Premium SUV
Honda	Honda	CR-Z	Mini Non-Premium Sporty
Honda	Honda	CROSSTOUR	Mid-Size Non-Premium SUV
Honda	Honda	FIT	Subcompact Non-Premium Car
Honda	Honda	INSIGHT	Compact Non-Premium Car
Honda	Honda	ODYSSEY	Mid-Size Non-Premium MPV
Honda	Honda	PILOT	Mid-Size Non-Premium SUV
Honda	Honda	RIDGELINE	Mid-Size Non-Premium Pickup Truck

In the next step, segment volume by manufacturer was compared between the baseline and IHS-Polk data sets. This is necessary to determine if all of the segments a manufacturer will produce in the future are currently represented by the 2014 certification data. The forecasts used in past rulemakings predicted very few new segments for manufactures. The new forecast from IHS-Polk projects that manufacturers will be entering more new segments (i.e., segments they currently do not participate in) than in previous forecasts. This requires making sure a manufacturers volume in the new segment be added to the volume of a manufacturers closest existing segment. The flow chart below (Figure 4.3) shows the process for determining this "closest class," This process worked well for the majority of manufacturers with the exception being Tesla and Aston Martin who will be entering the SUV segment in the future but in MY2014 were currently only in the car segment. We believe that this process of establishing closest class surrogates provides the best estimate of the potential current performance of a given vehicle type and the technology that will be required to meet the 2025 standards.

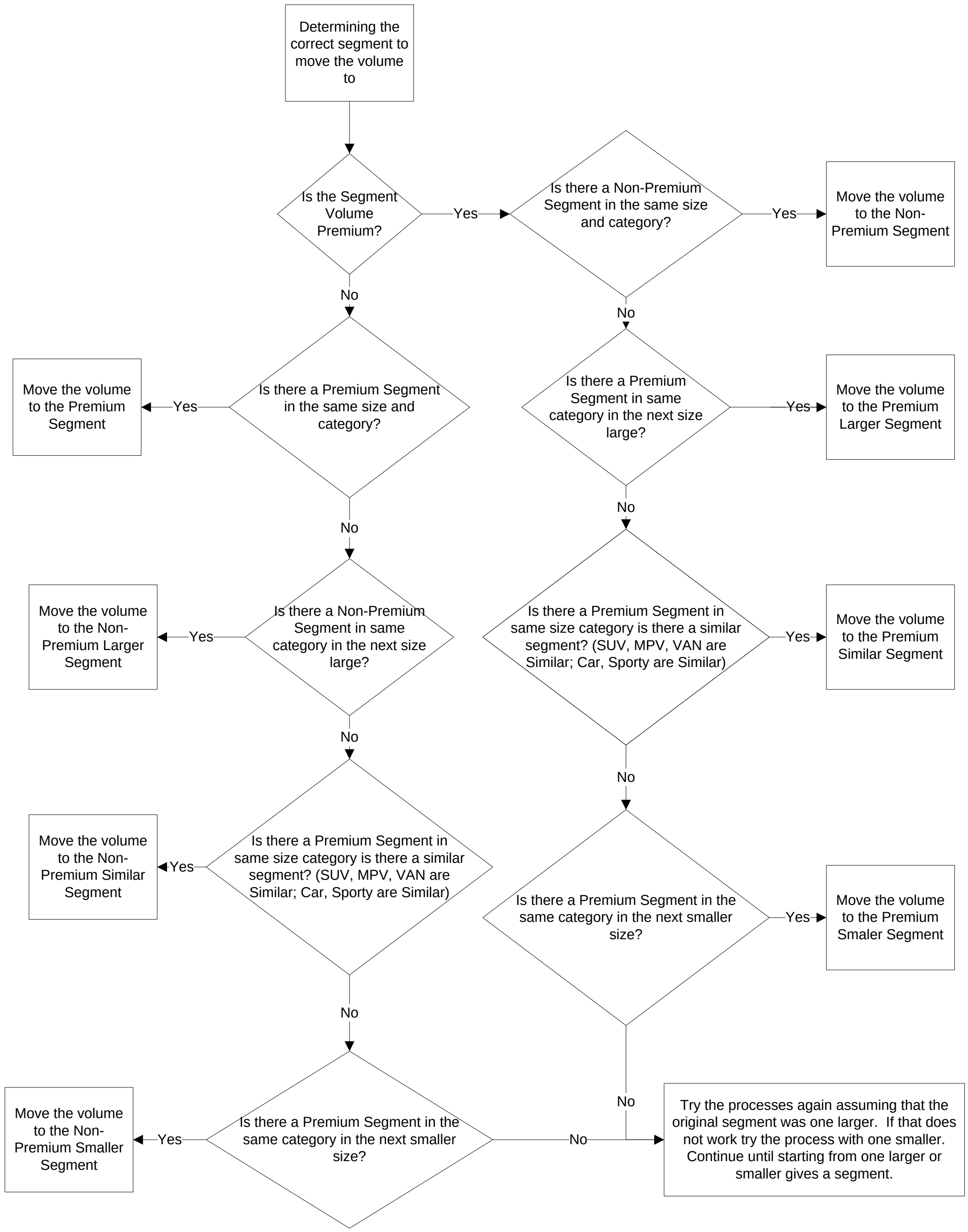

Figure 4.3 Process Flow for Determining where Segment Volume Should Move

Table 4.8 shows Honda's segments with their volumes for both the baseline data and IHS-Polk. Note that Compact Premium Sporty, Subcompact Non-Premium SUV, and Subcompact Premium SUV segments don't exist in the baseline data. The closest classes to those are Compact Non-Premium Car, Compact Non-Premium SUV, and Compact Premium SUV.

It is also important to note the difference between Model Year (MY) and Calendar Year (CY) sales. Model Year sales can be shorter or longer than a full calendar year due to product launch and change decisions made by a manufacturer. As a result the Model Year (MY[E]) sales can be less than or greater than a respective Calendar Year sales. In Table 4.8 below a manufacturer example is provided. For 2014 MY, Honda produced 26,689 vehicles that fell into the Compact Non-Premium Car class. The IHS data shows 276,287 vehicles in their CY forecast. This is because the baseline data represents what was built for 2014 model year in both calendar years 2013 and 2014; and, IHS-Polk data is showing the total volume for 2014 calendar year which has both 2014 and 2015 model year vehicles represented. In this case Honda was introducing a new Civic. It started 2014 calendar year building 2015 model year Civics instead of continuing to build 2014 model year Civics till June as is the usual practice. As a result, the 2014 MY vehicles were most likely built in 2013 CY and the 2014 CY volumes reflect a large volume 2015 MY Civics. In years that are close to the baseline year this can be a source of error, but as years progress, calendar year and model year volumes become the same in a forecast since models are not added or deleted in the forecast. This allows EPA to use a calendar year forecast since we are concerned with vehicles being built far enough in the future that calendar year and model year volumes are approximately the same.

Table 4.8 Example Honda 2014 Volumes by Segment from the IHS-Polk Forecast

Honda-Baseline Data	2014 MY	Honda-IHS-Polk Data	2014 CY[F]	2018 CY	Action
Compact Non-Premium Car	28,689	Compact Non-Premium Car	276,287	327,993	
Compact Non-Premium Sporty	239,044	Compact Non-Premium Sporty	49,696	30,053	
Compact Non-Premium SUV	383,890	Compact Non-Premium SUV	335,019	299,644	
Compact Premium Car	16,349	Compact Premium Car	17,854	15,379	
		Compact Premium Sporty	0	797	Move Volume to Compact Non-Premium Sporty
Compact Premium SUV	43,179	Compact Premium SUV	44,865	40,642	
Mid-Size Non-Premium Car	327,677	Mid-Size Non-Premium Car	353,508	338,848	
Mid-Size Non-Premium MPV	138,203	Mid-Size Non-Premium MPV	122,738	106,887	
Mid-Size Non-Premium Pickup Truck	13,790	Mid-Size Non-Premium Pickup	13,389	52,244	
Mid-Size Non-Premium Sporty	62,019	Mid-Size Non-Premium Sporty	34,866	0	
Mid-Size Non-Premium SUV	93,652	Mid-Size Non-Premium SUV	120,659	144,182	
Mid-Size Premium Car	27,055	Mid-Size Premium Car	39,447	44,876	
Mid-Size Premium SUV	68,547	Mid-Size Premium SUV	65,681	53,249	
Mini Non-Premium Sporty	3,473	Mini Non-Premium Sporty	3,562	10,915	
Subcompact Non-Premium Car	599	Subcompact Non-Premium Car	63,305	54,988	Move Volume to Compact Non-Premium Car
		Subcompact Non-Premium SUV	0	73,855	Move Volume to Compact Non-Premium SUV
		Subcompact Premium SUV	0	23,977	Move Volume to Compact Premium

[E] Model Year sales may begin as early as January 1 of the previous calendar year (MY -1).
[F] 2014 Calendar Year can include both 2014 and 2015 Model Year vehicle sales if both are built in the calendar year.

A step that is related to the comparison step is the filtering of Class 3 vehicles from the IHS-Polk forecast. IHS-Polk includes Class 2b and Class 3 vehicles (vans and large pickup trucks) in its light-duty forecast. Class 2b vans are all appropriately classified as MDPVs (Medium Duty Passenger Vehicles) and must be included in the forecast since they are regulated under the light-duty GHG program. Class 2b large pickup trucks, however, are not regulated under the light-duty GHG program (rather under the medium-duty and heavy-duty fuel efficiency and GHG programs, see 76 FR 57120), and must therefore be removed from the forecast. Since, IHS-Polk labels the Class 2b/3 pickup trucks with an HD, it was readily apparent which Class 2b pickup trucks to filter from the forecast. Vans in the IHS-Polk forecast on the other hand have both Class 2b and 3 and MDPVs in their totals and must have a correction factor applied. This is accomplished by creating a multiplier for each manufacturer's Full-Size Non-Premium Vans and applying it to each manufacturer's Full-Size Non-Premium Van volume every model year in the IHS-Polk forecast; specifically, by taking a manufacturer's 2014 model year Full-Size Non-Premium Van baseline volume and dividing its 2014 calendar year Full-Size Non-Premium Van IHS-Polk volume. Table 4.9 shows the volumes and the resulting multiplier for FCA, while

Table 4.10 shows the 2025 IHS-Polk volume, the multiplier and the result of applying the multiplier to the original volume for FCA.

Table 4.9 Example Values Used to Determine the MDPV Multiplier for FCA

Manufacturer	NEW SEGMENT	IHS-Polk 2014 Volume	2014 CAFE Volume	MDPV Multiplier
FCA	Full-Size Non-Premium Van	24,840	10,485	0.42

Table 4.10 Example Values Used to Determine FCA's 2025 Van Volume

Manufacturer	NEW SEGMENT	Original 2025 Volume	MDPV Multiplier	2025 Volume after Multiplier
FCA	Full-Size Non-Premium Van	15,074	0.42	6,331

EPA next created individual manufacturer segment multipliers to be used with the individual 2014 vehicle volumes to create projections for the future fleet. The individual manufacturer segment multipliers are created by dividing each year of the IHS-Polk forecast's individual manufacturer segment volume by the manufacturer's individual segment volume determined using 2014 data. Table 4.11 has the 2014 Volume, the 2025 IHS-Polk Full-Size Non-Premium Van volume after Class 2b vehicles were removed, and the individual manufacturer volume for Full-Size Non-Premium Van. The multiplier is the result of dividing the 2025 volume by the 2014 volume.

Table 4.11 Example Values Used to Determine FCA 2025 Individual Full-Size Non-Premium Van Multiplier

Manufacturer	IHS-Polk Segment	2014 Cafe Volume	2025 Volume after Multiplier	Fiat/Chrysler Individual Full-Size Non-Premium Van Multiplier for 2025
FCA	Full-Size Non-Premium Van	10,485	6,331	60.4%

Now that the individual manufacturer segment multipliers are calculated, they can be applied to each vehicle in the 2014 data. The segment multipliers are applied by multiplying the 2014 volume for a vehicle by the multiplier for its manufacturer and segment. Table 4.12 shows the 2014 volumes, the individual manufacturer segment multipliers, and the result of multiplying the multiplier and the volume for 2025 project volumes for many of FCA's Full-Size Non-Premium Van

Table 4.12 Example Applying the Individual Full-Size Non-Premium Van Multiplier for FCA

Manufacturer	Model	IHS-Polk Segment	2014 CAFE Volume	Fiat/Chrysler Individual Full-Size Non-Premium Van Multiplier for 2025	2025 Project Volume Before AEO Normalization
FCA	Cargo Van A	Full-Size Non-Premium Van	10,428	60.4%	6,374
FCA	Cargo Van B	Full-Size Non-Premium Van	57	60.4%	34

Normalizing to unforced AEO 2015 forecast for cars and trucks must be done once the individual manufacturer segment multipliers have been applied to all vehicles across every year (2011-2025) of the IHS-Polk forecast. In order to normalize a year, the number of trucks and the number of cars produced must be determined. Then, the truck and car totals from the unforced AEO 2015 are used to determine a normalizing multiplier. Table 4.13 has the 2025 car and truck totals before normalization, the unforced AEO 2015 car and truck totals in 2025, and the multipliers which are the result of dividing the unforced AEO 2015 totals by totals before normalization.

Table 4.13 Example Unforced AEO 2015 Truck and Car Multipliers in MY2025

Vehicle Type	2025 Total **B**efore Normalization	2025 Total **from AEO 2015**	2025 Normalizing Multiplier
Cars	10,317,314	8,597,413	83%
Trucks	6,588,526	7,827,599	119%

The final step in creating the reference volumes is applying the unforced AEO multipliers. The AEO multipliers are applied C/T type. Table 4.14 shows the normalized volume, the unforced AEO 2015 truck multiplier for MY2025, and the final resulting volume for a number of FCA Full-Size Non-Premium Vans.

Table 4.14 Example Applying the Unforced AEO Truck Multiplier to FCA Full-Size Non-Premium Vans

Manufacturer	Model	C/T Type	2025 Project Volume Before Unforced AEO 2015 Normalization	Unforced AEO 2015 Truck Multiplier for 2025	2025 Project Volume with Unforced AEO 2015 Normalization
FCA	Cargo Van A	Truck	6,374	119%	7,585
FCA	Cargo Van B	Truck	34	119%	41

4.1.2.2 What Are the Sales Volumes and Characteristics of the MY2014 Based Reference Fleet?

Table 4.15 and Table 4.16 below contain the sales volumes that result from the process above for MY2014 and 2021-2025.

Table 4.15 Vehicle Segment Volumes

Segment	**Actual and Projected Sales Volume**					
	2014	**2021**	**2022**	**2023**	**2024**	**2025**
SubCmpctAuto	1,031,572	748,954	765,720	813,046	813,046	837,044
CompactAuto	2,545,441	2,463,368	2,433,865	2,470,343	2,470,343	2,590,597
MidSizeAuto	3,538,186	2,753,505	2,780,716	2,792,830	2,792,830	2,914,865
LargeAuto	479,217	412,879	423,053	420,770	420,770	430,890
SmallPickup	12,143	15,227	14,222	16,067	16,067	16,123
LargePickup	1,917,061	2,110,946	2,061,737	2,048,645	2,048,645	2,089,897
SmallSuv	2,012,400	2,607,502	2,566,936	2,562,497	2,562,497	2,602,465
MidSizeSuv	1,547,977	2,018,262	2,005,227	2,032,018	2,032,018	2,027,569
LargeSuv	1,053,497	1,447,471	1,416,403	1,404,005	1,404,005	1,394,281
ExtraLargeSuv	664,625	769,029	786,535	736,815	736,815	717,962
MiniVan	602,694	553,890	579,944	582,605	582,605	576,009
CargoVan	68,613	80,731	80,598	86,960	86,960	92,852

Table 4.16 Car and Truck Volumes

Vehicle Type	Actual and Projected Sales Volume					
	2014	2021	2022	2023	2024	2025
Cars	9,206,786	8,136,376	8,143,641	8,269,894	8,410,497	8,597,413
Trucks	6,311,548	7,960,213	7,884,714	7,820,048	7,798,752	7,827,599
Cars and Trucks	15,518,335	16,096,589	16,028,354	16,089,941	16,209,249	16,425,012

Table 4.17 below contains the sales volumes by manufacturer and C/T type for MY2014 and MY2021-2025.

Table 4.17 Car and Truck Definition Manufacturer Volumes

Manufacturers	C/T Type	2014 Baseline Sales	2021 Projected Volume	2022 Projected Volume	2023 Projected Volume	2024 Projected Volume	2025 Projected Volume
All	Both	15,517,776	16,096,589	16,028,354	16,089,941	16,209,249	16,425,012
All	Cars	9,206,227	8,136,376	8,143,641	8,269,894	8,410,497	8,597,413
All	Trucks	6,311,548	7,960,213	7,884,714	7,820,048	7,798,752	7,827,599
Aston Martin*	Cars	1,272	1,324	1,252	1,238	1,213	1,345
Aston Martin*	Trucks	-	-	-	-	-	-
BMW	Cars	297,388	298,980	310,188	322,601	330,953	324,223
BMW	Trucks	81,938	110,369	106,188	103,272	101,755	101,636
FCA	Cars	648,377	607,666	622,729	610,278	607,979	622,911
FCA	Trucks	1,446,365	1,444,140	1,436,314	1,442,585	1,437,882	1,470,099
Ferrari*	Cars	2,301	2,255	2,234	2,361	2,605	2,735
Ferrari*	Trucks	-	-	-	-	-	-
Ford	Cars	1,258,732	935,011	923,142	899,877	884,594	929,684
Ford	Trucks	1,075,502	1,359,683	1,354,424	1,329,699	1,310,402	1,289,230
GM	Cars	1,556,701	1,211,835	1,210,542	1,271,586	1,275,810	1,287,730
GM	Trucks	1,164,610	1,324,550	1,336,118	1,279,587	1,272,362	1,280,168
Honda	Cars	868,337	794,566	805,183	817,840	851,073	844,715
Honda	Trucks	577,828	751,770	753,442	761,501	751,782	738,106
Hyundai/Kia	Cars	1,017,541	1,109,815	1,108,568	1,115,024	1,131,799	1,154,680
Hyundai/Kia	Trucks	67,198	159,409	151,953	153,506	154,656	157,166
JLR	Cars	12,323	24,161	25,231	26,015	25,855	25,245
JLR	Trucks	55,233	103,489	101,072	96,894	96,194	95,454
Lotus*	Cars	280	234	232	231	232	233
Lotus*	Trucks	-	-	-	-	-	-
Mazda	Cars	217,333	249,017	247,556	240,049	248,180	259,477
Mazda	Trucks	78,826	108,003	113,502	116,282	113,869	114,518
McLaren*	Cars	279	900	991	1,120	1,290	1,263
McLaren*	Trucks	-	-	-	-	-	-
Mercedes	Cars	278,126	226,604	230,007	240,403	243,482	245,341
Mercedes	Trucks	92,312	159,880	155,589	152,041	151,376	151,199
Mitsubishi	Cars	60,679	47,096	49,341	53,787	58,324	59,327
Mitsubishi	Trucks	29,828	29,325	28,931	30,024	29,533	33,126
Nissan	Cars	935,995	767,876	758,406	786,515	794,964	827,952
Nissan	Trucks	389,639	559,691	545,463	529,810	529,675	542,008
Subaru	Cars	109,078	134,897	141,558	138,204	139,851	144,187
Subaru	Trucks	356,818	473,112	452,946	482,833	483,575	499,218
Tesla	Cars	17,791	86,636	84,235	92,841	96,530	103,502
Tesla	Trucks	-	-	-	-	-	-
Toyota	Cars	1,420,641	1,132,086	1,123,827	1,132,703	1,183,829	1,207,430
Toyota	Trucks	772,809	1,026,564	1,008,534	1,011,496	1,018,822	997,624
Volkswagen	Cars	487,086	464,804	459,367	479,608	494,474	512,191
Volkswagen	Trucks	107,580	303,810	292,272	285,503	303,415	311,139
Volvo	Cars	16,526	40,612	39,052	37,614	37,462	43,244
Volvo	Trucks	15,063	46,418	47,964	45,013	43,454	46,908

*Note: These manufacturers are shown here for reference but are not in the analysis in Chapter 12 or considered in the ZEV sales that are part of the analysis fleet as discussed in Section 4.1.4.

Table 4.18 also shows how the change in fleet make-up may affect the footprint distributions over time. The resulting data indicate that footprint will not change significantly between 2014 and 2025.

Table 4.18 Production Weighted Foot Print Mean

Model Year	Average Footprint of all Vehicles	Average Footprint Cars	Average Footprint Trucks
2014	49.7	46.0	55.0
2017	50.0	46.0	54.0
2018	50.1	46.1	54.0
2019	50.1	46.1	54.1
2020	50.0	46.1	54.0
2021	50.0	46.1	54.1
2022	50.0	46.1	54.1
2023	49.9	46.0	54.0
2024	49.9	46.0	54.0
2025	49.8	46.1	54.0

Table 4.19 below shows the changes in engine cylinders over the model years. The current assumptions show that engines shrink slightly between 2014 and 2017 and then remain relatively constant over the 2018-2025 time frame with only a very slight shift to 4 cylinders in trucks (may be due to an increase in small SUVs).

Table 4.19 Percentages of 4, 6, and 8 Cylinder Engines by Model Year

	Trucks			Cars		
Model Year	4 Cylinders	6 Cylinders	8 Cylinders	4 Cylinders	6 Cylinders	8 Cylinders
2014	24.4%	50.4%	25.3%	78.1%	19.1%	2.8%
2017	26.7%	51.4%	21.9%	78.8%	18.4%	2.7%
2018	27.7%	50.2%	22.1%	78.3%	18.9%	2.8%
2019	28.0%	49.9%	22.1%	78.4%	18.9%	2.7%
2020	28.2%	49.9%	21.9%	78.6%	18.7%	2.7%
2021	28.2%	50.1%	21.7%	78.6%	18.6%	2.8%
2022	27.9%	50.7%	21.5%	78.3%	18.8%	2.9%
2023	28.4%	50.4%	21.1%	78.4%	18.8%	2.8%
2024	28.5%	50.3%	21.2%	78.6%	18.6%	2.8%
2025	28.7%	49.9%	21.4%	78.7%	18.5%	2.8%

4.1.2.3 What Are the Differences in the Sales Volumes and Characteristics of the MY2008 Based and the MY2014 Based Reference Fleets?

This section compares some of the differences between the fleet based on MY2008 data and the fleet based on MY2014 data. The 2008 fleet projection is based on MY2008 data, a long range forecast provided by CSM, and interim unforced AEO 2011. The 2014 fleet projection is based on MY2014 data, a long range forecast provided by IHS-Polk Automotive, and the unforced AEO 2015. All tables in this section show the differences using the two fleets (2008 and 2014).

Table 4.20, Table 4.21, and Table 4.22 below contain the sales volume differences between the two fleets, calculated by subtracting the 2008 MY based fleet projection from the 2014 MY based fleet projection. The sales in MY2014 were significantly higher (by 1,077,263 vehicles) than in MY2008. This shows a recovery from the recession that is higher than was forecasted.

For 2014, there is an increase in the number of compact and midsize autos, large trucks, and all SUVs except the largest. For 2025, one of the biggest difference between the two forecasts is the number of cars, which in part seem to be replaced by small and midsize SUVs. The shift from cars to trucks is due to application of the unforced AEO 2015 data while the shifts within segments are due to the data from the IHS-Polk forecast.

Table 4.20 Vehicle Segment Volumes Differences

Reference Class Segment	Actual Sales Volume	Difference in Projected Sales Volume				
	2014-2008	2021	2022	2023	2024	2025
SubCmpctAuto	-265,541	-1,787,930	-1,830,082	-1,815,047	-1,888,930	-1,944,516
CompactAuto	584,624	-39,361	-139,737	-143,393	-254,771	-232,670
MidSizeAuto	446,370	-679,286	-757,981	-889,726	-948,257	-889,366
LargeAuto	-86,859	27,223	59,207	52,386	58,527	55,876
SmallPickup	-165,354	-134,896	-132,916	-135,248	-138,560	-138,714
LargePickup	352,618	758,085	726,969	761,061	790,453	843,144
SmallSuv	403,602	1,055,347	1,009,846	1,019,382	989,326	1,013,801
MidSizeSuv	256,647	580,907	565,592	594,599	578,514	564,831
LargeSuv	402,787	383,384	334,685	298,936	241,424	202,637
ExtraLargeSuv	-84,450	76,700	65,578	-11,772	2,028	-23,134
MiniVan	-116,835	-292,166	-269,726	-266,845	-248,133	-263,443
CargoVan	35,229	-12,829	-11,526	-5,960	78	4,280

Table 4.21 2014 Projection - 2008 Projection Total Fleet Volumes Differences

C/T Type	Difference in Actual Sales Volume	Difference in Projected Sales Volume				
	2014 - 2008	2021	2022	2023	2024	2025
Cars	1,077,263	48,868	-2,251,770	-2,472,828	-2,576,436	-2,724,393
Trucks	729,925	-2,251,770	2,300,638	2,204,913	2,156,799	2,147,390
Cars and Trucks	1,807,188	48,868	-267,915	-419,637	-577,003	-674,315

Table 4.22 below contains the differences in sales volumes by manufacturer and C/T type between the 2008 MY based fleet and the 2014 MY based fleet. The manufacturers with the next largest increases in sales in 2014 MY (from 2008) are FCA, Ford, Hyundai/Kia, Nissan, Subaru, and Volkswagen. The manufacturers with a net decrease in sales in 2014 (from 2008) are Aston Martin, Honda, GM, Mazda, Mitsubishi, Toyota, and Volvo. The manufacturers with the next largest increases in sales in 2025 MY are FCA, Subaru, Tesla, The manufacturers forecasted to have significant net decrease in sales in 2025 are BMW, Ferrari, GM, Honda, Hyundai/Kia, Mercedes, Mitsubishi, Nissan, Toyota, and Volvo. Table 4.22 also shows the market down overall in MY2025 by 674,315 vehicles.

Table 4.22 2014 Projection - 2008 Projection Manufacturer Volumes Differences

Manufacturers	Segment Type	2014-2008 Difference in Sales	2021 Difference in Volume	2022 Difference in Volume	2023 Difference in Volume	2024 Difference in Volume	2025 Difference in Volume
All	Both	1,807,188	48,868	-267,915	-419,637	-577,003	-674,315
All	Cars	1,077,263	-2,251,770	-2,472,828	-2,576,436	-2,724,393	-2,817,863
All	Trucks	729,925	2,300,638	2,204,913	2,156,799	2,147,390	2,143,548
Aston Martin	Cars	-98	266	203	197	72	163
Aston Martin	Trucks	0	0	0	0	0	0
BMW	Cars	5,592	-60,118	-49,847	-37,960	-57,241	-81,033
BMW	Trucks	20,614	-18,355	-22,710	-24,248	-44,771	-43,772
FCA	Cars	-54,781	186,653	198,556	186,395	181,963	186,432
FCA	Trucks	489,573	1,095,527	1,073,306	1,081,521	1,092,920	1,138,337
Ferrari	Cars	851	-4,803	-4,904	-4,866	-4,836	-4,924
Ferrari	Trucks	0	0	0	0	0	0
Ford	Cars	302,033	-466,606	-492,079	-574,919	-619,077	-610,426
Ford	Trucks	261,308	645,503	640,158	629,695	621,548	604,754
GM	Cars	-30,690	-352,442	-368,014	-334,909	-360,995	-386,206
GM	Trucks	-343,187	-205,470	-171,535	-217,232	-221,235	-243,840
Honda	Cars	-138,302	-404,314	-432,321	-447,724	-456,778	-495,606
Honda	Trucks	72,688	215,854	214,207	224,604	214,788	180,409
Hyundai/Kia	Cars	457,692	165,141	141,503	137,970	122,208	114,647
Hyundai/Kia	Trucks	-45,432	-92,489	-100,234	-103,371	-107,554	-108,623
JLR	Cars	2,727	-34,516	-34,118	-34,625	-37,873	-40,173
JLR	Trucks	-351	45,336	42,482	38,029	38,213	38,648
Lotus	Cars	28	-44	-58	-68	-77	-83
Lotus	Trucks	0	0	0	0	0	0
Mazda	Cars	-29,328	-25,723	-33,595	-56,861	-52,435	-47,327
Mazda	Trucks	22,941	48,775	53,195	54,315	51,899	53,150
McLaren	Cars	279	900	991	1,120	1,290	1,263
McLaren	Trucks	0	0	0	0	0	0
Mercedes	Cars	69,931	-73,775	-74,731	-72,104	-88,855	-95,378
Mercedes	Trucks	13,177	60,431	54,654	46,727	44,292	50,132
Mitsubishi	Cars	-24,679	-18,755	-17,920	-13,893	-12,404	-13,978
Mitsubishi	Trucks	14,457	-5,984	-6,295	-5,445	-6,468	-3,260
Nissan	Cars	218,126	-144,753	-179,042	-167,825	-187,807	-186,824
Nissan	Trucks	84,093	151,662	133,579	112,689	107,458	115,554
Subaru	Cars	-6,957	-95,883	-97,055	-103,408	-108,432	-112,784
Subaru	Trucks	274,272	400,339	380,210	409,812	409,433	424,496
Tesla	Cars	16,991	58,013	55,866	64,691	65,668	71,529
Tesla	Trucks	0	0	0	0	0	0
Toyota	Cars	163,060	-765,818	-856,205	-898,122	-890,407	-894,262
Toyota	Trucks	-178,327	-188,975	-226,518	-213,484	-189,191	-212,392
Volkswagen	Cars	173,911	-163,081	-176,598	-160,301	-156,657	-165,029
Volkswagen	Trucks	61,784	143,834	134,137	120,206	135,067	145,636
Volvo	Cars	-49,123	-52,114	-53,460	-59,225	-61,720	-57,863

Volvo	Trucks	-17,685	4,650	6,278	2,982	993	4,319

Table 4.23 shows the difference in footprint distributions between the 2014 based fleet projection and the 2008 based fleet projection. The differences between MYs 2014 and 2008 are small and are just the result of the manufacturers' product mix in those model years. MY2025 shows an increase in both the average truck and average car footprints. This is due to the significant decrease in subcompact cars forecast in the 2014 based fleet projection. Because the total numbers of cars and trucks differs, production weighting can affect the average for the whole fleet as compared to the averages for cars and trucks. This can cause a counterintuitive result when taking the difference of the averages.

Table 4.23 2014 Projection - 2008 Projection Production Weighted Foot Print Mean Difference

Model Year	Difference in Average Footprint of all Vehicles	Difference in Average Footprint Cars	Difference in Average Footprint Trucks
2014-2008	49.7- 48.9 = 0.8	46.0 – 45.4 = 0.6	55.0 - 54.0 = 1.0
2017	50.0 - 48.3 = 1.7	46.0 - 44.9 = 1.1	54.0 - 53.8 = 0.2
2018	50.1 - 48.1 = 2.0	46.1 - 44.9 = 1.2	54.0 - 53.7 = 0.3
2019	50.1 - 48.0 = 2.1	46.1 - 44.9 = 1.2	54.1 - 53.6 = 0.5
2020	50.0 - 48.0 = 2.0	46.1 - 44.9 = 1.2	54.0 - 53.7 = 0.3
2021	50.0 - 48.0 = 2.0	46.1 - 44.9 = 1.2	54.1 - 53.6 = 0.5
2022	50.0 - 47.9 = 2.1	46.1 - 44.9 = 1.2	54.1 - 53.6 = 0.5
2023	49.9 - 47.9 = 2.0	46.0 - 44.9 = 1.1	54.0 - 53.5 = 0.5
2024	49.9 - 47.7 = 2.2	46.0 - 44.9 = 1.1	54.0 - 53.4 = 0.6
2025	49.8 - 47.7 = 2.1	46.1 - 44.9 = 1.2	54.0 - 53.3 = 0.7

Table 4.24 shows the difference in engine cylinders distribution between the 2014 MY based fleet and the 2008 MY based fleet. MY2014 has fewer vehicles with 6 and 8 cylinder engines than MY2008 did. Fewer 6 and 8 cylinders in the baseline fleet along with vehicle mix changes results in more 4 cylinder engines in trucks and cars by 2025.

Table 4.24 Differences in Percentages of 4, 6 and 8 Cylinder Engines by Model Year

	Trucks			Cars		
Model Year	4 Cylinders	6 Cylinders	8 Cylinders	4 Cylinders	6 Cylinders	8 Cylinders
2014-2008	13.8%	-5.2%	-8.7%	20.4%	-17.8%	-2.5%
2017	15.6%	-11.8%	-3.8%	16.8%	-14.5%	-2.2%
2018	16.9%	-13.8%	-3.1%	16.2%	-14.0%	-2.2%
2019	17.4%	-15.0%	-2.4%	16.3%	-14.0%	-2.3%
2020	17.7%	-15.2%	-2.6%	16.8%	-14.5%	-2.3%
2021	17.7%	-15.7%	-2.0%	16.5%	-14.3%	-2.1%
2022	17.5%	-15.6%	-1.9%	15.8%	-13.8%	-1.9%
2023	18.0%	-16.9%	-1.2%	16.0%	-14.0%	-2.0%
2024	17.9%	-17.3%	-0.6%	16.1%	-14.1%	-2.1%
2025	18.0%	-17.8%	-0.2%	16.1%	-14.0%	-2.1%

4.1.3 Relationship Between Fuel Economy and Other Vehicle Attributes

The previous discussion has described the EPA baseline fleet of MY 2014 vehicles, and development from that baseline fleet to the reference fleet -- the projection of the vehicle fleet to MY 2022-2025 if the standards remained at the MY 2021 standard levels. Also as discussed above, EPA's reference fleet assumes that, while relative production volumes will continue to evolve through 2025, all characteristics of individual vehicle models and configurations (except GHG emissions and fuel economy driven by the standards) will remain unchanged through 2025. In other words, for purposes of assessing the regulatory impacts analysis of the MY 2022-2025 standards, and for properly accounting for the cost of the additional technology required to meet those standards, EPA is making the modeling assumption that added technology will be used to reduce greenhouse gas emission and not to improve vehicle performance and utility. EPA used a similar approach in the 2012~2016 standards rule and the 2017~2025 standards setting rule. Manufacturers may choose to apply technology to improve vehicle performance in lieu of efficiency and that could result in higher costs than projected in this analysis. This section provides a discussion of that assumption.

For the Draft TAR analysis, EPA is assuming that the MY 2022-2025 reference fleet will have GHG emissions performance equal to that necessary to meet the MY 2021 standards (in effect a "flat" reference fleet). This is consistent with the assumption used in the MY 2017-2025 rulemaking, where EPA presented a detailed rationale for assuming that there would be no decrease in fleetwide GHG emissions performance in the reference case fleet for MY 2017-2025 beyond the GHG emissions performance necessary to meet the MY 2016 standards.[7] Key elements of the rationale were: 1) projections that gasoline prices would be relatively stable out to 2025, 2) historical evidence that during periods of stable gasoline prices and fuel economy standards, the only companies that typically over-complied with fuel economy standards were those that produced primarily lighter vehicles that inherently over-complied with the older universal (one size fits all) fuel economy standards, 3) that under increasingly stringent footprint-based GHG and fuel economy standards for the five years from MY 2012-2016, it was likely that most major manufacturers would be constrained by the standards and unlikely to voluntarily over-comply, and 4) if there were individual manufacturer over-compliance in a reference case scenario, that manufacturer would likely generate credits that could be sold to other companies, and therefore not lead to fleetwide over-compliance.

EPA believes that the case for a flat GHG reference case fleet is even stronger for the MY 2022-2025 timeframe for the following reasons: 1) gasoline prices are about $1 per gallon lower today than in October 2012 when the MY 2017-2025 final rule was published, 2) AEO 2015 projections for fuel prices in the MY 2022-2025 timeframe are relatively stable and approximately $1 per gallon lower than the AEO 2012 Early Release projections upon which we relied in the final rulemaking analysis, 3) another five years of increasingly stringent footprint-based GHG and fuel economy standards under the National Program (i.e., the MY 2022-2025 reference case fleet must meet the MY 2021 standards, five years later than the MY 2016 standards that were the basis for the MY 2017-2025 reference case fleet) that will have led to significant commercialization of new technologies, and 4) due to the additional five years of increasingly stringent standards, credits generated in the MY 2022-2025 timeframe are likely to be even more valuable, and even more likely to be sold, than in the MY 2017-2021 timeframe. For all of these reasons, EPA believes that it is very unlikely that there would be any market-driven decrease in fleetwide GHG emissions performance in a MY 2022-2025 reference case fleet. In addition, the National Research Council[8] in its 2015 report states that assuming equivalent performance in the fleet "is equivalent to a reference case with no further technical change in the vehicle market from 2017 to 2025." This, it states, is inconsistent with past trends, where "the rate of technological progress in vehicle attributes and efficiency has been strong and continual over the past 30 years." From the 1980s to about 2005, as described in Chapter 3.1.5, horsepower and weight increased steadily, while fuel economy was either stable or declining. The NRC suggests developing a reference case that reflects technological progress over time, and its possible allocation to horsepower and weight, rather than assuming equivalent performance. Specifically, the NRC recommends:

"Recommendation 10.7: The agencies should consider how to develop a reference case for the analysis of societal costs and benefits that includes accounting for the potential opportunity costs of the standards in terms of alternative vehicle attributes forgone."[9]

The analysis of the MY 2022-2025 standards would begin with that reference case, containing vehicles with new and different vehicle characteristics. The cost and effectiveness analysis would involve adding technologies to those new vehicles, either holding those new vehicles' characteristics constant or explicitly acknowledging changes in those characteristics to achieve the standards.

The technological innovation referred to by the NRC has been an ongoing process in the auto industry. Several recent studies,[10] discussed in Section 4.1.3.1 below, have sought to estimate the magnitude of innovation by calculating the relationship between power, fuel economy, and weight each year. Over time, if it is possible to have more fuel economy for a constant amount of power and weight (or more power or weight for constant fuel economy), those studies define that increase as innovation. Similarly to Chapter 3.1.5, these studies argue that most of that innovation has in the past gone into improvements in vehicle power. The authors expect that the vehicle GHG and fuel economy standards are instead directing that innovation toward fuel economy. As a result, because technological innovation has not been directed toward power, vehicles in the reference case must be less powerful than they would be in the absence of the standards. Thus, such studies would suggest that the reference case should be revised to project that power would have been higher; if vehicles subject to the standards do not achieve that new reference-case level of power, then the agencies should account for the opportunity cost of the forgone power.

In contrast, a working paper from Cooke[11] argues that the reference case should not include these increases in power or other attributes, because the agencies are not required to do more than preserve the baseline attributes. Cooke argues that increases in power or other vehicle attributes are optional to manufacturers, and thus not the responsibility of the agencies. If those technologies were instead applied to vehicle performance or other attributes rather than fuel economy, and it then becomes more expensive to meet the standards, Cooke argues that that increase in costs is not attributable to the standards.

EPA expects that manufacturers will continue to consider ways to improve vehicle utility and performance, and the potential for tradeoffs between reducing GHG emissions and improving other vehicle attributes deserves consideration. In principle, methods such as those used in the studies discussed in Section 4.1.3.1 could be used to develop a reference case that would include the potential for improvements over time in vehicle attributes or other attributes associated with improving fuel economy.[G] In practice, though, estimating these effects and their magnitudes involve a number of complexities, including challenges in estimating the tradeoffs and the innovation likely to occur in the absence of the standards, the role of the standards in promoting innovation, and the potential for ancillary benefits associated with GHG-reducing technologies.

The remainder of Chapter 4.1.3 describes these complexities in more detail. Chapter 4.1.3.1 focuses on the estimation process mentioned above, for the tradeoffs between fuel economy, power, and weight, and for the measures of innovation. The magnitudes of both the tradeoff estimates and the innovation estimates may not yet be known with confidence. The literature does point to an important aspect of the standards, though: they may increase the amount of innovation over the reference-case level. Chapter 4.1.3.2 examines this question more closely. In particular, it draws on the literature on innovation to distinguish between "incremental," small-scale innovation, and "major" innovation. It proposes a thesis that incremental technology is likely to be what would happen in the absence of the standards, while the standards may trigger major technology. If so, both the benefits and the costs of major innovation are associated with the standards. If incremental innovation can happen irrespective of the standards – that is, the benefits and costs of incremental innovation are unaffected by the standards – then the only tradeoffs important for the standards are those associated with major innovations. While Chapter 6.4.1.2 discusses recent EPA research exploring whether there are possible adverse effects of fuel-saving technologies, Chapter 4.1.3.3 points out that some of these technologies have ancillary benefits. Finally, Chapter 4.1.3.4 discusses how EPA might evaluate the impact of the standards on other vehicle characteristics in the benefit-cost analysis.

[G] As discussed in the Guidelines for Preparing Economic Analyses (U.S. Environmental Protection Agency, 2014, https://yosemite.epa.gov/ee/epa/eed.nsf/webpages/Guidelines.html, Chapter 5), the baseline (referred to in this chapter as the reference case) "is defined as the best assessment of the world absent the proposed regulation or policy action." In other words, the analysis should take into account that change is likely to happen even without the regulation or action.

4.1.3.1 Recent Studies of the Engineering Tradeoffs between Power and Fuel Economy, and Increases in Innovation

The recent studies[12] that estimate both technological improvements over time in the auto industry, as well as the engineering tradeoffs among fuel economy, power, and weight (and sometimes other characteristics) have much in common with each other. They all estimate an equation roughly of the form,

$$\ln(\text{fuel economy}) = \beta 0 + \beta 1 * \ln(\text{horsepower}) + \beta 2 * \ln(\text{weight}) + \beta 4 * \text{Other Characteristics} + \varepsilon,$$

where:

ln refers to the natural logarithm of the term in parentheses,

βs are coefficients to be estimated in the statistical analysis (and measure elasticities of fuel economy with respect to its associated variable)

ε is an error term

They differ in the additional vehicle characteristics that they include in the regressions, and in their ways of measuring technological change. Estimates of the elasticities of fuel economy with respect to horsepower – that is, the engineering tradeoffs between fuel economy and horsepower – include values from -0.16 (Klier and Linn) to -0.32 (Knittel 2012); the elasticities between fuel economy and weight include values from -0.336 (Klier and Linn 2016) to -0.521 (MacKenzie and Heywood 2015).[H]

Regarding measures of technological change, Knittel (2011) and MacKenzie and Heywood (2015) use annual shifts in the tradeoff curves; Klier and Linn (2016) use engine redesign cycles for individual vehicles; and Wang (2016) uses a time trend and the level (stringency) of fuel economy standards. The papers all find technological innovation, defined as an increase over time in fuel economy not explained by changes in horsepower, weight, or other characteristics, to be ongoing. Knittel (2011) finds truck and car efficiency to have increased about 50 percent from 1980 to 2006, with innovation higher before 1990 than in subsequent years. MacKenzie and Heywood find that efficiency measured using horsepower and weight increased about 50 percent from 1975-2009, but nearly 60 percent using acceleration and weight; using acceleration, features, and functionality led to an estimate of 70 percent improvement. Klier and Linn (2016) find that technological innovation varies with the stringency of predicted standards and with the enactment of new standards but do not provide estimates of the magnitudes of baseline innovation. Wang (2016) finds that cars innovated 1.19 percent per year, and trucks 0.66 percent per year; a 1 percent increase in CAFE standards led to an additional increase of 0.32 percent in innovation for cars, and 0.62 percent for trucks. These last two studies argue that GHG and fuel economy standards increase technological innovation above levels without regulation.

[H] The papers include multiple specifications: they may include different regressions for different vehicle classes, a variety of additional covariates, or different functional forms. Some of the studies include torque or zero-to-60 times instead of or in addition to horsepower. The values given here are from comparing preferred specifications specifically using horsepower and weight. The values in different specifications include values within and outside these ranges; the ranges cited here thus potentially understate the variation in point estimates.

MacKenzie and Heywood (2015) raise questions with the approach adopted by many of these studies (focusing on Knittel 2012). In particular, they argue that horsepower and weight are not necessarily good proxies for characteristics that consumers want, and that estimates both of the tradeoffs of these characteristics with fuel economy and of technological change are sensitive to the additional vehicle characteristics considered in the regressions.

If horsepower and weight are not themselves of primary interest to vehicle buyers, then, according to MacKenzie and Heywood, the measured tradeoffs of horsepower or weight for fuel economy do not measure changes in metrics important to consumers. Horsepower, for instance, does not by itself measure the full range of performance-related attributes, which include other features such as low-end torque, handling, and acceleration. MacKenzie and Heywood (2012)[13] find that acceleration performance in 2010 is 20 to 30 percent faster than comparable vehicles in the 1970s;[I] in other words, horsepower is not directly proportional to acceleration. Because acceleration is likely to be of more importance to consumers than horsepower itself, the tradeoff for horsepower identified in these analyses may not accurately measure impacts important to consumers.

Similarly, it is unlikely that consumers care directly about vehicle weight; rather, they are probably more interested in size, safety, cargo capacity, or other characteristics that are imperfectly correlated with weight. In these studies, a large vehicle with significant mass reduction and improved fuel economy would show up in the data to have the same attributes as a small efficient car, though consumers would view them very differently.

The use of weight and horsepower in these regressions may also bias the estimates of technological innovation. In these studies, technological innovation is measured as a residual improvement in fuel economy after other factors that influence fuel economy are considered. Including a characteristic (including but not limited to horsepower and weight) in the regressions means that technological innovation will not affect that characteristic; its fuel economy elasticity is fixed. MacKenzie and Heywood (2015) show this effect by using horsepower in their analysis in one regression, and acceleration (0-to-60 time) in other regressions. When they use acceleration instead of horsepower, the amount of technological innovation due to the relationship between power and acceleration ends up included in their measure of innovation; that addition increases the estimated level of technological innovation. They also point out that technological change to reduce weight will not show up as innovation in these other papers, because, as mentioned above, a large vehicle with mass reduction and improved fuel economy looks in the data like a small, efficient car rather than a vehicle with advanced technology.[J]

The measures of technological change are also sensitive to the other characteristics used in the regressions. For instance, Knittel (2011) and Klier and Linn (2016) both include powertrain types as additional characteristics. By assumption, then, powertrain types are not innovations, or subject to innovation; a hybrid or diesel will not become more (or less) efficient relative to a

[I] They attribute this change to improvements in the transformation of engine power to acceleration.
[J] In their paper, MacKenzie and Heywood separately apply an adjustment to account for innovations in weight reduction.

gasoline vehicle over time.[K] MacKenzie and Heywood (2015) argue that an analysis should not include those factors because "shifts toward more inherently efficient powertrain technologies are themselves a part of the overall process of technology change, so it is desirable to capture their contributions to overall efficiency in the year fixed effects" that measure innovation (p. 922).

It is also possible that the estimates for the relationships between fuel economy and other attributes from these studies may not represent pure technology tradeoffs, and may therefore be biased. Manufacturers do not produce vehicles with all possible combinations of horsepower, fuel economy, and weight; instead, the vehicles they produce include a mix of those characteristics that the companies believe consumers prefer. MacKenzie and Heywood (2015) find that accounting for a vehicle's specific power relative to the specific power of other vehicles in the fleet (the quintile of specific power) affects fuel economy, as well as the responsiveness of fuel economy to acceleration or weight. If these tradeoff curves were purely about technological relationships, they would not be affected by whether a vehicle was relatively powerful, but only by its absolute power. They suggest that "the relative sophistication of a vehicle's engine (compared to others in the same model year) is correlated with weight and acceleration performance; new technologies are not applied uniformly across all vehicles" (p. 922). As a result, the tradeoff estimates may not represent strictly technological tradeoffs, but also manufacturer choices that potentially bias tradeoff estimates.

Based on MacKenzie and Heywood's (2015) work, then, these other studies may not accurately measure tradeoffs involving characteristics of interest to vehicle owners. Weight, for instance, is unlikely to matter to consumers, except if that weight comes from size or added features. In other work (MacKenzie and Heywood 2012), in which they focus on the relationship between horsepower and acceleration, they question whether improvements in acceleration are going to continue indefinitely; they find that trends in 0-to-60 time are consistent with decay toward an asymptote, and that vehicles in 2010 were within 1 second of the 0-to-60 time asymptotic level.[L] It is not known if this slowdown in acceleration improvements is due to physical limits or limits in consumer interest.

Although MacKenzie and Heywood's analysis presents a more detailed discussion of these issues compared to the other studies examined here, it is not clear that it is suitable for quantitative development of a new reference case. First, even 0-to-60 time as a measure of acceleration may be too narrow a criterion for evaluating performance. Performance, as a consumer experiences it, is a complex combination of multiple characteristics including initial launch, ability to pass another vehicle at highway speeds, handling, and cornering. Second, Klier and Linn (2016) and Wang (2016) suggest that the rate of technological innovation is affected by the level of the standards. MacKenzie and Heywood's analysis does not examine this effect. Because of the possibility of a downward bias in innovation from those two studies, their estimates of innovation are not likely to be sufficient. In addition, the standards for MY2012-

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[K] Interacting the characteristic with a measure of time allows for innovation specifically in that characteristic; for instance, Knittel interacts the manual transmission variable with a time trend, which allows the fuel consumption of a manual transmission relative to an automatic transmission to vary over time. These papers have few such interactions; this is the only one in Knittel (2011).

[L] They present the analysis, not only for an average vehicle, but also for vehicles in the fifth and ninety-fifth percentiles for acceleration. They all show this flattening.

2025 are more significant in magnitude than any changes since the introduction of CAFE in the late 1970s; it is likely that innovation currently underway in the auto industry is of a different magnitude and kind than in the past. As a result, estimates of innovation from any of these studies may not be applicable to what is currently happening in the auto industry.

4.1.3.2 The Role of the Standards in Promoting Innovation

As discussed above, some authors point to the role of standards in promoting innovation. This section discusses how innovation may be induced by the standards, and how this innovation should be viewed differently in accounting for opportunity costs than innovation that may have occurred in the absence of the standards.

There is a wide body of literature concerning technological change in general.[14] The process of technological change can be divided into three stages: invention, where a new product or process is first developed; innovation, where the product or process is first commercialized; and diffusion, where the product or process is widely adopted throughout an industry. This can be a challenging process: most inventions never make it to the innovation stage;[15] if they are introduced by a small number of initial adopters, many technologies never diffuse and thus ultimately fail.[16]

It is generally agreed that innovation – the first commercialization of a new product – occurs on a continuum between two extremes: "major" innovation where product characteristics change, and "incremental" innovation[M] which exploits relatively minor changes to the existing product.[17] Although accurately and completely categorizing innovation may be more complex than applying a simple one-dimensional continuum (as Henderson and Clark (1990) claim), the one-dimensional model does offer some insight into how industries implement innovation.

A good example of a major innovation, and the role of environmental regulations in spurring technology diffusion, is gasoline direct injection (GDI). Mercedes introduced a four-stroke GDI engine into production in 1955.[18] Nonetheless, in 2008, prior to the establishment of the MY2012-2016 standards, only 2 percent of vehicles used gasoline direct injection.[19] By 2014, this number had risen to 38 percent, with a rate of adoption in 2011 – 2014 of 7 to 8 percentage points per year. This changeover shows a major innovation, based on previous inventions, moving from invention to innovation and eventually to diffusion only when stimulated by emissions standards.

As in the GDI example, major innovation does not necessarily proceed immediately (or at all) to diffusion for all promising technologies. In the absence of a forcing mechanism such as regulation, risk-averse manufacturers may prefer smaller, incremental innovations.[20] There are multiple reasons why manufacturers may prefer incremental innovation to major innovation, particularly the risk and uncertainty associated with major innovations.

When a company implements a major innovation, the development costs may be high and the market impacts uncertain. This results in a first-mover disadvantage (see also Chapter 6.3), where a pioneer company fronts the bill to test out a new technology. In doing so, it may briefly capture the market, but this allows all other companies to learn about the true demand for the

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[M] Abernathy and Utterback use "major" and "incremental" Henderson and Clark, with a two-dimensional framework, use "radical" and "incremental."

technology without themselves facing any risk.[21] Consumer response to the first mover may give the second mover valuable information about market acceptance. There are, therefore, incentives to delay the development or adoption of a new technology until a competitor has already proven that the technology is profitable. If all producers wait for another one to implement the innovation, the innovation will never enter the market at all.

In addition, Popp et al.[22] point out that there could be "dynamic increasing returns" to adopting some new technologies, wherein the value of a new technology may depend on how many other companies have adopted the technology. This could be due to network effects or learning-by-doing. In a network effects situation, the usefulness of the technology depends on adoption of complementary components – for instance, the value of switching to a new fuel depends on the infrastructure available for providing that fuel, and the value of the infrastructure depends on the number of vehicles using the new fuel. Learning by doing (see also Chapter 5.3.2) is the concept that the costs (benefits) of using a particular technology decrease (increase) with use. Both of these incentivize firms to pursue a "wait and see" strategy when it comes to adopting new technologies.

Finally, fixed costs and switchover disruptions[23] delay technology adoption. Firms often face major problems in integrating new technologies resulting from major innovations into their products; in some cases, they may temporarily reduce output.

First-mover disadvantage, dynamic increasing returns, fixed costs, and switchover disruptions all create barriers to major innovation. Incremental innovations typically face less of these problems. Thus, in the absence of a driving factor such as regulation, manufacturers are likely to choose incremental innovations over major innovation.[N]

Both scientific research[24] and popular press[25] suggest that the current CAFE and light duty GHG standards drive innovation. The mechanism by which the standards affect innovation is the reduction of the barriers to manufacturers for applying major innovation to new vehicles.[O]

Since all manufacturers are required to comply with regulations on the same time schedule, and the technological pace required often outstrips that obtainable by incremental innovation alone, manufacturers are assured that their competition is likely to implement major technological innovations simultaneously. Thus, instead of the first-mover disadvantage, there is a regulation-driven disincentive to "wait and see." It should be noted that companies differ both in the degree of effort that they face due to the standards, and in the strategies that they choose in

[N] This discussion is not intended to imply that major innovation will not happen in the absence of regulation. Many factors affect the likelihood of a technology proceeding from invention through to widespread dissemination, including some degree of luck in having the right invention at the right place at the right time with support from key stakeholders.

[O] The U.S. Department of Energy's Advanced Technology Vehicles Manufacturing (ATVM) Loan Program provides an example of another mechanism to reduce these barriers. The ATVM provides long-term, low-interest rate loans to support the domestic manufacturing of advanced technology vehicles and automotive components. It can finance a wide range of project costs, including the construction of new manufacturing facilities; retooling, reequipping, modernizing, or expanding an existing facility in the U.S; and the engineering integration costs necessary to manufacture eligible vehicles and components. It is designed to ensure that rising fuel economy standards do not disadvantage domestic manufacturing. With more than $16 billion in remaining loan authority, the ATVM program can provide financing to support the manufacturing of fuel-efficient technologies and components. See http://www.energy.gov/lpo/atvm for more information.

response. Nevertheless, the benefits of generating (or avoiding the need for) credits suggest that all companies have incentives to pursue major innovations. In addition, there can be synergies from companies (including suppliers) working on the same technologies at the same time.[26]

Because of the global nature of the auto industry, it is likely that innovations from U.S. regulations are likely to affect vehicles in other countries, and regulations from other countries are likely to affect U.S. vehicles. Because technologies to reduce GHG emissions do not need to be reinvented for each country, the fixed costs of innovation can be spread over a global market. It is even likely that many of these technologies will be used in countries without GHG standards, due to the use of common manufacturing platforms across countries and to the ancillary benefits associated with many of these technologies.

Developing a revised reference case could entail estimating *incremental* technological change, and projecting vehicle attributes resulting from that innovation, in the absence of the standards. Developing the control case – the case with the standards in place – could then entail estimating *major* technological change induced by the standards and projections of vehicle characteristics using that greater innovation. The discussion above suggests that conducting such an analysis may involve inaccurate estimates of the amount of innovation both in the absence of and in the presence of the standards, and may provide inaccurate estimates of the consequences of this innovation for specific vehicle characteristics.

Rather than assume a control case with "equivalent performance" to the baseline, one approach could involve assuming a control case with "equivalent performance" to the reference case. Since innovations in the reference case are incremental, such an approach could define, not the reference and control case performance specifically, but rather the difference between them.

In the reference case, it could be assumed that manufacturers would improve vehicle attributes consistent with historical trends due to the implementation of incremental innovations. Some of these changes might affect additional implementation of GHG/fuel economy technologies; in other cases (for example, infotainment systems, automobile connectivity, or active safety systems), the standards have no technical interaction with those changes.

In the control case, it could be assumed that the standards induce major technological improvement used to improve fuel economy. Incremental technological improvement would still be used to improve other vehicle attributes at the same pace as exhibited in the reference case. Thus, the differences between the control and reference cases are both the existence of fuel economy targets and the availability of major technological innovations (in addition to incremental innovations).

It should be noted that there is neither the requirement nor expectation that manufacturers allocate major innovations solely to fuel economy improvement and incremental innovations solely to other vehicle attributes. The standards give manufacturers the flexibility to choose what technologies to apply to which vehicle, when to apply them, and the use of each individual technology. If major innovations driven by the GHG/fuel economy standards were used to enhance these other attributes, though, it should be noted that these other attributes would not have been enhanced in the absence of the standards; those enhancements are ancillary benefits of the standards.

4.1.3.3 Potential Ancillary Benefits of GHG-Reducing Technologies

Yet another complication associated with assessing an appropriate reference case is the potential existence of ancillary benefits of GHG-reducing technologies. These can arise due to major innovation enabling new features and systems that can provide greater comfort, utility, or safety.[P] The studies discussed above all assume that, other than through innovation, improving fuel economy reduces power or weight, and thus imposes opportunity costs; and innovation can be channeled only to fuel economy, weight, or some single-dimensional measure of performance, such as 0-60 acceleration. When performance is characterized more broadly as a combination of multiple characteristics, it will often not be possible to strictly maintain performance along every dimension with the application of technological innovations. For example, a new technology may have unequal effects on the various measures of acceleration performance, so that an attempt to maintain performance along one dimension by resizing the vehicle powertrain will result in an increase or decrease along other dimensions. In addition, some technologies provide ancillary benefits that improve vehicle performance and utility along dimensions that are unrelated to acceleration and powertrain sizing. In such cases, the technologies implemented to reduce GHG emissions enhance other vehicle characteristics, providing entirely new capabilities and desirable features or resulting in lower costs for these features than would be otherwise possible.

Some examples of the potential ancillary benefits of GHG reducing technologies are listed here.

- Mass reduction can provide benefits of improved braking and handling performance, and on towing vehicles can enable additional towing and hauling capability with same or similar engine sizing.
- Mass reduction achieved through material substitution from non-ferrous metals provides greater corrosion resistance.
- Accessory Load reductions achieved through the use of pulse-width modulation (PWM) on accessory motors for HVAC blower fan speeds provide the benefit of improved durability.
- Air conditioning system improvements achieved through variable displacement compressors which adjust automatically rather than shutting off completely provide the benefit of smoother compressor transitions and less noise.
- Advanced transmissions with wider overall gear ratios and lower 1st gear ratios provide the benefit of improved launch feel.
- Electric power steering (EPS) systems enable automakers to implement customer features that utilize automatic steering such as automatic parking features, or trailer hitch connection assistance.
- EPS systems also provide the capability for variable ratio steering systems which allow greater steering responsiveness close to center, and reduced effort at large steering angles, while also reducing the lock-to-lock turns.
- Head-integrated exhaust manifolds and improved thermal management systems reduce warm-up time for the cabin and provide greater passenger comfort in cold climates.

[P] It is also possible that these new technologies may have undesirable adverse effects – hidden costs – associated with them, such as noise or vibration. EPA's analysis to identify hidden costs through review of professional auto reviews, discussed in Chapter 6.4.1.2, did not find evidence of systematic hidden costs of the new technologies.

- PEVs which can be remotely activated or programmed to precondition the vehicle in a garage when plugged in provide greater passenger comfort and convenience. In cold weather, the vehicle can be pre-warmed and defrosted, and in warm weather the vehicle can be pre-cooled.
- PEV systems with an electric axle on AWD vehicles, or even each individual wheel with electric drive motors, can provide torque vectoring for improved driving dynamics as the increased torque on the outside wheel is able to steer the car into the corner.
- LED headlights enable adaptive automotive headlight systems, in which lighting intensity and direction can be automatically controlled to road, ambient lighting, and weather conditions.

Additional discussion of the effects of each technology considered in this Draft TAR is provided in Chapter 5.

4.1.3.4 Estimating Potential Opportunity Costs and Ancillary Benefits

As this discussion has shown, the standards could potentially lead to opportunity costs in terms of reduced power or other adversely affected vehicle attributes. At the same time, the standards could induce major innovations that may be used in part to mitigate those opportunity costs, and that may in addition lead to ancillary benefits. Because the standards may contribute both benefits and costs to other vehicle attributes, measuring the net effect on consumer impacts requires estimates of the values of these attributes to consumers.

The most common sources of estimates of willingness to pay for these attributes are models developed to understand vehicle purchase decisions. These studies quantitatively estimate the role of various vehicle characteristics, such as size, power, and fuel economy, in those purchase decisions. The parameters estimated for these characteristics can usually be used to derive estimates of the value – the willingness to pay (WTP) -- of each attribute to consumers. It is common in this literature, though, for the researchers themselves not to have done the WTP calculation. In a 1988 study, Greene and Liu[27] reviewed the literature to that time; they found, "The dispersion of estimated attribute values both within and across models is striking," varying by factors of 5 to 10 or more; for performance, they considered the variation "wild. . . from -$8 to $4,081 per 0.01 cubic inches per pound." To our knowledge, there has not been a study since that time that has done a comprehensive review of consumers' willingness to pay for vehicle attributes.[Q] [28]

EPA has commissioned a new review of the literature to understand what is known about consumer valuation of vehicle characteristics. This review is looking at the metrics various studies have considered important for consumer vehicle purchase decisions, and is calculating the WTP values implied by the estimates in those studies. The goal is to determine whether there are robust WTP values that could be used for monetizing at least some of the opportunity costs and ancillary benefits. A draft of that report is expected in summer 2016.

[Q] Greene (2010) conducted a review of consumers' willingness to pay for one attribute, fuel economy, and found wide ranges of values.

4.1.4 Incorporation of the California Zero Emissions Vehicle (ZEV) Program into the EPA Reference Fleet

4.1.4.1 The ZEV Regulation in OMEGA

In its analysis, EPA has considered sales of electrified vehicles as projected to be needed to meet State Zero Emission Vehicle (ZEV) requirements. Because these ZEVs are already required by separate regulations in California and nine other states, these vehicles are built into the EPA reference fleet. This approach reasonably avoids attributing costs to the federal GHG program which necessarily occur due to another existing requirement and assures that those costs are not double counted. (Note that this reflects a change from the 2012 FRM where EPA did not account for compliance with the ZEV regulations in the reference case fleet for the 2017-2025 standards. However, this was because CARB was simultaneously substantially revising the ZEV regulation in early 2012 just prior to the release of the 2012 FRM and EPA had not yet acted upon California's waiver request for the ZEV program).

This analysis is meant to be one example representation of how the ZEV program requirements could be fulfilled; it is in no way meant to reflect the exact way in which any given manufacturer would actually comply with the ZEV program. Rather, it is meant as an illustration to reflect the potential number and penetration of ZEVs across the national fleet as part of the reference case. To accomplish this, the baseline fleet with future sales projections had to be adjusted to account for the projected ZEV sales. Those sales adjustments are described in detail below (see 4.1.4.2). The analysis fleets used in OMEGA and in EPA's benefit cost analysis are shown in Tables 4.24 through Table 4.28.

Note that, in Tables 4.24 through Table 4.28, EPA shows "Baseline" EV and PHEV sales and "Additional ZEV Program" EV and PHEV sales. The "baseline" sales are sales projected in EPA's MY2014-based baseline fleet. In other words, these vehicles are part of the future fleet described in Section 4.1.2.1. The "additional ZEV program" sales are EV and PHEV sales above and beyond those projected in Section 4.1.2.1. The "additional ZEV program" sales were taken from the ICE-only sales that were projected in Section 4.1.2.1. We have not increased the size of the fleet, but have "converted" some ICE-only vehicles to EVs and PHEVs to meet the projected sales required by the ZEV program in California and nine other states. We describe the process of doing this in the text following the tables. Importantly, the costs of "converting" the "additional ZEV program" sales are attributable to those programs adopting the ZEV program and, therefore, those costs are not considered in the EPA analysis. Similarly, any benefits from those vehicles are not considered explicitly in the EPA analysis. However, there is an implicit benefit that is considered. Since the ZEV program vehicles are part of the analysis fleet, they reduce slightly the compliance burden for any manufacturer required to meet the ZEV program because of their low tailpipe emissions when averaged with other vehicles in that manufacturer's fleet. We model the fleet in this way because this is how ZEV program vehicles will be treated in the National Program.

Table 4.25 OMEGA MY2021 Car Fleet using the AEO 2015 Reference Fuel Price Case

Manufacturer	ICE-only Car Sales	Baseline EV Sales	Baseline PHEV Sales	Additional ZEV Program EV Sales	Additional ZEV Program PHEV Sales	Total Car Sales
BMW	282,880	3,273	8,770	2,543	1,514	298,980
FCA	586,667	6,909		2,429	11,660	607,666
Ford	904,320	1,355	7,007	9,952	12,378	935,011
GM	1,174,858	600	26,201	9,612	564	1,211,835
Honda	768,430	11	719	10,093	15,312	794,566
Hyundai/Kia	1,090,833	0	0	7,396	11,587	1,109,815
JLR	21,101	0	0	1,192	1,868	24,161
Mazda	243,393	0	0	2,191	3,433	249,017
Mercedes-Benz	214,942	3,944	0	888	6,829	226,604
Mitsubishi	45,378	1,344	0	0	374	47,096
Nissan	742,674	8,201	0	5,031	11,970	767,876
Subaru	131,755	0	0	1,224	1,918	134,897
Tesla		86,636	0	0	0	86,636
Toyota	1,093,150	1,418	10,630	13,091	13,797	1,132,086
Volkswagen	447,866	0	0	6,599	10,339	464,804
Volvo	38,574	0	0	794	1,244	40,612
Fleet	7,786,822	113,691	53,327	73,035	104,787	8,131,662

Note: The analysis fleet differs from the baseline fleet by removing small volume manufacturers (Aston Martin, Ferrari, McLaren, and Lotus) and by adjusting sales to account for projected ZEV sales.

Table 4.26 OMEGA MY2021 Truck Fleet using the AEO 2015 Reference Fuel Price Case

Manufacturer	ICE-only Truck Sales	Baseline EV Sales	Baseline PHEV Sales	Additional ZEV Program EV Sales	Additional ZEV Program PHEV Sales	Total Truck Sales
BMW	110,369	0	0			110,369
FCA	1,438,814	0	0	918	4,408	1,444,140
Ford	1,358,371	0	0	585	727	1,359,683
GM	1,323,614	0	0	884	52	1,324,550
Honda	741,722	0	0	3,992	6,057	751,770
Hyundai/Kia	157,915	0	0	582	912	159,409
JLR	103,489	0	0			103,489
Mazda	106,222	0	0	694	1,087	108,003
Mercedes-Benz	159,880	0	0	0	0	159,880
Mitsubishi	29,109	0	0	0	216	29,325
Nissan	555,586	0	0	1,215	2,890	559,691
Subaru	462,747	0	0	4,038	6,327	473,112
Tesla	0	0	0	0	0	0
Toyota	1,019,912	0	0	3,238	3,413	1,026,564
Volkswagen	303,810	0	0	0	0	303,810
Volvo	46,418	0	0	0	0	46,418
Fleet	7,917,977	0	0	16,147	26,088	7,960,213

Note: The analysis fleet differs from the baseline fleet by removing small volume manufacturers (Aston Martin, Ferrari, McLaren, and Lotus) and by adjusting sales to account for projected ZEV sales.

Table 4.27 OMEGA MY2025 Car Fleet using the AEO 2015 Reference Fuel Price Case

Manufacturer	ICE-only Car Sales	Baseline EV Sales	Baseline PHEV Sales	Additional ZEV Program EV Sales	Additional ZEV Program PHEV Sales	Total Car Sales
BMW	298,264	3,859	10,692	7,224	4,184	324,223
FCA	587,738	6,678	0	10,454	18,041	622,911
Ford	881,873	1,460	6,772	19,758	19,821	929,684
GM	1,231,982	768	27,823	19,694	7,463	1,287,730
Honda	797,320	11	786	21,696	24,901	844,715
Hyundai/Kia	1,121,220	0	0	15,384	18,076	1,154,680
JLR	20,341	0	0	2,255	2,649	25,245
Mazda	249,487	0	0	4,593	5,397	259,477
Mercedes-Benz	225,277	5,065	0	4,488	10,511	245,341
Mitsubishi	56,667	1,477	0	360	823	59,327
Nissan	786,957	8,523	0	13,423	19,048	827,952
Subaru	138,497	0	0	2,616	3,074	144,187
Tesla		103,502	0	0	0	103,502
Toyota	1,142,185	1,616	10,384	27,666	25,579	1,207,430
Volkswagen	481,441	0	0	14,138	16,612	512,191
Volvo	39,666	0	0	1,645	1,933	43,244
Fleet	8,058,914	132,959	56,458	165,394	178,112	8,591,837

Note: The analysis fleet differs from the baseline fleet by removing small volume manufacturers (Aston Martin, Ferrari, McLaren, and Lotus) and by adjusting sales to account for projected ZEV sales.

Table 4.28 OMEGA MY2025 Truck Fleet using the AEO 2015 Reference Fuel Price Case

Manufacturer	ICE-only Truck Sales	Baseline EV Sales	Baseline PHEV Sales	Additional ZEV Program EV Sales	Additional ZEV Program PHEV Sales	Total Truck Sales
BMW	101,636	0	0	0	0	101,636
FCA	1,459,761	0	0	3,793	6,545	1,470,099
Ford	1,286,443	0	0	1,391	1,396	1,289,230
GM	1,277,635	0	0	1,837	696	1,280,168
Honda	722,752	0	0	7,149	8,205	738,106
Hyundai/Kia	154,756	0	0	1,108	1,302	157,166
JLR	95,454	0	0			95,454
Mazda	111,360	0	0	1,452	1,706	114,518
Mercedes-Benz	151,199	0	0	0	0	151,199
Mitsubishi	32,515	0	0	186	425	33,126
Nissan	535,267	0	0	2,787	3,954	542,008
Subaru	480,683	0	0	8,522	10,013	499,218
Tesla	0	0	0	0	0	0
Toyota	984,287	0	0	6,930	6,407	997,624
Volkswagen	311,139	0	0	0	0	311,139
Volvo	46,908	0	0	0	0	46,908
Fleet	7,751,796	0	0	35,153	40,649	7,827,599

Note: The analysis fleet differs from the baseline fleet by removing small volume manufacturers (Aston Martin, Ferrari, McLaren, and Lotus) and by adjusting sales to account for projected ZEV sales.

To generate the fleet inclusive of the ZEV program sales, we began with the fleet shown in the above tables exclusive of the additional ZEV program sales. That fleet included some EVs and PHEVs consistent with the sales in the MY2014 baseline fleet as projected forward to MYs 2021 and 2025. Those sales are shown in the tables Table 4.25 through Table 4.28 above. The additional ZEV program sales shown above, rather than being EVs and PHEVs, were internal combustion cars and trucks in the original fleet. For example, Table 4.28 shows additional ZEV program truck fleet sales of 35,153 EVs and 40,649 PHEVs. Those combined 75,802 vehicles were originally ICE vehicles meaning that the baseline ICE sales were the 7,751,796 shown in column 2 of the table above plus an additional 75,802, or 7,827,598 in total. To "generate" the projected additional 75,802 ZEV program vehicles, each model within a manufacturer's fleet was mapped into a vehicle type[R] matching its characteristics and capability. For this analysis, it was assumed that only vehicle types classified as non-towing would be considered for conversion from an ICE to a ZEV to meet the ZEV program requirements. The eight vehicle types considered for additional ZEV program sales include all of the passenger car vehicle types (vehicle types 1 through 6) along with the two small truck and small CUV/SUV vehicle types (vehicle types 7 and 13). Table 4.29 lists the 19 possible vehicle types including the towing or non-towing designation and consideration as a "ZEV-source platform," Rather than selecting which individual vehicle models or platforms would be the most likely sources, all ICE vehicles within those eight vehicle types in a manufacturer's fleet were considered as a source for additional ZEV program sales. Each manufacturer's additional ZEV program sales were then created by converting, on a platform-level sales weighted basis across all eligible vehicle types, the necessary number of ICE vehicles into the respective EV and PHEV sales. The tables below are meant to provide clarity with a simple example of how this was done.[S]

[R] We discuss "vehicle types" in Appendix C.

[S] The Excel spreadsheets used to generate the ZEV program fleet are in the docket and on our website at https://www3.epa.gov/otaq/climate/models.htm, the filenames include the keyword "FleetsABC."

Table 4.29 Vehicle Types Considered for Conversion to ZEVs

Vehicle - Engine - Valve Type	Vehicle Type	Towing(T)/ Non-towing(N)	ZEV Platform
SubCompactAuto - I4 - DOHC	1	N	Y
Auto - I4 - DOHC	2	N	Y
Auto - V6 - DOHC	3	N	Y
Auto - V6 - SOHC	4	N	Y
Auto - V8 - DOHC	5	N	Y
Auto - V8 - OHV	6	N	Y
MPV - I4 - DOHC	7	N	Y
MPV - V6 - DOHC	8	T	N
MPV - V6 - SOHC	9	T	N
MPV - V6 - OHV	10	T	N
MPV - V8 - DOHC	11	T	N
MPV - V8 - OHV	12	T	N
Truck - I4 - DOHC	13	N	Y
Truck - V6 - DOHC	14	T	N
Truck - V6 - OHV	15	T	N
Truck - V8 - DOHC	16	T	N
Truck - V8 - SOHC	17	T	N
MPV - V8 - SOHC	18	T	N
Truck - V8 - OHV	19	T	N

First, consider a simple manufacturer fleet consisting of seven vehicle models built on five platforms which we have mapped into three vehicle types with total fleet sales of 600 vehicles, see Table 4.30.

Table 4.30 Example Manufacturer Fleet from which ZEVs are to be Created

Platform index	Vehicle index	Model	Fuel	VehType	Baseline sales
100	1	A	G	1	100
100	2	B	G	1	100
101	3	C	G	2	75
101	4	D	G	2	75
102	5	E	G	1	100
103	6	F	G	2	50
104	7	G	G	17	100
Total					600

For this manufacturer, we will assume that the needed additional ZEV program sales are 50 EVs and, for simplicity, no PHEVs. As noted above, only vehicle types 1-7 and 13 are considered to be ZEV-source platforms. Thus, the 50 ZEV program vehicles cannot come from platform 104 since that is vehicle type 17. We determine the number of EVs to create from each platform according to its sales weighting within ZEV-source platforms.[T] This is shown in Table 4.31. We also need to know how many vehicles within each vehicle model to convert to a ZEV program vehicle. This is shown in Table 4.32.

Table 4.31 Number of Additional ZEV Program Sales from each Platform

Platform index	VehType 1	VehType 2	Total	%in Platform	# of ZEV program sales
100	200		200	40%	20
101		150	150	30%	15
102	100		100	20%	10
103		50	50	10%	5
Total	300	200	500	100%	50

Table 4.32 Percentage of Additional ZEV Program Sales from Each Vehicle Model

Platform index	Model A	Model B	Model C	Model D	Model E	Model F	Total
100	50%	50%					100%
101			50%	50%			100%
102					100%		100%
103						100%	100%

With the details shown in Table 4.31 and Table 4.32, we can then convert ICE vehicles into ZEV program vehicles as shown in Table 4.33.

Table 4.33 Example Manufacturer's OMEGA Fleet including ZEV Program Sales

Platform index	Vehicle index	Model	Fuel	VehType	Baseline Sales	OMEGA fleet with ZEV program sales
100	1	A	G	1	100	90
100	2	B	G	1	100	90
101	3	C	G	2	75	68
101	4	D	G	2	75	68
102	5	E	G	1	100	90
103	6	F	G	2	50	45
104	7	G	G	17	100	100
100	8	ZEV	E	1	0	20
101	9	ZEV	E	1	0	15
102	10	ZEV	E	2	0	10
103	11	ZEV	E	2	0	5
Total sales G					600	550
Total sales E					0	50
Total sales					600	600

[T] The ZEV-source platforms are those platforms "mapped" into the 8 "ZEV platform" vehicle types presented in Table 4.29. The point of Table 4.29 is to make clear that we are creating ZEV program vehicles in only those types of vehicles that we believe to make the most sense. Those types of vehicles being passenger cars and the smallest sport and cross-over utility vehicles that have 4-cylinder engines and therefore are not "towing" vehicles. The ZEV program vehicles are created only from within those vehicle types and, therefore, the creation of ZEV program vehicles is done using sales-weighting within those vehicle types rather than within all vehicles.

As noted above, we then created each manufacturer's ZEV program fleet by converting, on a platform-level sales weighted basis, the necessary number of ICE vehicles into the respective EV and PHEV sales. Staff considered an alternate approach to look instead at which specific platforms, or even vehicle models, were the best candidates for conversion to EV/PHEV. However, that approach was rejected because a problem with that is, by what measure does one determine the best candidates for conversion? The smallest cars? The lightest cars? Those that already have an EV or PHEV version? We were concerned that any attempt at determining the "best" candidates for conversion might be seen as "cherry picking" in order to provide a certain result. Some might see us as choosing all of the smallest vehicles thereby leaving all of the larger, perhaps dirtier vehicles as ICE vehicles needing costly improvements to comply with the future standards. Others might see us as choosing all of the largest vehicles thereby leaving all of the smaller, perhaps cleaner vehicles as ICE vehicles needing less costly improvements to comply with future standards. Further, there is no clear trend as to which vehicles or platforms manufacturers are currently using for EV or PHEV platforms. Current and publicly announced near term models span platforms from subcompact cars to large cars, large SUVs to minivans, and use of shared or dedicated platforms. Our final decision was to choose equally (by sales weighting) from each ZEV source platform such that there would be no net impact on the sales weighted footprint of remaining ICE vehicles needing technology to comply.

4.1.4.2 The ZEV Program Requirements

The preceding discussion describes how we determined which vehicles would be converted from ICE technology to EV/PHEV. Here we discuss how many vehicles to actually convert or, in other words, what the additional ZEV program sales are projected to be.

4.1.4.2.1 *Overview*

California requires the largest vehicle manufacturers to manufacture ZEV credit producing vehicles to comply with the increasing number of ZEV credits required through 2025.[U] The ZEV credits can be generated by producing battery electric vehicles, fuel cell electric vehicles, and plug-in hybrid vehicles. In addition to the requirements applying in California (CA), several other states[V] have used section 177 (S177) of the federal Clean Air Act to adopt the California ZEV requirements (referred to as S177 ZEV States). These states, when combined with CA, account for nearly 30 percent of all new light-duty vehicles sold in the United States.

Under the ZEV regulation, manufacturers are required to generate ZEV credits to fulfill an annual obligation based on their cumulative vehicle sales as summarized in Table 4.34. Requirements are satisfied by producing vehicles that generate credit which, for MY2018 and beyond, means a combination of plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV), and fuel cell electric vehicles (FCEV). Each PHEV, BEV, and FCEV earns between 0.4 and 4 credits per vehicle depending on its electric range over a test cycle. For example, a PHEV with a 10 mile electric range earns 0.4 credits and a BEV or FCEV with a 350 mile test range earns 4.0 credits.

[U] Title 13, California Code of Regulations, section 1962.2 "Zero-Emission Vehicle Standards for 2018 and Subsequent Model Year Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles."

[V] Section 177 ZEV states: Connecticut, Maine, Maryland, Massachusetts, New York, New Jersey, Oregon, Rhode Island, and Vermont.

To incorporate the ZEVs into the OMEGA fleet, the ZEV regulation credit requirements were converted to a vehicle sales requirement as follows:

1) Determine how many total ZEV credits each manufacturer will need in CA and the S177 ZEV states for the two years being modeled in OMEGA (MY2021 and MY2025).

2) Develop a nominal BEV electric range (described in Table 4.33) and a nominal PHEV set of electric range characteristics (described in Table 4.34) that are projected to be representative of BEV and PHEV capability in the MY2021-2025 time frame. The range and characteristics are then used to determine how many ZEV credits each vehicle will generate.

3) Calculate the incremental ZEV credits needed beyond those generated by any ZEVs already included in the OMEGA reference fleet projections and expected to be sold in CA and the S177 ZEV states.

4) Determine how many incremental BEVs and PHEVs each manufacturer will need to sell to satisfy their ZEV credit obligations for MY2021 and MY2025.

4.1.4.2.2 ZEV Credit Requirement

Each manufacturer's ZEV credit obligation is calculated by multiplying its projected total light duty vehicle sales in CA and S177 ZEV states by the ZEV credit percentage required (see Table 4.34 below). The total projected CA and S177 ZEV states sales volume for each manufacturer was calculated by multiplying the manufacturer-specific reference fleet national sales volumes in OMEGA by the current (MY 2014) CA and S177 ZEV states sales volume ratio. For example, if manufacturer "A" is projected to sell 250,000 vehicles nationally in MY 2021, and it's MY 2014 CA and S177 ZEV state sales are 40 percent of its national sales, its projected MY 2021 CA and S177 ZEV state sales would be 100,000 (250,000*40%). Although the regulation has flexibilities in the technologies a manufacturer may use to generate credits, there is a cap on the portion of the credits that can be satisfied with PHEVs as identified in Table 4.34. For example, if manufacturer "A" sells 100,000 vehicles in CA and the S177 ZEV states in 2021, it is required to generate 12,000 ZEV credits (100,000*12%) in 2021 and, of those 12,000 ZEV credits, only 4,000 (100,000*4%) can come from PHEVs. For the purpose of this analysis, manufacturers are projected to comply with the ZEV requirements by maximizing their ZEV credits earned using PHEVs and using BEVs to generate the remaining credits.

Table 4.34 ZEV Regulation Credit Requirements

	ZEV Credit Requirements							
	2018	2019	2020	2021	2022	2023	2024	2025
Total ZEV Credit Required	4.50%	7.00%	9.50%	12.00%	14.50%	17.00%	19.50%	22.00%
Max. Credits From PHEVs	2.50%	3.00%	3.50%	4.00%	4.50%	5.00%	5.50%	6.00%

4.1.4.2.3 Projected Representative of PHEV and BEV Characteristics for MY2021-2025

The first step to calculate the number of ZEVs needed in the projected fleet to meet the manufacturer's credit obligation is to determine the type of vehicles that will be used to comply with the regulation. The primary characteristic for determining ZEV credits per vehicle is the urban dynamometer driving schedule (UDDS) test cycle range for BEVs and the UDDS test cycle "equivalent all electric range" for PHEVs.[W] Given that these would be future vehicles for which actual specifications are not yet known, assumptions were made regarding what future range(s) might be in the MY 2021 and MY 2025 timeframe. Further simplifications of such projections were also necessary to fit within the existing model framework of OMEGA including baseline vehicles and technology packages. These simplifications include the use of a single nominal BEV range and a single nominal PHEV range for all manufacturers and all vehicle classes with characteristics projected to be representative of BEVs and PHEVs in the MY2021 to 2025 timeframe. Given these constraints, this projection reflects a scenario for minimum compliance with the ZEV regulation using a representative nominal BEV and PHEV but not a 'likely' scenario that might reflect a wide variety of different ranges of PHEV and BEV offerings across manufacturers, vehicle classes, and model years or the inclusion of FCEVs that have already begun to enter the market.

To develop the nominal BEV and PHEV electric range, staff first looked at the relative impact of battery pack costs for a variety of battery costs (dollars per kilowatt-hour (kWh)). For this simplified analysis, vehicle energy consumption was assumed to be constant for all vehicle types; therefore all-electric vehicle range and battery pack size increase proportionally. The relative costs to achieve longer range were then compared to the number of ZEV credits earned for the increased range. The qualitative results are shown in Figure 4.4. As the figure shows, building individual BEVs with a longer range directionally results in a lower cost per ZEV credit earned (i.e., satisfying the ZEV credit obligation with fewer long range BEVs is directionally more cost-effective than using a larger volume of shorter range BEVs). And, as Figure 4.4 illustrates, the relative impact is even larger at lower battery costs. Accordingly, the nominal BEV and PHEV packages targeted longer range variants of both types of ZEVs rather than multiple variants of shorter and longer range vehicles. Note that the range of battery costs used in the figure (from $150/kWh to $300/kWh in the 2021-2025 time frame) is consistent with the projections of the EPA battery costing analysis for PHEVs and BEVs as shown in Tables 5-84 through 5-88. The reasonableness of EPA's projected costs used in both the 2012 FRM and this Draft TAR is supported elsewhere, particularly in Section 5.2.4.4.9 where we evaluate the 2012 FRM battery cost projections, and in Section 5.3.4.3.7.6 where we discuss Draft TAR battery cost projections.

[W] As defined in "California Exhaust Emission Standards and Test Procedures for 2018 and Subsequent Model Zero-Emission Vehicles and Hybrid Electric Vehicles, in the Passenger Car, Light-Duty Truck and Medium-Duty Vehicle Classes," adopted March 22, 2012, last amended May 30, 2014.

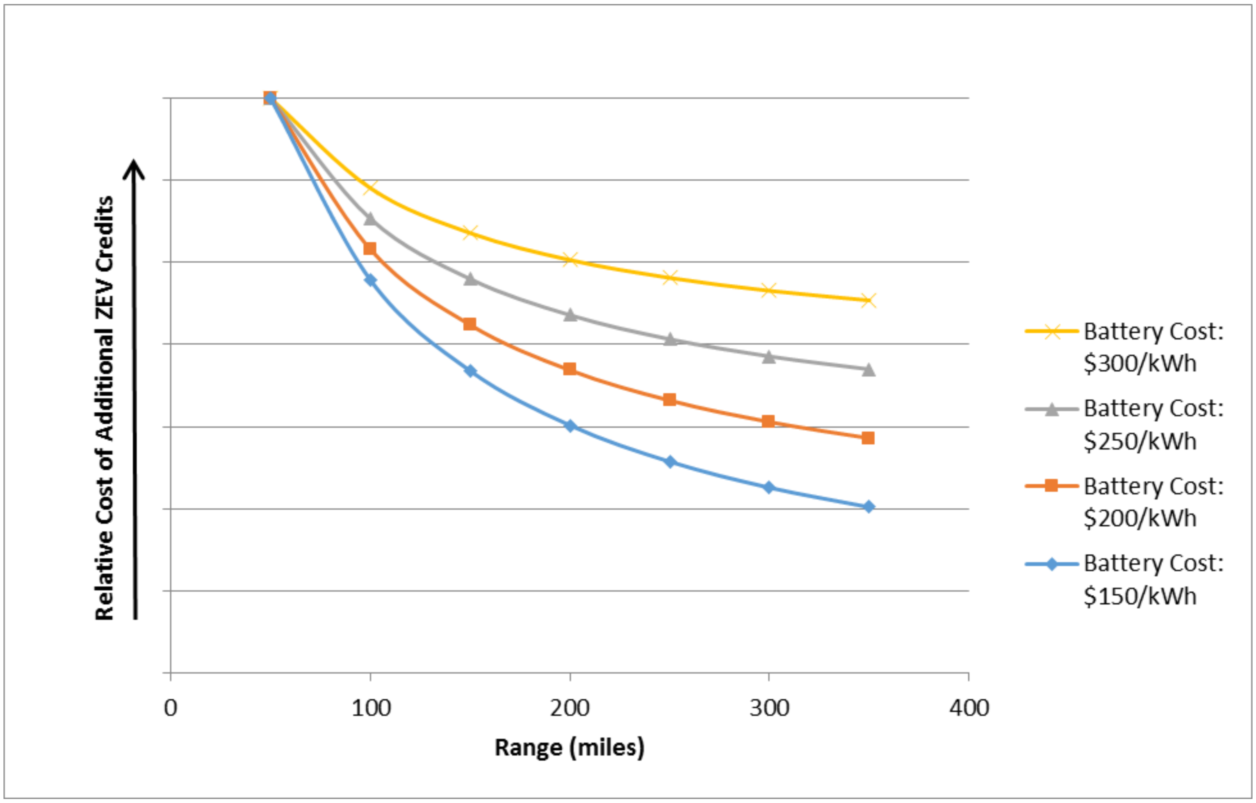

Figure 4.4 Relative Cost of ZEV Credits for Different Ranges and Battery Costs

The projected range for the nominal BEV and PHEV in the MY2021 to 2025 timeframe was developed assuming a constant improvement from the current sales-weighted average range. The MY2014 BEV sales-weighted label range is ~156 miles, as shown in Table 4.33 below; for MY2014 PHEVs, the sales-weighted label electric range is ~26 miles as shown in Table 4.36.

Table 4.35 Range Characteristics of BEVs for MY2014

Brand	Model	EPA Label All-electric Range (miles)
BMW	i3	81
Chevrolet	Spark EV	82
Fiat	500e	87
Ford	Focus Electric	76
Honda	Fit EV	70
Mercedes-Benz	Smart fortwo Convertible	68
Mercedes-Benz	Smart fortwo Coupe	68
Mitsubishi	i-MiEV	50
Nissan	Leaf	84
Tesla	Model S 60	200
Tesla	Model S 85	270
Tesla	Model S AWD (P85D)	270
Toyota	RAV4 EV	80
Sales-Weighted Average Range (Label Miles)		155.5

Table 4.36 Range Characteristics of PHEVs for MY2014

Brand	Model	EPA Label All-electric Range (miles)
Ford	C-Max Energi	21
Ford	Fusion Energi	21
Cadillac	ELR	37
Chevrolet	Volt	38
Honda	Accord Plug-In	13
Toyota	Prius Plug-In	11
Sales-Weighted Average Range (Label Miles)		26.2

For this analysis, the range for future vehicles was estimated to increase at a rate of 5 percent per year until the sales-weighted range reaches 245 miles which correlates to the maximum number of ZEV credits earned by any one vehicle. While manufacturers are not expected to actually redesign vehicles to increase the range every year or to cap the range when they reach the 245 mile range, this rate of annual improvement is consistent with the improvements manufacturers have been making over more discrete intervals such as redesigns, refreshes, or other updates. For example, new or updated model introductions and announcements for the Ford Focus EV, VW e-Golf, Nissan Leaf, Tesla Model S, Tesla Model 3, GM Bolt EV, GM Volt, and BMW i3 have all included increased range compared to their predecessors. The 5 percent rate of growth is an estimated average of both longer and shorter range vehicles. It is not expected that BEVs with 200+ miles of range, such as some Teslas, will increase their range as quickly as shorter range vehicles such as the BMW i3. This is supported by the 2.5 percent per year increase observed in the Model S (85 to 90 kW-h) compared to the 9 percent per year increase seen by the GM Volt and the BMW i3. Additionally, while some OEMs may continue offering BEVs with lower ranges, these may be offset by longer range offerings such as hydrogen fuel cell electric vehicles (FCEV) like those announced by Toyota and Honda with ranges that well exceed 200 miles.

Given that the time period of interest for the midterm evaluation is MY2021-2025 and that the ZEV requirements increase annually, a nominal range for the single BEV variant to be used for all model years was determined by calculating the sales-weighted average for the years being evaluated. Table 4.37 combines the results from Table 4.33 for average electric range with the projected BEV sales for MY 2021-2025 to calculate a sales-weighted average BEV for MYs 2021-2025. The sales-weighted average was calculated as 237 miles. Although this projection results in an estimated 237 mile range, a final range of 200 miles was chosen to account for a potential slower-than-historical increase in range and to be consistent with an existing technology package in OMEGA. A 200 mile label range is reasonable given recent announcements in this magnitude for the Tesla Model 3, GM Bolt EV, and an announced future Ford BEV which will all be available prior to MY2021. ZEV credits are generated based on UDDS range, not label range, and a review of current certified BEVs indicates a UDDS range to label range correction factor of between 0.65 and 0.76. For this analysis, a value of 0.7 was used for the nominal BEV. As a result, for the model years being evaluated, all BEV200s are assumed to have a label range of 200 miles and a UDDS range of 286 miles which generates 3.36 ZEV credits per vehicle.

Table 4.37 Projected Sales Weighted BEV Range for MY2021-2025

Model year	EV real-world range	BEV sales (% of whole fleet)	BEV sales (% of 2021-2025 cumulative sales)
2021	218.1	2%	14%
2022	229.0	3%	17%
2023	240.5	3%	20%
2024	245.0	4%	23%
2025	245.0	4%	26%
		Range Based on Sales Weighting MY2021-2025	237.5

The projected ranges for PHEVs in the MY2021-2025 time frame were calculated in a similar manner to the BEV ranges with one minor difference. PHEVs generate credits based not only on electric range on the UDDS cycle but also on the ability to drive all electrically for at least 10 miles of the US06 supplemental FTP test cycle. PHEVs that can meet this US06 criterion earn an additional 0.2 credits per vehicle. While the reality is that motor, inverter, and battery pack sizing along with the powertrain architecture all play a role in determining whether a PHEV can meet this criterion, for this analysis, the ability to meet it was assumed to increase linearly for vehicles with electric range from 20 to 40 miles (i.e., 0 percent of PHEVs with 20 mile range, 50 percent of PHEVs with a 30 mile range, and 100 percent of PHEVs with 40 mile range can meet the US06 criterion). The analysis summarized in Table 4.38 shows that, for MY2021-2025, the sales-weighted average PHEV is projected to have a range of about 41 miles which was rounded down to a final range of 40 miles to be consistent with an existing PHEV40 technology package in OMEGA. A PHEV40 is assumed to be 100 percent US06 capable so it generates 1.07 credits per vehicle after adjusting from a 40 mile label range to an equivalent UDDS range and including the additional credits for US06 capability. For perspective, the newly revised MY2016 GM Volt already exceeds this capability and other manufacturers are expected to further increase their range and capability over the next 5-9 years.

Table 4.38 Projected Sales Weighted PHEV Range and US06 Capability for MY2021-2025

Model year	EV real-world range	PHEV sales (% of whole fleet)	PHEV sales (% of 2021-2025 cumulative sales)
2021	36.8	4%	17%
2022	38.6	4%	19%
2023	40.6	5%	20%
2024	42.6	5%	21%
2025	44.7	5%	23%
		Range Based on Sales Weighting MY2021-2025	40.9

4.1.4.2.4 Calculation of Incremental ZEVs Needed for ZEV Program Compliance

Next, the number of ZEV credits that would be generated from vehicles already included in the projected reference fleet was subtracted from the total credit obligation. Given the projected reference fleet only included national sales numbers for ZEVs, those numbers were first scaled to CA and S177 ZEV state sales using the current (MY2014) manufacturer-specific percentage of national ZEV sales in CA and the S177 ZEV states. For this analysis, all manufacturers are projected to generate ZEV credits using the same nominal sales-weighted BEV and PHEV all electric ranges and each manufacturer is projected to fulfill their credit requirements without exercising any of the various additional flexibilities included in the ZEV regulation. These earned credits were then subtracted from each manufacturer's credit obligation to calculate the remaining incremental credits needed. For example, if a manufacturer's ZEV credit obligation for MY2021 is 12,000 credits and the original baseline projected 1000 BEV sales in CA and the S177 ZEV states, its incremental obligation is 8,640 ZEV credits (12,000 credits -1000 vehicles*3.36 credits/vehicle).

Finally, the incremental credits needed were translated to the number of additional PHEV and BEV sales for each manufacturer. For this analysis, it was assumed that each manufacturer would satisfy the maximum amount of ZEV credits allowed with PHEVs and the remaining portion with BEVs so both the ZEVs in the original reference fleet and those incrementally added take this PHEV limitation into account. No ZEV credit trading and banking was included in this analysis; each manufacturer was assumed to meet its ZEV obligation in MY2021 and MY2025 with vehicles produced for those model years. An example analysis can be found in Table 4.39 and Table 4.40. For the projected sales volumes used in this draft TAR, the overall effect of the ZEV regulation is an addition of approximately 220,000 and 420,000 ZEVs in the reference fleet for model years 2021 and 2025, respectively. This increases the percent of ZEVs in the OMEGA reference fleet from 1.0 percent of national sales to 1.7 percent in MY2021, and 1.2 percent to 3.0 percent in MY2025.

Table 4.39 Incremental PHEV40s and BEV200s needed in MY2021

		Reference Fleet Characteristics						Total ZEVs Needed		Incremental ZEVs Needed	
Row Labels	Sum of Annual Sales - Cycle 1	National BEV200 sales	National PHEV40 sales	%CA+S177 BEV and PHEV40	% Total Sales in CA+S177	CA+S177 BEV200 sales	CA+S177 PHEV40 sales	TOTAL BEV200 Sales Needed CA+S177	TOTAL PHEV sales CA+S177	Incremental BEV	Incremental PHEV40s needed
BMW	409349	3273	8898	66%	48.0%	2144	5828	4687	7342	2543	1514
FCA	2051806	6909	0	100%	21.0%	6909	0	10256	16068	3347	16068
Ford	2294695	1355	7239	67%	20.9%	901	4814	11438	17919	10537	13105
GM	2536385	600	26470	62%	18.0%	372	16411	10868	17027	10496	616
Honda	1546336	11	744	96%	38.3%	10	714	14095	22083	14085	21369
Hyundai/Kia	1269224	0	0	81%	26.4%	0	0	7978	12499	7978	12499
JLR	127650	0	0	0%	39.2%	0	0	1192	1868	1192	1868
Mazda	357020	0	0	0%	33.9%	0	0	2885	4520	2885	4520
Mercedes-Benz	386483	3944	0	88%	47.3%	3471	0	4359	6829	888	6829
Mitsubishi	76422	1344	0	35%	24.1%	471	0	439	688	0	590
Nissan	1327567	8201	0	40%	30.0%	3239	0	9485	14860	6246	14860
Subaru	608009	0	0	0%	36.3%	0	0	5263	8245	5263	8245
Tesla	86636	86636	0	56%	56.8%	48083	0	1172	1836	0	0
Toyota	2158650	1418	10898	97%	34.4%	1368	10516	17697	27726	16329	17210
Volkswagen	768613	0	0	98%	36.0%	0	0	6599	10339	6599	10339
Volvo	87030	0	0	0%	38.3%	0	0	794	1244	794	1244
Grand Total	16091875										

Table 4.40 Incremental PHEV40s and BEV200s needed in MY2025

		Reference Fleet Characteristics						Total ZEVs Needed		Incremental ZEVs Needed	
Row Labels	Sum of Annual Sales - Cycle 1	National BEV200 sales	National PHEV40 sales	%CA+S177 BEV and PHEV40	% Total Sales in CA+S177	CA+S177 BEV200 sales	CA+S177 PHEV40 sales	TOTAL BEV200 Sales Needed CA+S177	TOTAL PHEV sales CA+S177	Incremental BEV	Incremental PHEV40s needed
BMW	425859	3859	11104	66%	48.0%	2527	7273	9751	11458	7224	4184
FCA	2093010	6678	0	100%	21.0%	6678	0	20925	24586	14247	24586
Ford	2218913	1460	7180	67%	20.9%	971	4775	22120	25991	21149	21217
GM	2567898	768	28546	62%	18.0%	476	17698	22007	25858	21530	8159
Honda	1582821	11	834	96%	38.3%	11	800	28856	33906	28845	33106
Hyundai/Kia	1311846	0	0	81%	26.4%	0	0	16492	19378	16492	19378
JLR	120699	0	0	0%	39.2%	0	0	2255	2649	2255	2649
Mazda	373995	0	0	0%	33.9%	0	0	6045	7103	6045	7103
Mercedes-Benz	396540	5065	0	88%	47.3%	4457	0	8945	10511	4488	10511
Mitsubishi	92453	1477	0	35%	24.1%	517	0	1063	1249	546	1249
Nissan	1369960	8523	0	40%	30.0%	3367	0	19576	23002	16210	23002
Subaru	643404	0	0	0%	36.3%	0	0	11138	13087	11138	13087
Tesla	103502	103502	0	56%	56.8%	57444	0	2800	3291	0	0
Toyota	2205054	1616	10878	97%	34.4%	1559	10497	36156	42483	34596	31986
Volkswagen	823330	0	0	98%	36.0%	0	0	14138	16612	14138	16612
Volvo	90151	0	0	0%	38.3%	0	0	1645	1933	1645	1933
Grand Total	16419435										

4.2 Development of the CAFE Light Duty Analysis Fleet

4.2.1 Why did NHTSA Develop the Analysis Fleet?

In considering potential new CAFE standards, NHTSA considers manufacturers' potential responses to those standards. To do so, NHTSA uses a modeling system—often referred to as "the CAFE model" or "the Volpe model"—developed by DOT's Volpe National Transportation Systems Center (Volpe Center). NHTSA's CAFE model relies on many inputs, including an analysis fleet. The analysis fleet is a forecast of the future vehicle market—defined in terms of specific manufacturers, vehicle models, and vehicle model configurations—during the model years to be covered in the analysis. As such, the analysis fleet provides a starting point for NHTSA's analysis.

The fleet used for today's analysis is the set of vehicles offered for sale in 2015MY, with individual vehicle models described by attributes like vehicle specifications, technology features, and sales volumes. The analysis fleet also covers fleet mix and fuel consumption. Once the analysis fleet is defined, NHTSA estimates how each manufacturer could potentially deploy (not "should," "must," or "will" deploy) additional fuel-saving technology in response to a given series of attribute-based standards. With a representative analysis fleet, NHTSA tracks the application of technology that may benefit fuel economy and CO_2 emissions in the current fleet. When NHTSA accounts for how manufacturers may improve fleet fuel economy with additional technology, a representative analysis fleet prevents the CAFE model from "double counting" the benefits of a technology. The model does not allow technology to be added to a vehicle already equipped with that technology. Beyond the current fleet, the model also uses projections of future sales from MYs 2016-2030. Details appear in the input file. The analysis fleet grounds assumptions about vehicle sales and technology proliferation and helps NHTSA understand potential pathways to compliance for attribute-based standards.

The structure of the analysis fleet file includes vehicle models sold that year, listed by row. For each vehicle row, the columns list observable and assignable attributes, including technology used, sales volumes, vehicle platform, and other inputs for the CAFE model. As discussed below, the basic data for vehicle configurations are provided by each manufacturer. In many cases, manufacturers provided details about technologies, platforms, engines, transmissions, and other vehicle information. In some cases, the model required information that was not volunteered by manufacturers. In these instances, NHTSA/Volpe supplemented the analysis fleet file with information available from commercial and public sources.

4.2.2 How the MY2015 Analysis Fleet Was Developed

4.2.2.1 Background

In CAFE rulemakings since 2001, NHTSA has used either confidential, forward-estimating product plans from manufacturers or publicly available data on vehicles already sold. These two sources present a tradeoff: confidential product plans provide a comprehensive representation of what vehicles a manufacturer expects to produce in coming years, accounting for plans to introduce new vehicles and fuel-saving technologies and, for example, plans to discontinue other vehicles and even brands. However, for competitive reasons, most of this information is provided on a confidential basis and must be redacted prior to publication with rulemaking documentation. Since 2010, NHTSA has based its analysis fleets almost exclusively on information from commercial and public sources. Therefore, unlike an analysis fleet based primarily on confidential business information (CBI), an analysis fleet based primarily on public sources can be released to the public, allowing any interested parties to reproduce NHTSA's analysis. However, being "anchored" in an earlier model year, such an analysis fleet holds vehicle characteristics unchanged over time and may not reflect manufacturers' actual plans to apply fuel-saving technologies (e.g., a manufacturer may apply turbocharging to improve not just fuel economy, but also to improve vehicle performance), or manufacturers' plans to change product offerings by introducing some vehicles and brands and discontinuing other vehicles and brands. For example, in the 2012-2016 Final Rule the 2008 Model Year fleet was used, while for the 2017-2025 Final Rule both the 2008 and 2010 Model Year fleets were used. In addition to reflecting the near dissolution of Chrysler due to market turmoil in that year, the 2008-based fleet included a significant proportion of models and brands discontinued between 2008 and 2010.

4.2.3 NHTSA Decision to use 2015 Foundation for Analysis Fleet

NHTSA chose to use the 2015 model year as the foundation for today's analysis fleet because the data include the most recent possible mix of commercially available technologies and vehicle configurations, and the data may be made available to the public. If NHTSA began with information from an earlier model year, the information could be disclosed, but the analysis fleet would neither include new vehicles recently introduced (e.g., the Ford F-150 that was redesigned for 2015), nor would the data include the most recent estimated sales mix. If NHTSA used 2016 model year data, the agency would have needed to use product planning information that could not be made available to the public.

Although model year 2015 vehicles were still in production when DOT staff compiled available information regarding the 2015 fleet, such that final production and fuel economy values may be slightly different for specific model year 2015 vehicle models and configurations than are indicated in today's analysis, other vehicle characteristics (e.g., footprint, curb weight, technology content) important to DOT's analysis should ultimately be the same or virtually the same as indicated here. Although final CAFE compliance data is available for earlier model years, even that data can be subject to later revision (e.g., if errors in fuel economy tests are discovered). In any event, considering also the range of important changes in model year 2015 (discussed below) to product offerings, DOT's judgment is that using available data regarding the 2015 model year provides the most realistic characterization of the 2015 market. Insofar as future product offerings are likely to be more similar to vehicles produced in 2015 than to vehicles produced in earlier model years, DOT's judgment is further that using available data regarding the 2015 model year provides the most realistic publicly releasable foundation for constructing a forecast of the future vehicle market.

NHTSA will consider options regarding the set of vehicles upon which to base development of the analysis fleet to be used for subsequent modeling to evaluate potential new CAFE standards. For example, one option will be to rely primarily on model year 2015 data, making updates to reflect final production volumes giving the actual sales of each model and any other new information about characteristics of specific vehicles. Another option will be to develop an updated analysis fleet based on any information that can be obtained regarding, for example, vehicles produced in the 2016 model year. NHTSA seeks comment on these and any other options, and on the tradeoffs between, on one hand, fidelity with manufacturers' actual plans and, on the other, the ability to make detailed analysis inputs and outputs publicly available.

4.2.4 Developments in 2015

Many new, technologically advanced models were introduced in 2015 Model Year. For instance, Ford released an aluminum-bodied F150. Acura, BMW, Hyundai, Kia, Lexus, Porsche, and Volkswagen released new hybrid, plug-in hybrid, and alternative fuel vehicles. Additionally, manufacturers redesigned many high-volume vehicles for the 2015 model year.

The following list includes new vehicles, significantly refreshed vehicles, and discontinued vehicles for 2015:

Table 4.41 Summary of Portfolio Revisions by Manufacturer.

Manufacturer	New Model Entrants (2015)	Significant Redesigns (2015)	Retired Models
BMW	2-Series 235i 4-Series, M4 i3 i8 X4	3-Series X3 X6	
Daimler	Mercedes GLA	Mercedes C-Class	
FCA	Alfa Romeo 4C Ram Promaster Jeep Renegade	Dodge Charger Dodge Challenger	Chrysler 200 Dodge Avenger
Ford	Lincoln MKC Ford Transit Wagon	Ford F-150 Ford Expedition Ford Mustang, 2.3L Lincoln Navigator	Ford E-150 Ford E-250 Ford E-350
General Motors	Cadillac ATS, coupe Chevrolet City Express Chevrolet Colorado Chevrolet Impala, CNG Chevrolet Trax GMC Canyon	Cadillac Escalade Chevrolet Tahoe Chevrolet Suburban GMC Yukon	
Honda	Acura RLX, hybrid Acura TLX Honda Fit	Honda CRV	Acura ILX, hybrid Acura TL Acura TSX Honda Insight Honda Accord, PHEV Honda Fit, EV Honda FCX Clarity

			Honda Ridgeline
Hyundai Kia	Hyundai Tucson, Fuel Cell Kia K900 Kia Soul, EV		
JLR		Land Rover LR2	
Mazda			
Mitsubishi			Mitsubishi i-MiEV
Nissan	Infiniti Q40	Nissan Murano Infiniti QX70	Nissan Cube Nissan Maxima
SUBARU	Subaru WRX	Subaru Legacy Subaru Outback	Subaru Tribeca
Tesla		Tesla Model S, AWD	
TOYOTA	Lexus NX Lexus RC		Scion xD Toyota FJ Toyota Rav4, EV
Volvo			
VWA	Audi A3, Diesel Volkswagen e-Golf Porsche 918 Spyder Porsche Cayenne, HEV	Volkswagen Golf	Volkswagen Routan

4.2.5 Manufacturer-Provided Information for 2015

In 2015, NHTSA/Volpe Center staff worked with the Alliance of Automobile Manufacturers and the Association of Global Automakers to invite individual manufacturers to provide information on the 2015 model year fleet, including a range of vehicle characteristics, as well as mid-model year estimates of 2015 production volumes. In April 2015, NHTSA/Volpe Center staff provided a template of the input file for the CAFE model, indicating relevant characteristics of vehicles, engines and transmissions. By fall 2015, virtually all manufacturers provided extensive included fuel type, combined fuel economy, regulatory class, body style, footprint, curb weight, powertrain specifications and features, and sales volumes. Many manufacturers provided substantially more information about their vehicles, including drag coefficient, peak power and torque, and other specific technologies applied. NHTSA/Volpe Center staff contacted manufacturers to clarify and correct some information, and integrated the information into a single input file for use in the CAFE model.

NHTSA seeks information that could be used to refine its representation of the 2015 fleet, or to develop a similarly-detailed representation of a more recent fleet.

4.2.6 Other Data

4.2.6.1 Redesign/Refresh Schedules

Redesign schedules play an important role in the application of new technologies. Many technologies that may improve fuel economy or reduce CO_2 emissions may be difficult to include without a major product redesign. Therefore, the CAFE model includes redesign schedules as an input, and the model limits the introduction of most technologies on a vehicle to major redesign years or refresh years. In addition to nameplate refresh and redesign schedules, the CAFE model also accounts for platform refresh and redesign schedules.

NHTSA did not request future product plans from manufacturers. NHTSA used information from Ward's Automotive and other sources to project redesign cycles through 2022. For years 2023-2030, NHTSA extended redesign schedules based on Ward's projections, segment, and platform history, and anticipated competitive pressures. For some products with a history of extended production runs, NHTSA/Volpe Center staff estimated that the duration between future major redesigns could be shortened by a year or two.

In some cases, NHTSA judged the Ward's data to be incomplete, or misleading. For instance, Ward's identified some newly imported vehicles as new platforms, but the international platform was midway through the product lifecycle. While new to the U.S. market, treating these vehicles as new entrants would have resulted in artificially short redesign cycles if carried forward, in some cases. Similarly, Ward's labeled some product refreshes as redesigns, and vice versa. In these limited cases, NHTSA revised the Ward's forecast to reflect more realistic redesign and refresh schedules, for the purpose of the CAFE model.

Table 4.42 Estimated Average Production Life For Freshly Redesigned Vehicle, By Manufacturer, By Segment.

	Small Car	Medium Car	Small SUV	Medium SUV	Pickup
BMW	5.8	6.5	6.0	5.6	
Daimler	7.1	6.2	5.6	5.4	
FCA	5.5	6.7	7.0	6.8	8.1
Ford	7.9	6.5	8.6	7.5	5.9
General Motors	5.5	6.1	5.1	7.2	4.4
Honda	4.9	4.7	4.5	5.9	
Hyundai Kia	5.0	4.9	5.3	6.3	
JLR	7.3	7.6	6.6	6.3	6.3
Mazda	6.5	4.2	5.0	6.3	
Mitsubishi	5.7		9.6		
Nissan	6.0	7.1	7.7	6.1	9.7
SUBARU	5.0	5.3	5.1		
Tesla					
TOYOTA	5.6	6.4	5.8	6.3	9.5
Volvo		8.3	8.3	8.3	
VWA	7.8	7.0	6.7	6.9	

NHTSA Seeks Information that could be used to refine its Representation of the Future Schedules for Freshening and Redesigning Specific Vehicles.

4.2.6.2 Technologies

Manufacturers can add technology to a vehicle to improve fuel economy. Each technology may be more or less effective in reducing fuel consumption, depending on complementary equipment and vehicle attributes. As discussed below, Argonne National Laboratory supported NHTSA's analysis by using Autonomie—Argonne's full vehicle simulation tool—to estimate the impact of a wide range of potential combinations of different technology, producing a database of results informing inputs to the CAFE model. The CAFE model uses these inputs to estimate the potential benefits of applying specific combinations of technologies to specific vehicles in the analysis fleet.

The analysis fleet includes many technologies, including vehicle technologies, engine technologies, and transmission types. For instance, vehicle technologies include mass reduction, aerodynamic drag reduction, low rolling resistance tires, and others. Engine technologies cover core powertrain technologies. Internal combustion engines have attributes for fuel type, engine aspiration, valvetrain configuration, compression ratio, number of cylinders, size of displacement, and others. Hybrid and electric powertrains are also described in tiers. Transmission technologies include arrangements like manual, 6-speed automatic, 8-speed automatic, continuously variable transmission, and dual-clutch transmissions. With a portfolio of descriptive technologies, NHTSA can summarize the analysis fleet, and project how vehicles in that fleet may improve over time via the application of advanced technology.

In many cases, technology is clearly observable, but in some cases technology levels less discrete in nature. For the latter, like tiers of mass reduction, NHTSA conducted careful analysis to describe the level of technology already used in a given vehicle. Similarly, NHTSA uses engineering judgement to determine if higher mass reduction tiers may be used practicably and safely in a given vehicle.

Most manufacturers provided a summary of observable technology used in each of their vehicles. In some cases, NHTSA/Volpe supplemented supplied information with data available to the public, typically from manufacturer media sites. In limited cases, manufacturers did not supply adequate information, and NHTSA/Volpe Center staff used information from commercial and publicly available information.

4.2.6.3 Engine Utilization

Manufacturers submitted many details about engines and transmissions to NHTSA. NHTSA used submissions to understand the current level of technology in the fleet and to estimate powertrain families.

NHTSA catalogued engine and transmission specifications as part of the CAFE model input. For engines, NHTSA recorded number of cylinders, displacement, valvetrain configuration, aspiration, fuel type, compression ratio, power output, and others. For transmissions, NHTSA recorded number of forward gears, automatic or manual, driveline configuration (front-wheel drive, rear-wheel drive, all-wheel drive), and others. With an index of current equipment in the fleet, the CAFE model can project pathways for manufacturers to adapt and to adopt technologies and comply with regulations.

Similar to vehicle platforms, the CAFE model considers engine platforms. Manufacturer submissions varied widely in the degree to which engines were identified as unique, shared, or sharing common components. In some cases, manufacturers designated each engine in each application as a unique powertrain. For instance, a manufacturer may have listed two engines for a pair that share designs for the engine block, the crank shaft, and the head because the accessory drive components, oil pans, and engine calibrations differ between the two. In practice, many engines share parts, tooling, and assembly resources, and manufacturers often coordinate design updates between two similar engines. For the all engine portfolios, NHTSA/Volpe Center staff tabulated engine families. By grouping engines together, the CAFE model explores future product portfolios with reasonable powertrain complexity.

NHTSA assigned engines to families based on data driven criteria. If engines share a common cylinder count and configuration, valvetrain, and fuel type NHTSA considered grouping engines together. Additionally, if the compression ratio, horsepower, and displacement differed by no more than 15 percent, the engines were considered to be the same for the purposes of redesign and sharing. Similarly, in some cases NHTSA consolidated the number of transmission designs for a manufacturer. As a result, for manufacturers that submitted highly atomized engine and transmission portfolios, there is a practical cap on powertrain complexity and the ability of the manufacturer to optimize (a.k.a. “right size”) engines perfectly for each vehicle configuration.

4.2.7 Estimated Technology Prevalence in the MY2015 Fleet

The following tables show the estimated prevalence of major technologies, by sales volume weighting, in the MY2015 Light Duty analysis fleet. Numbers provided may differ from actual penetration rates based on projected sales and technology take rates. Separate tables cover conventional engine technologies, electrification technologies, and transmission technologies.

Table 4.43 Engine Technologies by Manufacturer.

Manufacturer	Diesel	DOHC	VVT	VVL	SGDI	Cylinder Deactivation	Turbo- or Super-Charging
BMW	4	100	96	95	95	0	100
Daimler	5	99	79	0	93	0	69
FCA	3	68	96	18	0	14	6
Ford	0	100	100	0	61	0	43
General Motors	0	64	91	7	87	38	11
Honda	0	51	51	100	48	32	0
Hyundai Kia	0	100	100	0	85	1	1
Jaguar / Land Rover	0	100	100	0	100	0	100
Mazda	0	100	100	92	86	0	0
Mitsubishi	0	89	98	11	0	0	3
Nissan	0	100	100	6	3	0	2
Subaru	0	100	100	0	4	0	4
Tesla	-	-	-	-	-	-	-
Toyota	0	100	99	1	5	0	1
Volvo	0	100	100	0	37	0	92
VWA	14	100	81	30	81	2	87
Light Duty Fleet	1	85	92	19	45	12	17

Few manufacturers rely on diesel engines for a large portion of sales. All manufacturers have deployed DOHC and VVT across the majority of the light duty fleet. Adoption of VVL, SGDI, cylinder deactivation, and air intake charging vary widely across the fleet and across manufacturers.

Table 4.44 Electrification Technologies by Manufacturer.

Manufacturer	SS12V	BISG / CISG	SHEV	PHEV	EV
BMW	93	0	0	0.1	0.1
Daimler	85	0	0	0	0.8
FCA	0	0	0	0	0.5
Ford	0	0	2	0.7	0.1
General Motors	7	0.1	0	0.5	0.1
Honda	0	0	1	0	0
Hyundai Kia	0	0	2	0	0.1
Jaguar / Land Rover	92	0	0	0	0
Mazda	0	0.5	0	0	0
Mitsubishi	0	0	0	0	0
Nissan	0	0	0	0	1.2
Subaru	0	0	2	0	0
Tesla	-	-	-	-	100
Toyota	0	0	9	0.2	0
Volvo	0	0	0	0	0
VWA	0	0	0	0.3	0.5
Light Duty Fleet	6	0	2	0.2	0.4

Many manufacturers have offered some type of alternative, electric powertrain to the market; however, electrification technologies currently have very modest market share. A few manufacturers have reported use of 12V start-stop systems, but very few report use of BISG or CISG systems. Many manufacturers offer some combination of strong hybrids and plug-in hybrids, but only Toyota has sales in these categories approaching 10 percent of total sales volume. Most manufacturers have dabbled with commercializing electric vehicles, but only Tesla remains fully committed to pure battery electric vehicle technology. Vehicles with electrification technologies continue to form a small fraction of the total light duty fleet.

Table 4.45 Transmission Technology by Manufacturer.

Manufacturer	Manual	CVT	AMT or DCT	Auto, 6+ speeds
BMW	4	0	3	93
Daimler	0	0	0	100
FCA	3	1	1	94
Ford	6	2	6	86
General Motors	1	1	0	98
Honda	3	63	1	33
Hyundai Kia	2	0	2	96
Jaguar / Land Rover	0	0	0	100
Mazda	9	0	0	91
Mitsubishi	8	90	0	3
Nissan	2	83	0	15
Subaru	7	93	0	0
Tesla				
Toyota	1	16	0	83
Volvo	0	0	0	100
VWA	7	2	91	0
Light Duty Fleet	3	20	4	73

The biggest trend for transmissions is that manufacturers are offering more speeds in automatics. Many six, seven, eight, and nine-speed automatic transmissions have entered the fleet, and manufacturers have announced publicly that ten-speed automatics will be widely available soon. Manufacturers who have limited deployment of six speed or higher automatic transmissions have committed to continuously variable transmissions. Despite the promise of high efficiency, early launches of dual-clutch transmissions have been plagued with drivability complaints, and the technology has seen limited application. Manual transmissions remain a niche technology for specialty performance vehicles and entry level vehicle packages. Conventional transmissions with six or more speeds makeup approximately 73 percent of the 2015 analysis fleet.

4.2.8 Engine and Platform Sharing

Over the past several decades, manufacturers have expanded product offerings to consumers at a rapid rate. Manufacturers share and standardize components, systems, tooling, and assembly processes within their products (and occasionally with the products of another manufacturer) to cost effectively maintain vibrant portfolios. A “platform” refers to engineered underpinnings shared on several differentiated products.

4.2.8.1 Platform Sharing

The concept of platform sharing has evolved with time. Years ago, manufacturers rebadged vehicles and offered more exotic options on premium nameplates. Today, manufacturers share parts across highly differentiated vehicles. Engineers design chassis platforms with the ability to vary wheelbase, ride height, and even driveline configuration. Assembly lines can produce hatchbacks and sedans with large overlaps in manufacturing capacity. Engines made on the same line may power small cars or mid-size sport utility vehicles. Many manufacturers, including Ford, General Motors and Toyota have publicized strategies to reduce complexity with expanded use of common platforms. Now, vehicles with different looks and different capabilities may share the same platform.

Although NHTSA's analysis, like past CAFE analyses, considers vehicles produced for sale in the U.S., the agency notes that these platforms are not constrained to vehicle models built for sale in the United States; many manufacturers have developed, and use, global platforms. And the number of global platforms is shrinking across the industry. Several automakers (for example, General Motors and Ford) either plan to, or already have, reduced their number of platforms to fewer than ten and account for the overwhelming majority of their production volumes on that small number of platforms.

The CAFE model accounts for platform sharing and complexity management within the context of production for sale in the U.S. The model restricts significant advances in some technologies, like major mass reduction, to major redesign years. If one vehicle on the platform receives a treatment of technology, other vehicles on the platform also receive the technology as part of their next major redesign or refresh.

4.2.8.2 Engine Sharing & Inheritance

Similar to vehicle platforms, manufacturers create engines that share parts. For instance, common engine block castings may be bored out with marginally different diameters to create engines with an array of displacements. Head assemblies for different displacement engines may share many components across the engine family. Crankshafts may be finished with the same tools, to similar tolerances. One engine family may appear on many vehicles on a platform, and changes to that engine may or may not carry through to all the vehicles. Some engines are applied across a range of vehicle platforms.

The CAFE model currently accounts for sharing of engines by "truing up" technology among vehicles that share the same engine. If such vehicles have different design schedules, and a subset of vehicles using a given engine add engine technologies in the course of a redesign or freshening that occurs in an early model year (e.g., 2018), other vehicles using the same engine "inherit" these technologies at the soonest ensuing freshening or redesign. This is consistent with a view that, over time, most manufacturers are likely to find it more practicable to shift production to a new version of an engine than to indefinitely continue production of a "legacy" engine.

The CAFE model does not currently attempt to simulate the potential that, having no further regulatory need to improve fuel economy, a manufacturer might shift the application of technologies that improve technical efficiency to favor performance rather than fuel economy. Therefore, the model's representation of the "inheritance" of technology can lead to estimates that a manufacturer might eventually exceed fuel economy standards as technology continues to propagate across shared platforms and engines. Historical CAFE compliance data shows examples of extended periods during which some manufacturers exceeded one or both standards. On the other hand, notwithstanding the potential that doing so would reintroduce complexity that would come at some cost (e.g., to replace a naturally aspirated engine with a smaller turbocharged engine, and subsequently split the newer engine into versions with multiple displacements), NHTSA recognizes that buyers could continue to place enough value on vehicle performance and utility that a manufacturer would, having achieved compliance, take advantage of opportunities to cost-effectively shift technical capability in those directions. Still, the prospect of "splintering" engines and platforms may limit the extent to which manufacturers attempt to finely balancing fuel economy and performance for each vehicle configuration.

NHTSA will consider options to further refine its representation of sharing and inheritance of technology, possibly including model revisions to account for tradeoffs between fuel economy and performance when applying technology. The agency seeks comments on the sharing- and inheritance-related aspects of its analysis fleet and the CAFE model, and information that would support refinement of the current approach or development and implementation of alternative approaches.

4.2.9 Class Types and Assignment

The CAFE model makes use of four distinct class assignments: Regulatory Class, Safety Class, Technology Class, and Technology Cost Class.

4.2.9.1 Regulatory Class

Regulatory Class is a straightforward classification by Passenger Car or Light Truck (PC or LT). Assignment to PC or LT is defined by the criteria set forth in the corporate average fuel economy rules.

4.2.9.2 Safety Class

Each vehicle in the input fleet receives a Safety Class designation based on vehicle body style and vehicle weight. NHTSA uses safety class to conduct safety analysis, discussed separately.

4.2.9.3 Technology Class

Technology Class maps vehicle models in the analysis fleet to a set of Argonne simulation results that provide effectiveness values for each technology. Argonne currently supports five Technology Classes: (1) small car, (2) small SUV, (3) medium car, (4) medium SUV and (5) pickup. NHTSA assigns technology classes in the following way:

- All vehicles with Body Style = Pickup are classified as a Pickup. All body-on-frame vehicles are classified as Pickups, so some Vans and SUVs appear in the Pickup technology class.
- Big SUVs with unibody construction are medium SUVs. Medium SUVs also include vehicles with van body styles and vehicles with minivan body styles. Generally, SUVs with a larger than average footprint are designated medium SUVs.
- The small SUV technology class includes all vehicles with a wagon body style. In addition, SUVs that have a smaller than average footprint also earn a small SUV technology class assignment.
- Passenger cars with a greater than mean footprint are medium cars. The medium car technology class includes convertibles, coupes, hatchbacks, and sedans.
- Passenger cars with a less than mean footprint are small cars. The small car technology class includes convertibles, coupes, hatchbacks, and sedans.

4.2.9.4 Technology Cost Class

Technology Cost Class accounts for costs that vary by engine configuration (e.g. SGDI, VVT), and therefore provides a code for the number of cylinders, banks, and whether or not a vehicle uses an OHV valve train configuration. For example, 4C1B indicates an inline 4-cylinder engine with a conventional valvetrain, while 8C2B_ohv indicates a V8 engine with an OHV valvetrain configuration.

NHTSA seeks comment on this approach to grouping specific vehicles for these different analytical requirements, recommendations regarding any alternative approaches, and information that could be used to refine the assignment of specific vehicles to specific categories.

4.2.10 Mass Reduction and Aero Application

Unlike other technologies like valvetrain configurations or transmission arrangements, the degree of mass reduction already applied to a vehicle is not always straightforward to assign as a generic "level," Vehicles with lower mass and less aerodynamic drag often have higher performance. More so than other technologies, vehicle mass and aerodynamics are the product of hundreds of engineering decisions, material choices, design strategies and manufacturing approaches that together makeup a vehicle. The utility a vehicle provides a customer affects a vehicle's mass and aerodynamic characteristics: the general shape, number of openings, surface features of the car, and optional equipment factor into mass and aerodynamic performance.

NHTSA recognizes that in many cases manufacturers have already implemented mass savings technologies and drag reductions on many of their 2015MY products. As a result, not all vehicles in the analysis fleet have the same opportunities to further reduce mass and improve aerodynamic drag in future years. To account for the diverse progress on mass reduction and aerodynamics among the analysis fleet, NHTSA assigned each vehicle a level of mass reduction and aerodynamic treatment relative to a baseline case. NHTSA has adopted a relative performance approach to assess the application of mass reduction and aerodynamic technologies.

4.2.10.1 Mass Reduction

NHTSA developed cost curves for glider weight savings on baseline sedans and pick-ups. In order for NHTSA's cost curves to be used effectively in the NHTSA/Volpe model, vehicles in the analysis fleet must start at a position on the estimated cost curve that reflects the level of mass reduction technology currently used on the platform. This section describes the assignment process and summarizes the mass reduction assignment results.

NHTSA/Volpe Center staff developed regression models to estimate curb weights based on other observable attributes. With regression outputs in hand, Volpe evaluated the distribution of vehicles in the analysis fleet. Additionally, NHTSA/Volpe evaluated vehicle platforms based on the sales-weighted residual of actual vehicle curb weights vs. predicted vehicle curb weights. Based on the actual curb weights relative to predicted curb weights, NHTSA/Volpe assigned platforms (and the subsequent vehicles) a 2015MY mass reduction level.

For the curb weight regressions, NHTSA/Volpe Center staff grouped vehicles in the analysis fleet into three separate body design categories for analysis: 3-Box, 2-Box, and Pick-up.

Table 4.46 Mass Reduction Body Style Sets

3-Box	2-Box	Pick-up
Coupe Sedan Convertible	Hatchback Wagon Sport Utility Minivan Van (LT)	Pick-up (LT)

NHTSA/Volpe Center staff leveraged many documented variables in the analysis fleet as independent variables in the regressions. Continuous independent variables included footprint (wheelbase x track width), and powertrain peak power. Binary independent variables included strong HEV (yes or no), PHEV (yes or no), BEV or FCV (yes or no), all-wheel drive (yes or no), rear-wheel drive (yes or no), and convertible (yes or no). Additionally, for PHEV and BEV / FCV vehicles the capacity of the battery pack was included in the regression as a continuous independent variable. In some of the body design categories, the analysis fleet did not cover the full spectrum of independent variables. For instance, in the pickup body style regression, there were no front-wheel drive vehicles in the analysis fleet, so the regression defaulted to all-wheel drive and left an independent variable for rear-wheel drive.

Table 4.47 Regression Statistics for Curb Weight (lbs.)

	3-Box						2-Box						Pick-up					
Observations	822						584						453					
Adjusted R Square	0.865						0.883						0.461					
Standard Error	228.7						332.8						318.1					
REGRESSION STATISTICS	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-1581.63	98.5	-16.06	0.0000	-1775.0	-1388.3	-1930.09	142.5	-13.54	0.0000	-2210.0	-1650.2	1857.77	194.3	9.56	0.0000	1475.9	2239.7
Footprint (sqft)	100.50	2.2	44.79	0.0000	96.1	104.9	104.72	3.6	28.69	0.0000	97.5	111.9	41.67	3.2	12.92	0.0000	35.3	48.0
Power (hp)	1.22	0.1	14.85	0.0000	1.1	1.4	3.09	0.2	13.42	0.0000	2.6	3.5	1.57	0.3	5.11	0.0000	1.0	2.2
Strong HEV (1,0)	200.36	46.3	4.33	0.0000	109.5	291.2	358.97	80.3	4.47	0.0000	201.3	516.6	-	-	-	-	-	-
PHEV (1,0)	259.28	96.8	2.68	0.0075	69.3	449.2	462.90	169.7	2.73	0.0066	129.5	796.3	-	-	-	-	-	-
BEV or FCV (1,0)	602.33	215.0	2.80	0.0052	180.3	1024.3	374.24	152.1	2.46	0.0142	75.5	673.0	-	-	-	-	-	-
Battery pack size (KwH)	-2.48	4.1	-0.60	0.5461	-10.6	5.6	-1.32	3.7	-0.36	0.7187	-8.5	5.9	-	-	-	-	-	-
AWD (1,0)	294.51	24.5	12.03	0.0000	246.4	342.6	353.91	33.4	10.59	0.0000	288.3	419.5	-	-	-	-	-	-
RWD (1,0)	117.20	23.7	4.94	0.0000	70.6	163.8	208.02	54.1	3.84	0.0001	101.7	314.3	-240.32	30.2	-7.96	-	-299.7	-181.0
Convertible (1,0)	273.65	25.3	10.84	0.0000	224.1	323.2	-	-	-	-	-	-	-	-	-	-	-	-

The regression for pickup body style did not include independent variables for strong HEV, PHEV, BEV or FCV, battery pack size, or convertible. No vehicles in the analysis fleet matched these criteria for the pick-up body style. Additionally, with the inclusion of the 2015MY Ford F-150, a large portion of the pickup sample set is known to have adopted a significant amount of weight savings technology.

Each of the three regressions produced outputs that were effective for identifying vehicles with significant amount of mass reduction technology in the 2015MY analysis fleet. Many of the coefficients for independent variables provided clear insight into the average weight penalty for the utility feature. In some cases, like battery size, the relatively small sub-sample size and high collinearity with other variables confounded the coefficients. This was especially true for advanced PHEV's and BEV's, which are often vehicles that include high levels of weight saving technology on the vehicle glider. By design, no independent variable directly accounted for the degree of weight savings technology applied to the vehicle. The residuals of the regression captured weight reduction efforts and noise from other sources.

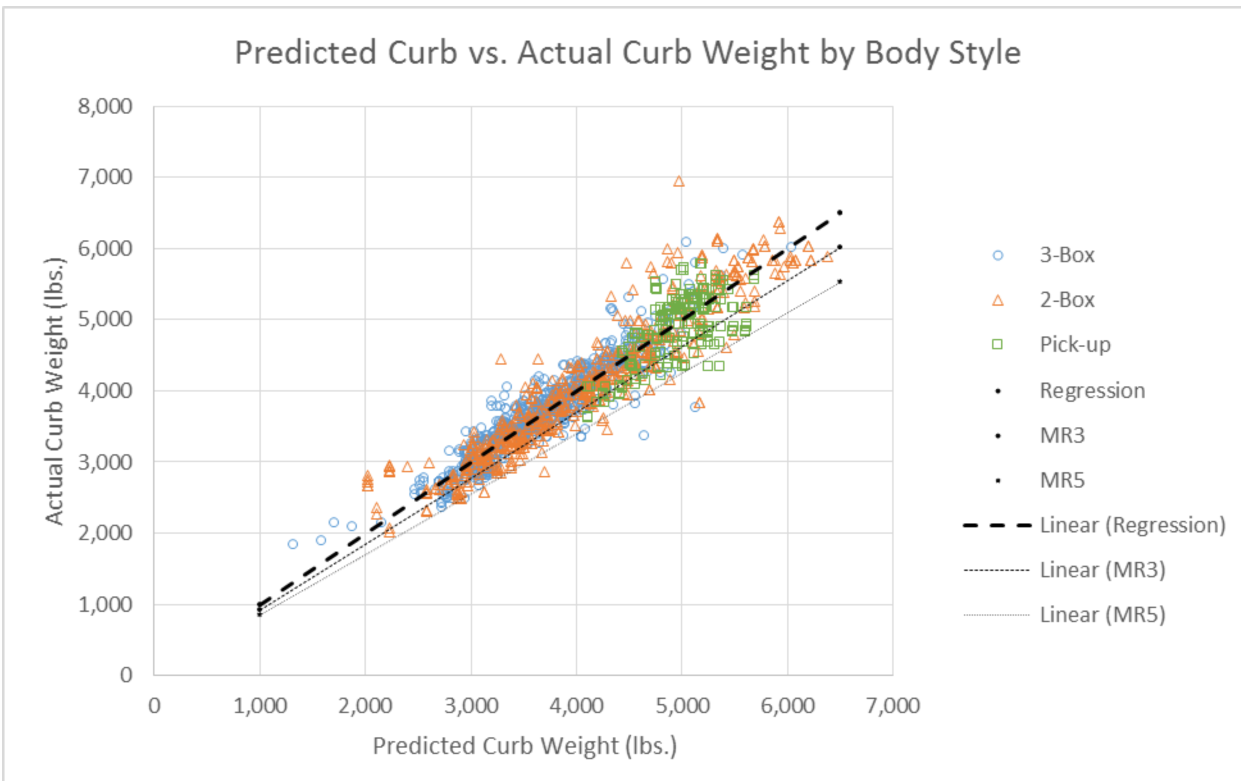

Figure 4.5 shows a plot of results from each of the three regressions on a predicted curb weight vs. actual curb weight. Points above the thick dashed "regression" line represent vehicles heavier than predicted; points below the thick dashed "regression" line represent vehicles lighter than predicted. For points with actual curb weight below the predicted curb weight, NHTSA/Volpe Center staff used the residual as a percent of predicted weight to get a sense for the level current mass reduction technology used in the vehicle, as described in inputs to the CAFE model (MR0, MR1, MR2, MR3, MR4, and MR5).

Generally, the residuals of the regressions as a percent of predicted weight appropriately stratified vehicles by mass reduction level. Most vehicles showed positive residuals or had actual curb weights very close to the predicted curb weight. Very few vehicles in the analysis fleet were identified with the highest levels of mass reduction. Most vehicles with the largest negative residuals have adopted advanced weight savings technologies at the most expensive end of the cost curve.

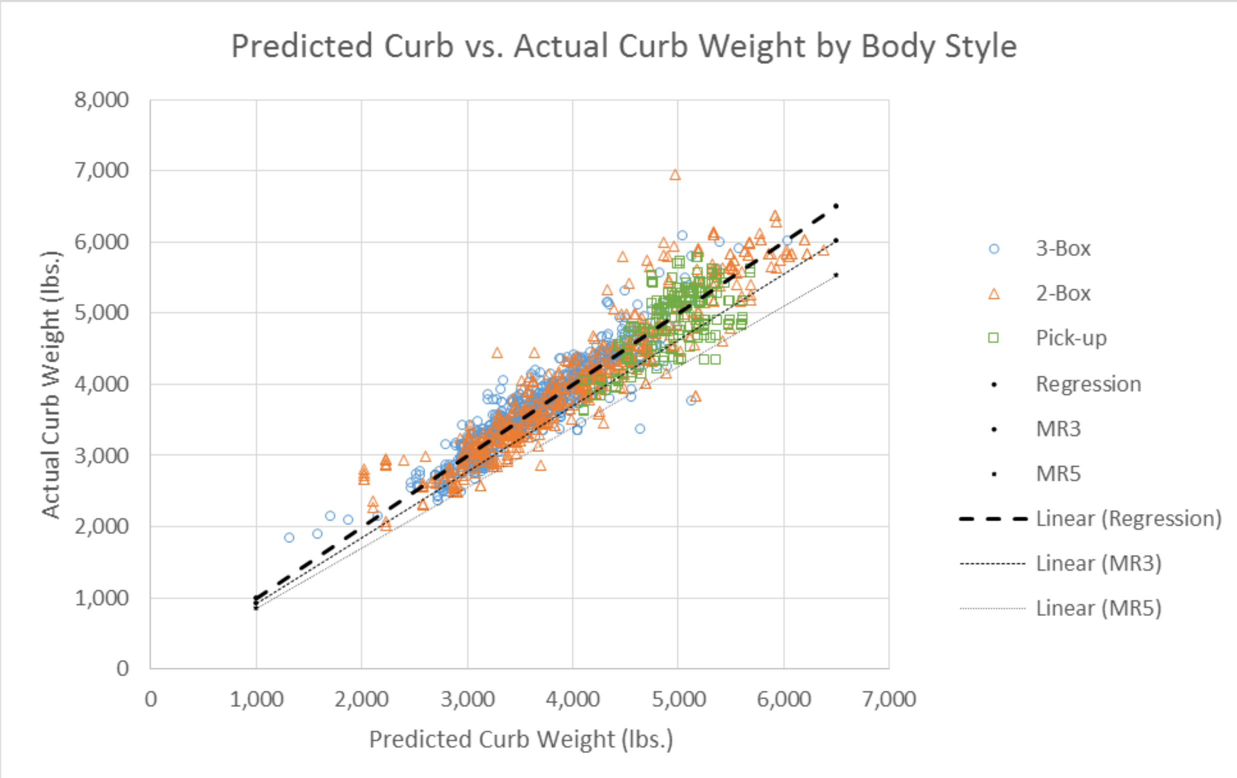

Figure 4.5 Mass Reduction Regression Residual Plot by Body Style

The CAFE model trues up levels of applied mass reduction within a platform, so vehicles that share the same platform receive a common starting point for mass reduction. This approach for assigning platforms levels of mass reduction reflects the observation that many weight savings opportunities, for instance in body and chassis structure, are shared across the platform. The platform approach also dampens the impact of potential weight variation by trim level on the analysis. To determine the starting level of mass reduction for each platform NHTSA/Volpe staff computed a sales-weighted average residual of all the vehicle variants for each platform. Based on the MY2015 platform average residual, NHTSA/Volpe staff assigned an initial level of mass reduction to the platform and corresponding vehicles.

Table 4.48 Mass Reduction Levels by Residual Error

Mass Reduction Technology Assignment	Residual as a Percent of Predicted Curb Weight
MR0	Predicted
MR1	-3.75%

MR2	-5.625%
MR3	-7.5%
MR4	-11.25%
MR5	-15.0%

With an 'MR' assignment, the CAFE model factors in that vehicles approach additional weight savings opportunities from different starting points, and vehicles may face incrementally higher or lower costs to shed additional weight.

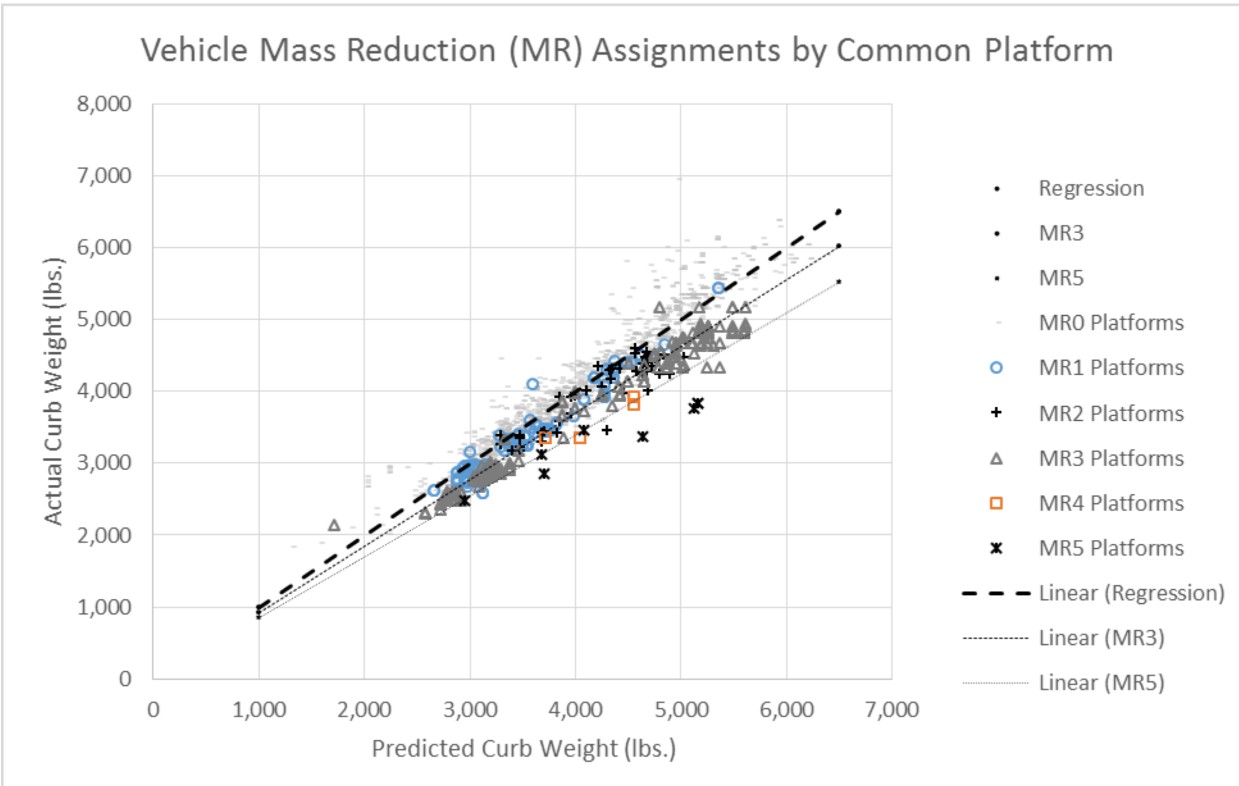

Figure 4.6 Mass Reduction Assignments by Platform

The following examples illustrate the result of this approach to assigning initial levels of mass reduction to the 2015MY fleet.

Table 4.49 Vehicle Platforms with Highest Estimated Levels of Mass Reduction Technology

CAFE MR Group	NHTSA/Volpe Platform Code	Example Nameplate	MR Residual%
MR5	VWA Veneno	Lamborghini Veneno Roadster	-27.6%
	VWA Porshe_918	Porsche 918 Spyder PHEV	-26.5%
	GM Sigma	Cadillac CTS-V Wagon	-25.7%
	BMW i3	BMW i3 PHEV	-16.9%
	FCA 4	Alfa Romeo 4C	-15.9%
	BMW i8	BMW i8 PHEV	-15.3%
MR4	VWA Aventador	Lamborghini Aventador	-15.0%
	GM Y	Chevrolet Corvette	-11.4%
MR3	Toyota_B	Toyota Prius C	-11.2%
	Nissan FF-1	Nissan Versa	-10.8%
	Daimler Daimler_R197	Mercedes SLS AMG GT Roadster	-10.5%
	Hyundai Kia HK_J5	Hyundai Elantra	-9.6%
	General Motors MST	GMC Canyon	-9.3%
	Hyundai Kia HK_UB	Kia Rio	-9.1%
	Mazda SkyActive_BM	Mazda 3	-9.1%
	Mazda NC	Mazda MX-5	-8.8%
	Ford Ford_F	Ford F-150	-8.2%
	Toyota FR_S	Toyota FR-S	-8.1%
	VWA VW_MSS	Audi R8	-8.1%
	Hyundai Kia HK_Sedona	Kia Sedona	-7.8%
	Hyundai Kia HK_PS	Kia Soul	-7.5%
MR2	Mazda SkyActive_GJ	Mazda 6	-7.2%
	Daimler Daimler_MRA	Mercedes C 300	-6.8%
	Honda HONDA_PILOT	Honda Odyssey	-6.8%
	VWA Veyron	Bugatti Veyron	-6.6%
	JLR XJ	Jaguar XJ	-6.1%
	Daimler Daimler_W246	Mercedes CLA 250	-6.0%
	Nissan FF-3	Nissan Altima	-5.9%

MR5 vehicles included the BMW i3, BMW i8, and some exotics. The Chevrolet Corvette received an MR4. The newly redesigned Ford F-150 and the recently redesigned GMC Canyon received MR3. The Mazda6 was binned as MR2. The Honda Civic was assigned MR1, with a platform residual very near the boundary for MR2. The 2011MY Honda Accord and the 2014MY Chevy Silverado served as benchmark vehicles as NHTSA developed cost curves for weight savings. The actual vs. predicted weight for each benchmark vehicle falls very near the predicted curb weight based on their independent variable vehicle attributes, and each vehicle would be assigned MR0. Both the MY2015 Honda Accord and MY2015 Chevy Silverado are MR0 vehicles. The table below summarizes the initial levels of mass reduction assigned for each manufacturer's MY2015 light-duty fleet.

Table 4.50 2015MY Mass Reduction Level by Manufacturer as a Percent of Vehicle Sales

Manufacturer	MR0	MR1	MR2	MR3	MR4	MR5
VWA	99.68%	0.00%	0.01%	0.23%	0.05%	0.04%
General Motors	95.71%	0.00%	0.00%	3.21%	1.06%	0.02%
BMW	99.69%	0.00%	0.00%	0.00%	0.00%	0.31%
FCA	91.33%	8.64%	0.00%	0.00%	0.00%	0.02%
TOYOTA	97.58%	0.00%	0.00%	2.42%	0.00%	0.00%
Nissan	17.33%	32.64%	40.61%	9.42%	0.00%	0.00%
Daimler	59.35%	0.00%	40.61%	0.03%	0.00%	0.00%
Hyundai Kia	32.13%	26.47%	0.00%	41.40%	0.00%	0.00%
Mazda	9.76%	32.77%	19.33%	38.15%	0.00%	0.00%
Ford	76.44%	0.00%	0.00%	23.56%	0.00%	0.00%
Honda	52.84%	29.86%	17.30%	0.00%	0.00%	0.00%
JLR	93.95%	0.00%	6.05%	0.00%	0.00%	0.00%
Tesla	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
Mitsubishi	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Volvo	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
SUBARU	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%

NHTSA seeks comment on this approach to assigning initial levels of mass reduction, and recommendations regarding any alternative approaches, taking into account the agency's representation of costs and fuel consumption impacts of additional mass reduction. The agency seeks any additional information that could be used to refine the agency's approach or develop and implement alternative approaches.

As part of the mass reduction regression analysis, NHTSA/Volpe staff evaluated trends in residuals. Based on prior work in the industry and observations from this analysis, a more detailed summary of residuals with respect to vehicle footprint, luxury content, and company heritage is included below.

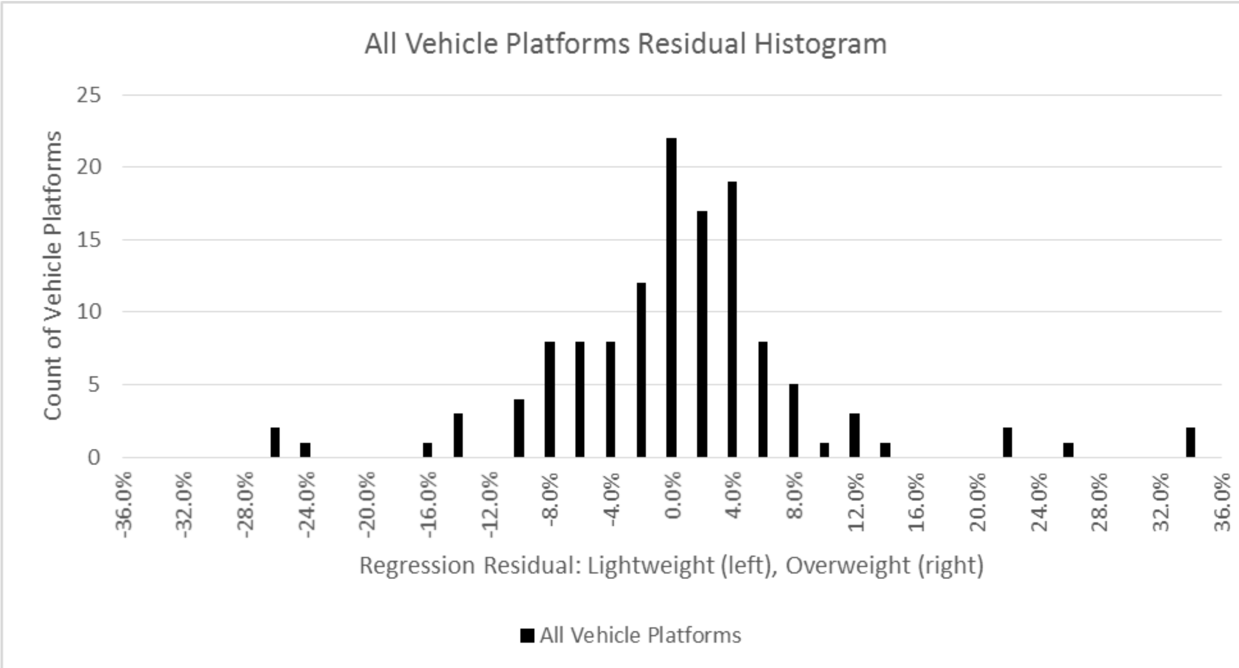

Figure 4.7 Mass Reduction Residual Histogram for All MY2015 Platforms

4.2.10.1.1 *Mass Reduction Residual Analysis for Footprint*

NHTSA/Volpe staff identified a meaningful trend in the regression residuals for vehicle footprint: vehicles under 41 square foot footprint tended to have large residuals as a percentage of predicted weight. The two smallest vehicles were estimated to be the most overweight based on content modeled in the regression.

Table 4.51 Mass Reduction Platform Residuals for Platforms with the Smallest Footprint

Sales Weighted Platform Average Footprint (sq.ft.)	Platform% Residual	Rank of Smallness of Platform Footprint (out of 128)	Rank of Heaviness on a Residual% Basis (out of 128)	Example Vehicle from Platform	Assigned MR Value
26.8	33.1%	1	1	Smart ForTwo	MR0
34.8	32.3%	2	2	Fiat 500	MR0
36.1	11.2%	3	7	Chevrolet Spark	MR0
37.4	-8.8%	4	112	Mazda MX-5	MR3
38.7	1.1%	5	48	Mini Cooper Coupe	MR0
39.9	6.2%	6	15	Porsche 911 Carrera	MR0
40.0	-3.8%	7	91	Honda CR-Z	MR1
40.1	-11.2%	8	119	Toyota Prius C	MR3
40.2	-0.6%	9	69	Ford Fiesta	MR0
40.5	-1.1%	10	72	Mini Cooper Hardtop, 4-door	MR0
40.8	-1.3%	11	76	Porsche Boxster	MR0
40.9	0.0%	12	60	Chevrolet Sonic	MR0
41.1	-15.9%	13	123	Alfa Romeo 4C	MR5
41.2	3.9%	14	24	BMW Z4	MR0
41.5	-10.8%	15	118	Nissan Versa	MR3
42.1	-3.6%	16	90	Mitsubishi Lancer	MR0

The NHTSA/Volpe staff proposes that this trend is a result of limited crush space in the smallest vehicles, so on a relative basis the smallest vehicles may include more mass in structure for a given set of content than their larger counterparts. As shown in the table above, and the figure below, this trend subsides after the platform exceeds a sales weighted average footprint of about 41 square feet.

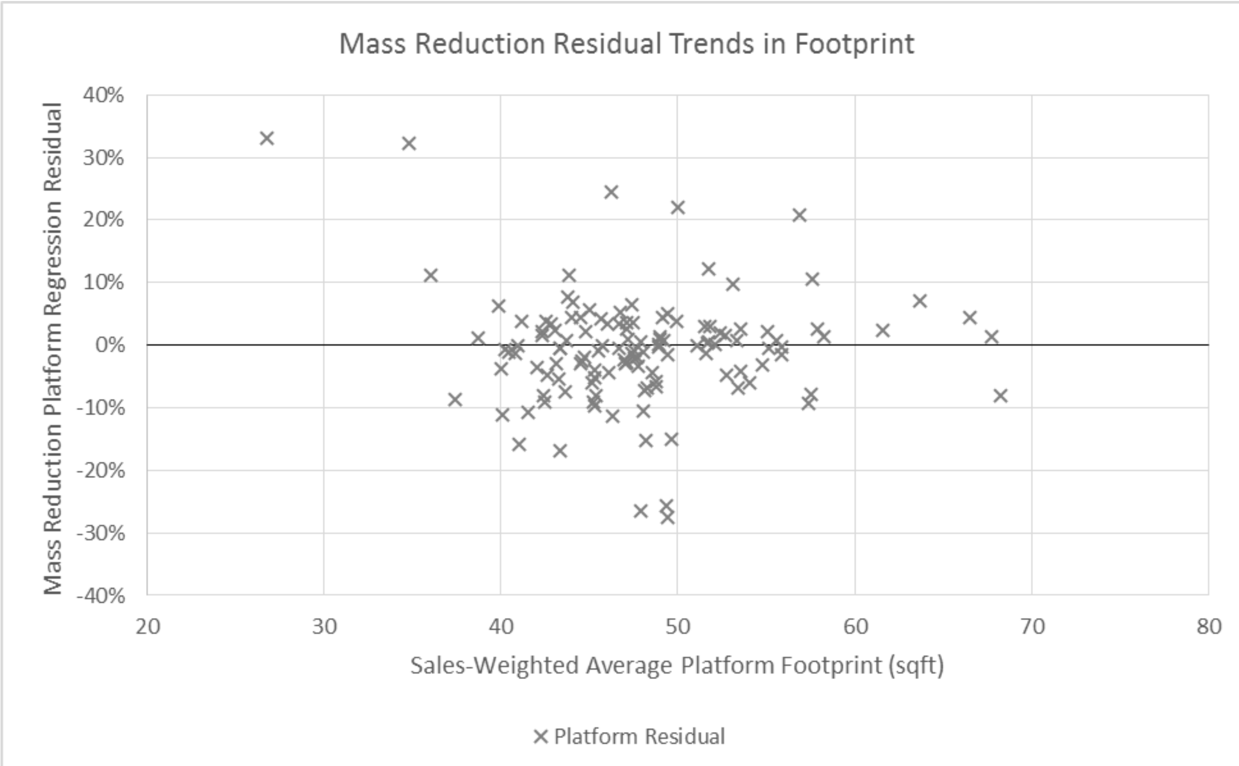

Figure 4.8 Mass Reduction Platform Residuals vs. Footprint

Chapter 8 discusses the agencies updated assessment of the effects of vehicle mass and size on overall societal safety. The complex relationship between a vehicle's mass, size, and fatality risk varies in different types of crashes, and NHTSA and others have been examining this relationship for over a decade. The principal findings and conclusions of NHTSA's updated mass-size safety analysis are that mass reduction in heavier light-duty trucks, while holding footprint constant, reduces societal fatality risk, whereas mass reduction in lighter passenger cars increases overall societal fatality risk. The agencies investigated the amount of mass reduction that is projected to maintain overall fleet safety. For the Draft TAR analyses, the agencies have limited the amount of mass reduction applied to passenger cars to achieve a safety neutral outcome. Therefore technology pathways shown by the agencies' analyses have a neutral effect on overall fleet safety. Based on such results, additional application of mass reduction technology is restricted, according to three criteria shown in Table 4.52.

Table 4.52 Criteria for Limiting Additional Application of Mass Reduction Technology in the CAFE Analysis

Platforms with a sales weighted average of less than 2800 lbs. may not apply more mass reduction technology.
SmallCar vehicles may not add new MR technology to proceed past MR2.
MediumCar vehicles may not add new MR technology to proceed past MR2.

As a result of these criteria, the model will not apply excessive mass reduction technologies to small vehicles.

4.2.10.1.2 Mass Reduction Residual Analysis for Low and High Price Platforms

In 2015, the California Air Resources Board published a study, "Technical Analysis of Vehicle Load Reduction Potential for Advanced Clean Cars"[29] that evaluated the distribution of applied mass reduction technology in the fleet. The study used similar modeling techniques as used for today's CAFE analysis. As part of that study, skewed residuals of 1.6 percent were observed for luxury sedans, and this was reasonably explained optional luxury content. With the result of those findings in mind, the NHTSA/Volpe evaluated the residuals for platforms with low base prices and with high base prices to investigate if some form of additional content should be accounted for in the regression.

Table 4.53 Mass Reduction Average Residual by Average Platform Base Price

		Average Residual	Platform Count
All Vehicle Platforms		-0.6%	128
Platform MSRP Average Base Price	$30k or Less	-0.5%	52
	$30k - $50k	-0.5%	37
	$50k or Greater	-0.8%	39

While option content may add weight on a vehicle basis, the CAFE analysis assigns levels of mass reduction at a platform level. Trends in the residuals do not provide strong evidence that some variable for premium content is needed to correct for a predicted weight bias among high priced vehicles.

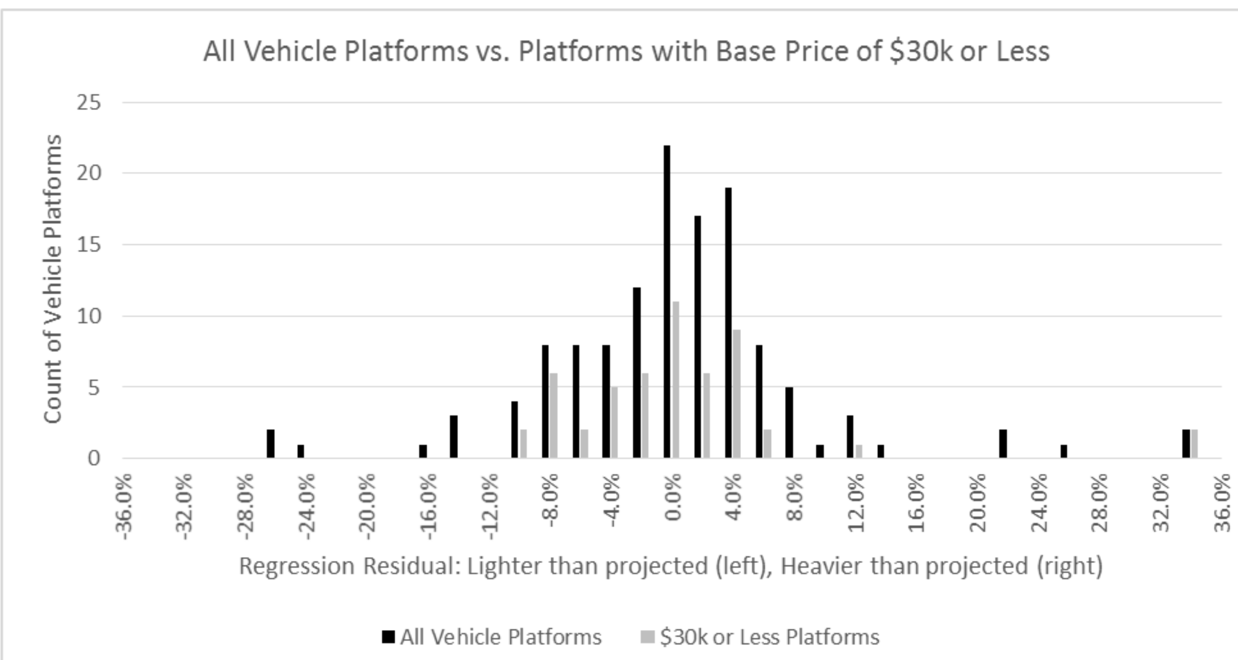

Figure 4.9 Mass Reduction Residual Distribution of Platforms with Base Price of $30k or Less

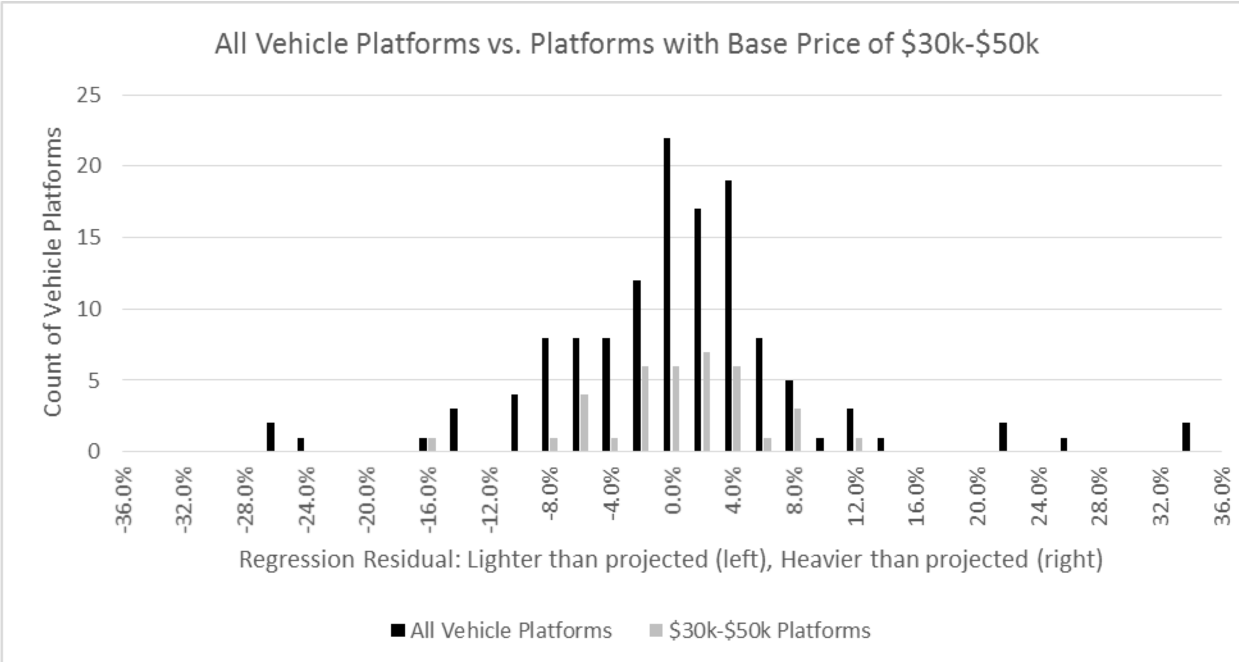

Figure 4.10 Mass Reduction Residual Distribution of Platforms with Base Price between $30k-$50k

Many of the largest residuals represent high priced platforms, and many of the smallest residuals also represent high priced platforms. Lower priced platforms tended to have actual weights clustered closer to the predicted weight and hence residuals with lower variance.

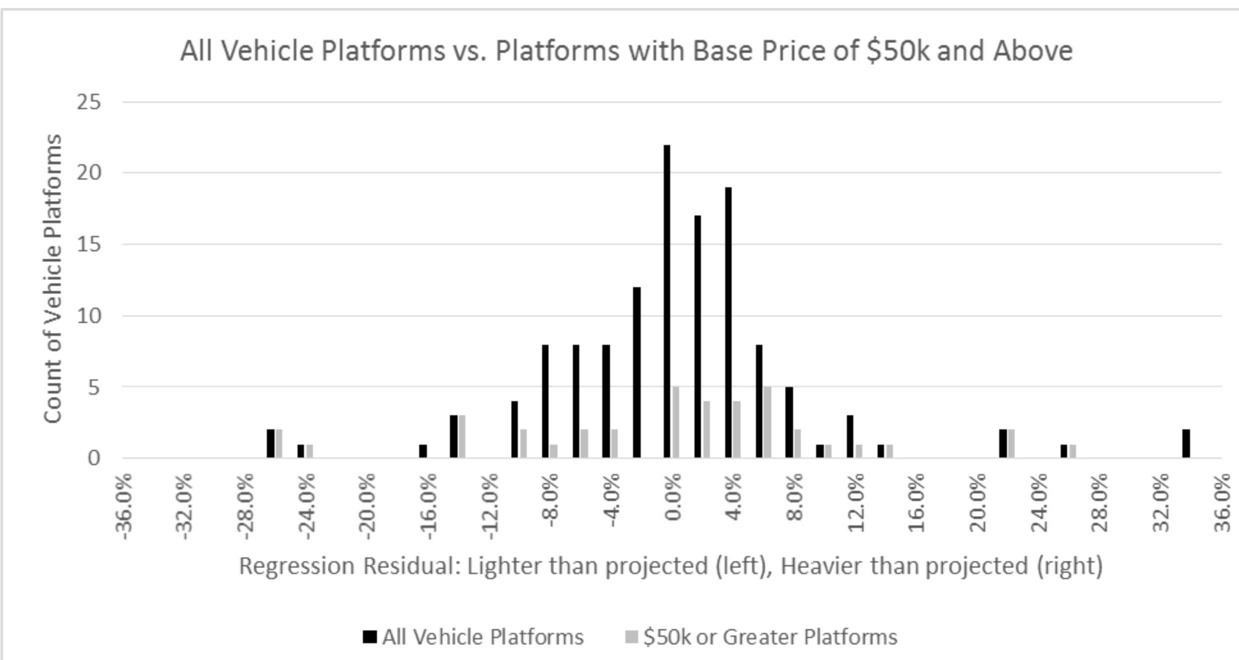

Figure 4.11 Mass Reduction Residual Distribution of Platforms with Base Price of $50k and Above

4.2.10.1.3 Mass Reduction Residual Trends for Company Heritage

The NHTSA/Volpe did observe a notable skew based on company heritage. Many vehicle platforms with Asian parent companies demonstrate a residual skew towards lightweight designs, or negative residuals when compared with vehicles of other heritage. For the purposes of this analysis, FCA platforms were binned as "North American" heritage.

Table 4.54 Mass Reduction Average Residual by Parent Company Heritage

		Average Residual	Platform Count
All Vehicle Platforms		-0.6%	128
Platform Parent Company Heritage	North America	0.1%	42
	Europe	0.7%	47
	Asia	-2.9%	39

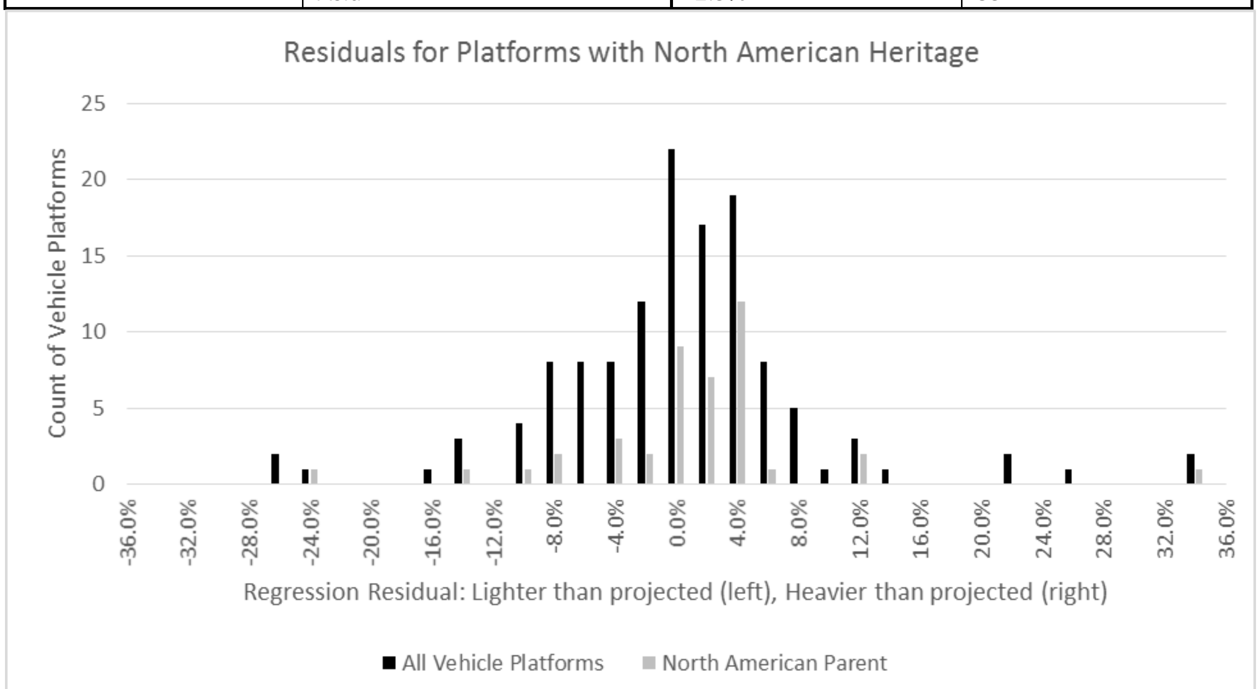

Figure 4.12 Mass Reduction Residuals for Platforms with North American Heritage

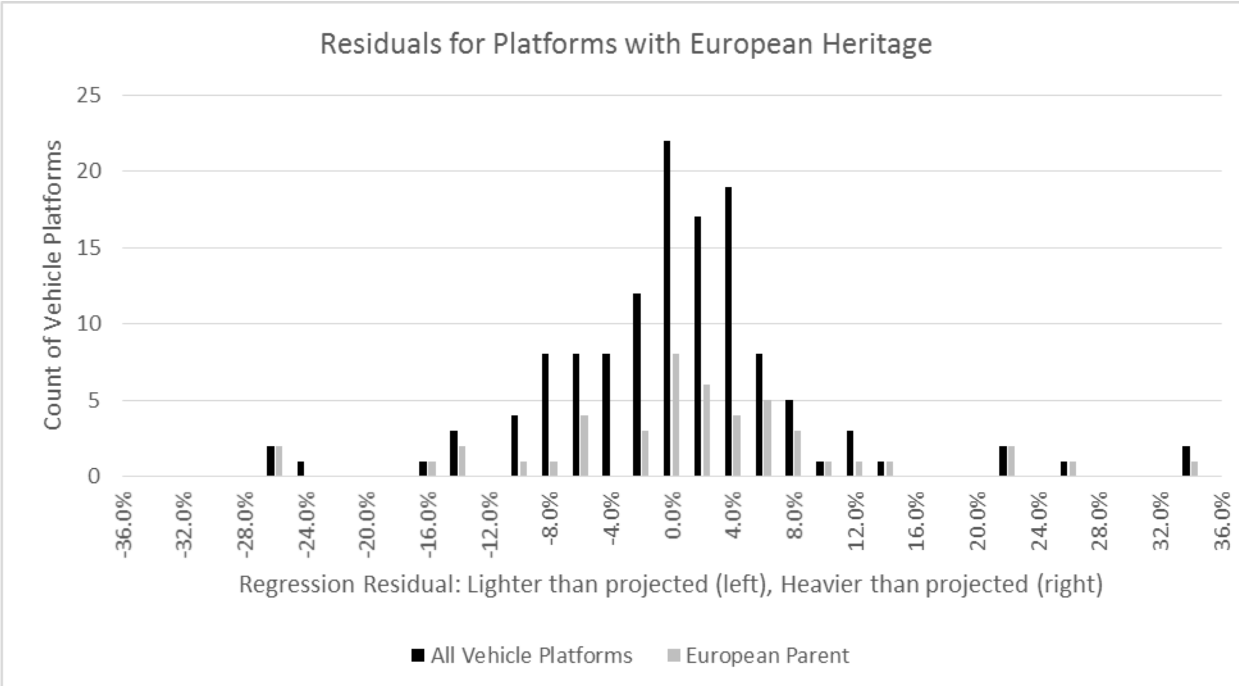

Figure 4.13 Mass Reduction Residuals for Platforms with European Heritage

Platforms with European heritage exhibit large variance and a modest skew towards positive residuals.

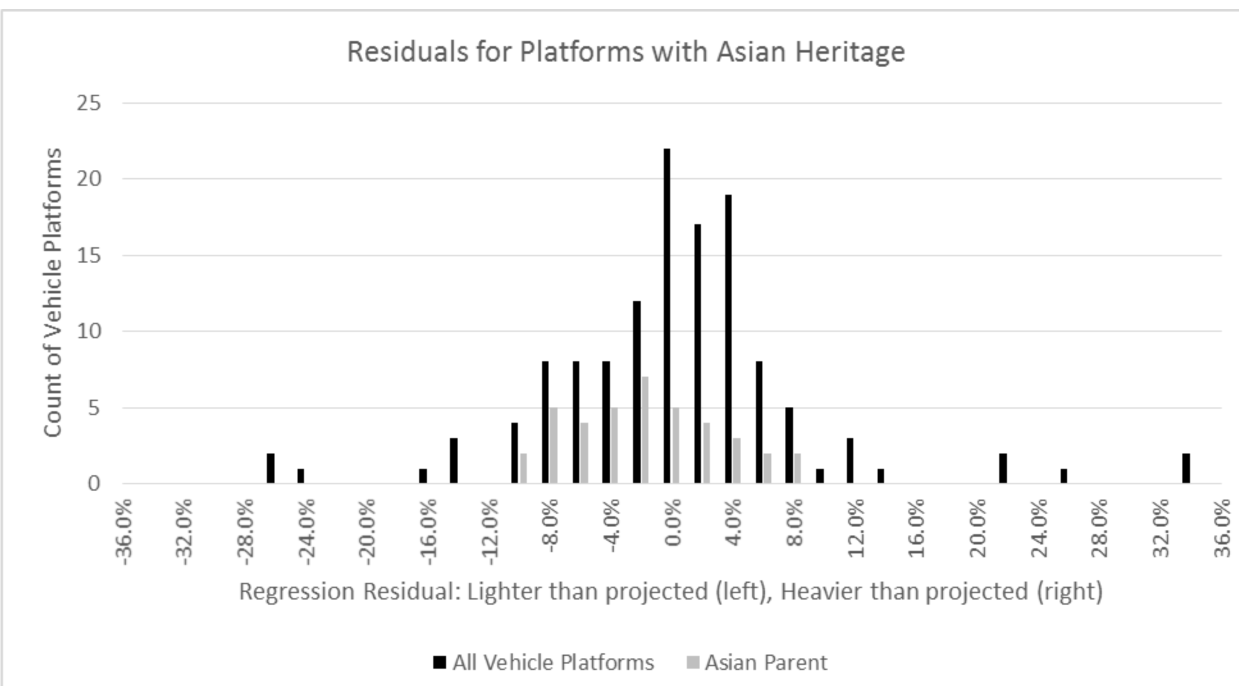

Figure 4.14 Mass Reduction Residuals for Platforms with Asian Heritage

4.2.10.2 Aerodynamic Application

Similar to mass reduction, NHTSA/Volpe Center staff used a relative performance approach to assign the current aerodynamic technology level to a vehicle. Different body styles offer different utility and have varying levels of baseline form drag. Additionally, frontal area is a major factor in aerodynamic forces, and the frontal area varies by vehicle. NHTSA/Volpe considered both frontal area and body style as utility factors that affect aerodynamic forces. NHTSA/Volpe computed an average coefficient of drag (Cd) for each body style segment in the 2015MY analysis fleet from drag coefficients published by manufacturers. By comparing coefficients of drag among vehicles that share body styles, the NHTSA/Volpe was able to estimate the level of aerodynamic improvement already present on specific vehicles.

NHTSA/Volpe Center staff assigned levels of aerodynamic technology to the 2015 fleet on a relative basis, based on the average aerodynamic drag coefficient (Cd) by body style and manufacturer reported drag coefficients. NHTSA calculated the average Cd for each body style by grouping vehicles by body style and then averaging the manufacturer reported or publicly available drag coefficients for each group.

In order for a vehicle to achieve AERO10, the aerodynamic drag coefficient needs to be at least 10 percent below the calculated average drag coefficient for the body style. In order to achieve AERO20, the Cd needs to be at least 20 percent better than the body style average. No aerodynamic application was assumed for vehicles with no manufacturer reported Cd.

The table below summarizes the best, worst, and average recorded Cd for each body style. The table also lists the thresholds for AERO10 and AERO20 that were used to assign an aerodynamic tech level for each vehicle.

Table 4.55 Aerodynamic Drag Coefficients by Body Style

Body style	Sample Size	Body style Average Cd	Body style Lowest Cd	Body style Highest Cd	AERO10	AERO20
Sedan	437	0.302	0.240	0.370	0.271	0.241
Coupe	175	0.319	0.240	0.440	0.287	0.255
Minivan	23	0.326	0.290	0.360	0.293	0.261
Hatchback	88	0.333	0.250	0.370	0.300	0.266
Convertible	92	0.334	0.290	0.410	0.301	0.267
Wagon	32	0.342	0.290	0.380	0.308	0.274
Sport Utility	346	0.363	0.300	0.540	0.327	0.290
Van	21	0.389	0.337	0.415	0.350	0.311
Pickup	361	0.395	0.360	0.420	0.355	0.316

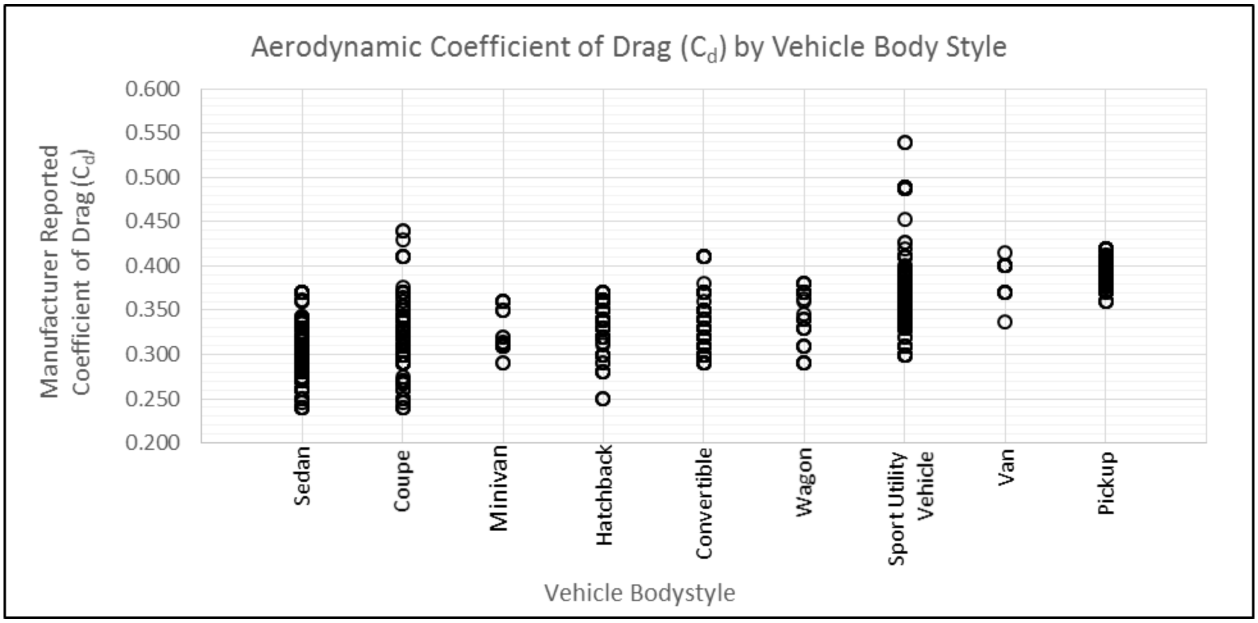

Figure 4.15 Distribution of Aerodynamic Drag Coefficients by Vehicle Body Style

Based on the results of the CAFE input assignment process, most manufacturers have the opportunity to further improve aerodynamic performance for a large portion of the fleet.

Table 4.56 Aerodynamic Application by Manufacturer as a Percent of MY2015 Sales

Manufacturer	AERO 0	AERO 10	AERO 20
BMW	86.7%	13.3%	0.0%
Daimler	41.7%	23.0%	35.3%
FCA	99.4%	0.6%	0.0%
Ford	100.0%	0.0%	0.0%
General Motors	99.8%	0.2%	0.0%
Honda	90.5%	9.5%	0.0%
Hyundai Kia	97.9%	2.1%	0.0%
JLR	100.0%	0.0%	0.0%
Mazda	100.0%	0.0%	0.0%
Mitsubishi	72.9%	27.1%	0.0%
Nissan	93.4%	6.6%	0.0%
SUBARU	100.0%	0.0%	0.0%
Tesla	0.0%	0.0%	100.0%
TOYOTA	74.4%	19.5%	6.2%
Volvo	88.8%	11.2%	0.0%
VWA	99.2%	0.8%	0.0%

NHTSA seeks comment on this approach to assigning initial levels of aerodynamic performance, and recommendations regarding any alternative approaches, taking into account the agency's representation of costs and fuel consumption impacts of additional aerodynamic improvements. The agency seeks any additional information that could be used to refine the agency's approach or develop and implement alternative approaches.

4.2.11 Projecting Future Volumes for the Analysis Fleet

In order to analyze the impact of alternative fuel economy standards in future model years, it was necessary to estimate vehicle production volumes for each manufacturer (and the models they offer for sale) in those years. Because the standards are based on the harmonic average of a manufacturer's fuel economy targets, which are themselves a function of vehicle footprint, the specific mix of vehicle footprints and regulatory classes that a manufacturer produces in each model year determines the standard for each manufacturer in that year.

The CAFE model operates at the level of specific model variants offered by each manufacturer (insofar as they vary by either footprint, fuel economy, or both), so any projection of future vehicle volumes must have a comparable resolution. For example, the MY2015 analysis fleet contains several variants of the Ford Fusion, where model variants are distinguished by drive type (FWD or AWD), engine type (cylinders, displacement), and degree of hybridization. So it was critical that our projection of future volumes produced estimated volumes for each variant of the Ford Fusion, rather than simply "the Fusion" or, even more coarsely, Ford's total volume within a market segment (of which "the Fusion" is a part).

To generate sales volumes for future model years, we combined three distinct sources of information about volumes. The first, and most fundamental, of these is the Mid-Model Year reports and attribute data that manufacturers supplied to NHTSA. These data informed decisions about the granularity of the model variants (how many different types of the Ford Fusion, for example, need to appear in the analysis fleet for modeling) and the relative sales of variants within a model and market segment for each manufacturer.

The second source of information used to project volumes is a proprietary production volume forecast that NHTSA purchased from IHS/Polk that covers the years from 2013 to 2032. This forecast contains volume projections for each vehicle model that is currently offered for sale in the United States (below 14,000 lbs GVW), as well as some legacy models that were phased out over the last two model years, and future models that have not yet been introduced in the U.S. market. Despite the high degree of resolution in the Polk forecast, modifications were required in order to match the level of resolution in the MY2015 analysis fleet. In particular, the model-level volume projections in the IHS/Polk forecast were insufficient to account for instances where one variant of a single model is regulated as a passenger car and another (typically a 4WD version) as a light truck. In those cases, we manually split the volume forecasts into a passenger car and a light truck variant based on the shares present in the Mid-Model Year submissions from manufacturers. We also treated the latest years of the forecast (2029 – 2032) as being static. While the Polk forecast shows changes in manufacturer market shares in those years, some of them abrupt, the discontinuities created by those changes are undesirable for a sequence of years that should primarily be driven by trend at that point[X]. However, the majority of the information in the Polk forecast was used, unaltered, to inform the volume projections for the analysis fleet.

The third source of volumes comes from a special set of runs of the National Energy Modeling System, NEMS, which forms the basis of the Energy Information Administration's Annual Energy Outlook 2015 (AEO 2015). These runs, rather than simulating fuel economy responses to the augural standards for 2022 – 2025 that NHTSA proposed in 2012, freeze the fuel economy standards at their 2021 level for the remainder of the model run, which continues to 2040. From these runs, we used the total volumes of passenger cars and light trucks (separately), synthesizing the three sources to approximately preserve these volumes for all future model years.

The three data sources were combined sequentially, and the process is depicted graphically in Figure 4.16, which shows the three data sources in blue and constructed elements in green.

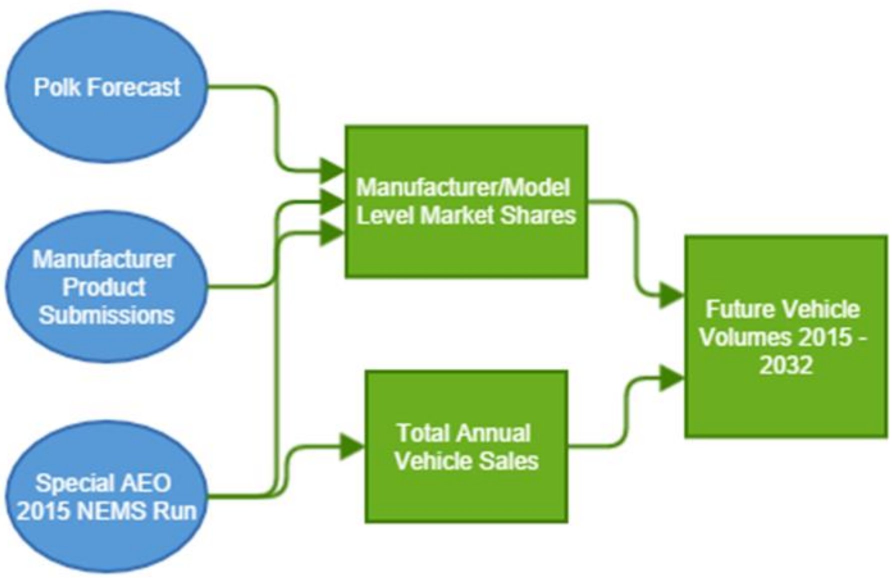

Figure 4.16 Data Sources and Construction of the Production Forecast

We constructed the manufacturer shares in each market segment by combining the AEO total volumes of passenger cars and light trucks for each (calendar) year with the IHS/Polk volumes for each manufacturer and body style within each of the passenger car/light truck categories. We distributed those volumes to each manufacturer's collection of unique model variants in each body style category based on each model's relative share in the data submitted by the manufacturers. It was necessary to ensure that the multiple categorizations of vehicle models

[X] In order to provide a forecast that covers all the years of concern for the Draft TAR, Polk combined information from a short-term forecasting model, and a long-term forecasting model. The years that would logically be driven by results from the long-term forecasting model were deemed insufficiently volatile for use in the primary forecast.

across the three sources were synchronized – so regulatory class, body style, and luxury brand (explained below) were added manually to either the IHS/Polk forecast, the manufacturer submissions, or both. We attempted to preserve the inherent market preferences represented by the relative market shares of different vehicle segments in the IHS/Polk forecast. However, there are many possible characterizations of these segments, most of them essentially arbitrary. With that in mind, we chose to use vehicle body style as a proxy for market segment in both the IHS/Polk forecast and the manufacturer data, ensuring that vehicle models were consistently categorized across the two sources. Since vehicle body style is a strong indicator of buyer usage and needs, it seemed a reasonable proxy for the market segments in which these vehicles exist.

In addition to offering a variety of body styles, many manufacturers have developed luxury brands that produce higher-end versions of models available in their other brands. Ford and Lincoln, for example, produce the Expedition and the Navigator, respectively, which share engines, transmissions and a common platform, but differ in styling and price. To the extent that the IHS/Polk forecast shows migration either to, or away from, luxury versions of comparable models between 2015 and 2032, we felt that distinction worth capturing in the synthesized forecast. It is less detailed than accounting for volumes within all of a manufacturer's brands (General Motors produces Buick, Chevrolet, GMC and Cadillac, for example), but superior to allocating luxury-brand volumes to non-luxury models (or vice versa).

We calculated the percentage of passenger car and light truck volumes, respectively, in the IHS/Polk forecast at the level of manufacturer, body style, and luxury brand (or not). Then we used the total number of passenger cars and light trucks from the AEO runs to calculate the total sales of each manufacturer's body style offerings, stratified by luxury (or not) and regulatory class. Those volumes were then allocated to the model variants in the market data file, based on the share of volumes for each model variant in the manufacturer, body style, luxury (or not) stratum. This process was applied such that the total volumes of passenger cars and light trucks estimated to be produced for the U.S. market aligns with corresponding volumes from AEO2015.

This process resulted in a market forecast that is broadly consistent with all three sources, without identically preserving the volumes, or shares, of any one. A consequence of the remixing described above is that, in some instances, we show manufacturers exiting the market (completely) for some body styles in future model years. The IHS/Polk forecast shows models entering and leaving the fleet, but we do not explicitly account for either in the synthesized forecast. In the case of new model entrants, the volumes associated with those were allocated to the remaining models in the manufacturer submissions that already exist within that body style, luxury, and regulatory class group based on their relative shares. In the case of models exiting the market segment, those volumes were also re-allocated to the models in that segment as of model year 2015. This implies that a manufacturer will always offer all of the current model variants in a given segment (as defined above) in future years, as long as the forecast shows them offering at least one model in that segment. If the Polk forecast shows a manufacturer exiting a market segment (as we've defined them) completely in some future year, then those volumes are not re-allocated to any models and are essentially lost to the manufacturer. While this was a rare occurrence, there are a few instances where this occurs in the synthesized forecast – particularly for later years.

The forecast used in NHTSA's Draft TAR analysis can be seen in full detail by downloading the CAFE Model's market data file. However, high level summaries of market shares by manufacturer appear in Figure 4.17 and Figure 4.18 for model years 2015 and 2025, respectively.

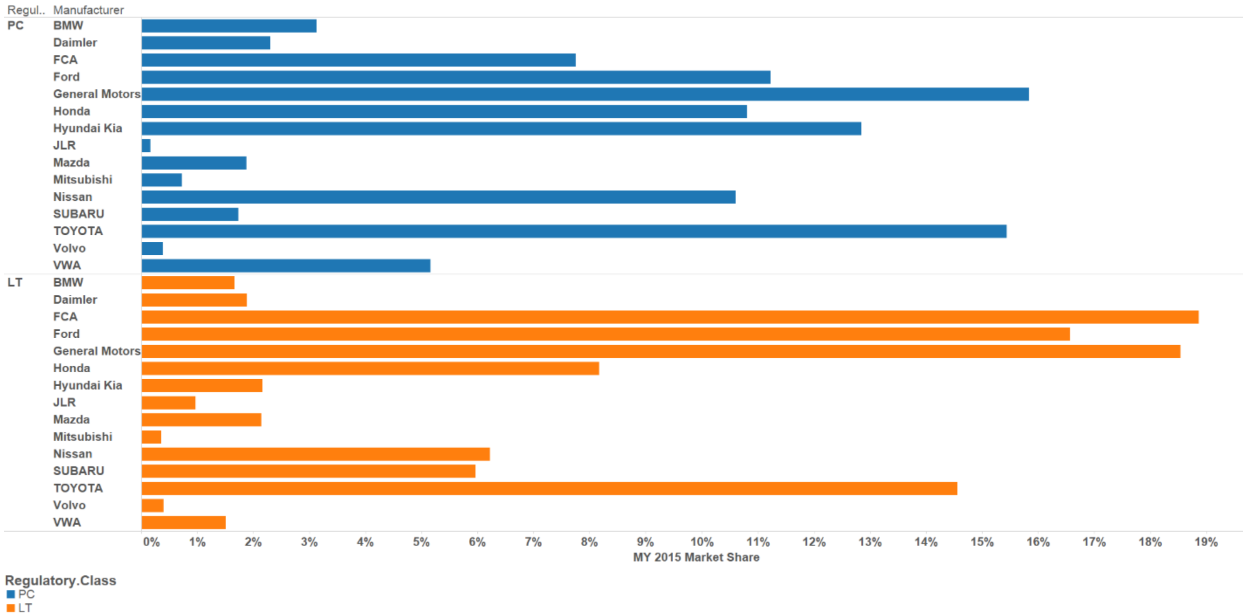

Figure 4.17 MY2015 Market Shares by Manufacturer

While some manufacturers are forecast to gain (or lose) market share between MY2015 and MY2025 (VW, for example, is forecast to gain small shares in both passenger car and light truck markets over the next decade), the changes are not dramatically different for any manufacturer relative to their current market shares.

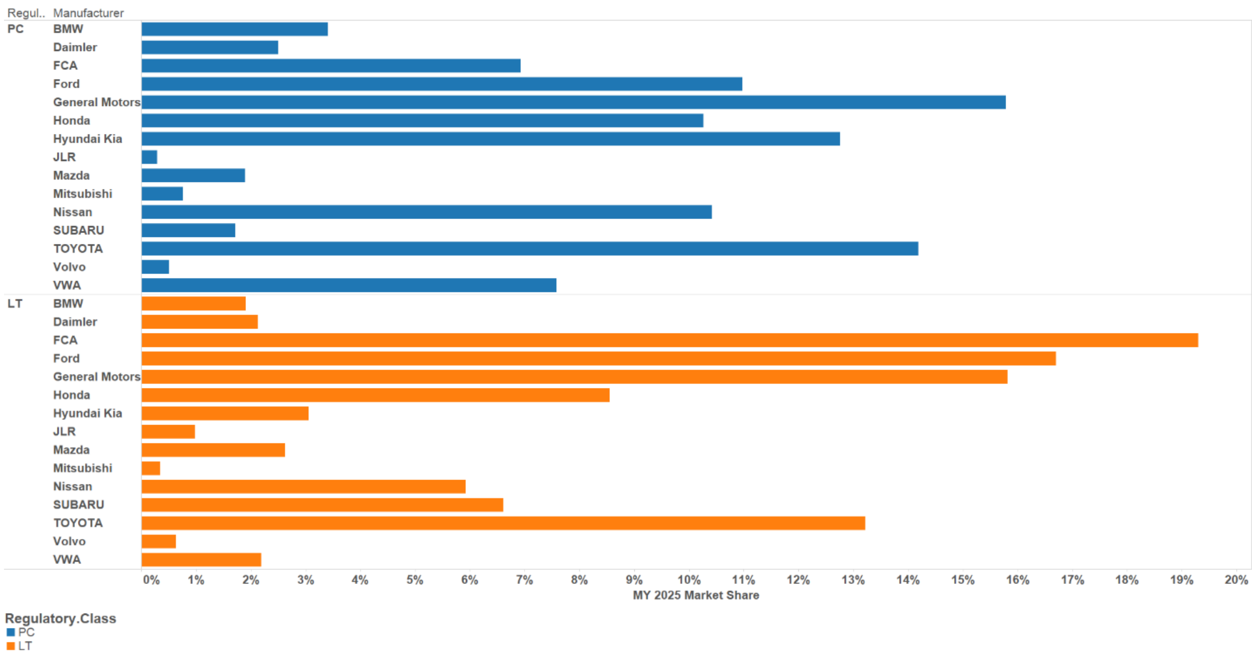

Figure 4.18 MY2025 Market Shares by Manufacturer

NHTSA seeks comment on the information and methods used to develop these estimates of future production volumes for specific vehicles, and recommendations and additional information that could be used to refine this approach or develop and implement alternative approaches.

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Chapter 5: Technology Costs, Effectiveness, and Lead-Time Assessment

5.1 Overview

The light-duty vehicle 2017-2025 final rule analysis was based on the agencies' assessment of technologies as of the 2012 calendar year timeframe. This included technologies that were currently in production at the time, or pending near term release, as well as consideration of further developments in technologies where reliable evidence was available. As described in Chapter 3, the penetration of these technologies into the fleet has proceeded steadily since then. The focus of this chapter is on the current state of technology and the likely future developments through MY2025, an explanation of all of the underlying new technical work that has been done to support the agencies' analyses, and a summary of the technology assumptions and inputs used. The agencies' modeling results are presented in Chapters 12 and 13 for the GHG and CAFE standards, respectively.

Throughout this initial phase of the Midterm Evaluation, EPA, NHTSA, and CARB have evaluated the state of technologies based on many sources including new vehicle certifications, internal full vehicle simulation modeling, technical literature reviews and technical conference information, vehicle manufacturer and supplier meetings, and the 2015 NAS report. This collaborative effort to collect information has produced a list of technologies for this report that builds upon that of the GHG and CAFE 2012 final rule assessments. At the same time, the CAFE and GHG assessments were done largely independently, due in part to differences in the agencies' statutory authorities and through independent decisions made in each agency. The agencies all agree that independent and parallel analyses can provide complementary results (as shown by the differing and mutually supporting analyses in sections III and IV, respectively, of both the MY 2012-2016 standard rulemaking preamble, and the 2017-2025 standards preamble). It is clear that the automotive industry is innovating and bringing new technology to market at a brisk pace and neither the GHG nor the CAFE analysis reflect all of the latest and emerging technology since the FRM.

While the cost, effectiveness,[A] and implementation feasibility of individual technologies are generally consistent with the compliance pathways projected in the FRM, some developments were not foreseen by the agencies. Several new technologies or unforeseen application of technologies are now under active development and some have emerged into the light-duty vehicle market since the LD 2017-2025 Final Rule was completed. These technologies include the application of direct injection Atkinson Cycle engines in non-hybrids, greater penetration of continuously variable transmissions (CVT) and greater market penetration of diesel engines. In addition, the development of several technologies has proceeded differently than was assumed in the FRM, including development of downsized turbo-charged engines, cylinder deactivation and vehicle electrification.

In general, the agencies have initially found the estimates of technology effectiveness used in the FRM to have been robust and accurate. Through analysis of current vehicle certification, benchmarking, literature reviews and modeling, the agencies have, in many cases, confirmed in

[A] The term 'effectiveness' is used throughout this Chapter to refer both to a reduction in tailpipe CO_2 emissions and a reduction in fuel consumption. In cases where the two are not equivalent (e.g., when changing fuel type), separate values are presented.

this initial analysis that the values used in the FRM are an appropriate estimate of technology effectiveness. This is not to imply that every manufacturer that has added technology has achieved the effectiveness estimated in the FRM. Some manufacturers have chosen to adopt technology and use it to improve other vehicle attributes, other than solely improving vehicle efficiency. These other attributes include 0 to 60 mph acceleration, increased cargo capacity, increased towing capability, and/or increased vehicle size and mass. Some applications of technology are in their first or second design iteration and we expect that each successive iteration will improve its effectiveness. One example of this is the emerging use of integrated and cooled exhaust manifolds and the resulting improved effectiveness from turbo-charged downsized engines. Vehicle manufacturers have adopted many examples of technologies that perform very well, such as the Mazda SKYACTIV-G® engine and the ZF 8-speed transmission, and when these technologies are combined with the sole intent of improving vehicle efficiency, our analysis shows that significant improvements from the baseline fleets are broadly achievable using conventional powertrains.

The agencies continue to assess technology as it becomes available and as it develops in the market and will revisit all of the technology effectiveness estimates for later steps of the midterm evaluation process, including the EPA's Proposed Determination and NHTSA's Notice of Proposed Rulemaking (NPRM). For several technologies, such as CVT's and Miller cycle engines, some ongoing projects were not completed at the time of publishing this Draft TAR; detailed benchmarking and simulation work will continue to be performed, and will be considered by the agencies as it becomes available. Further, there are longer-term research efforts underway that may be valuable in informing future technology developments, even beyond the timeframe of the 2025 standards. One such research program is the Department of Energy's Co-Optimization of Fuels and Engines initiative, which is working to accelerate the introduction of high-efficiency, low emissions engines and sustainable biofuels.[B] In addition to these and other examples of ongoing research on advancing technologies, the agencies will be considering new vehicle certifications, new work with regard to technology that is done in the public domain, and information that is shared by stakeholders in later steps of the midterm evaluation process and CAFE rulemaking. The agencies are therefore requesting public comments on vehicle technologies, including data on costs and effectiveness of technologies discussed here or additional information on technologies which could be in production in the 2022-2025 timeframe or are already in production today that may have been omitted from this Draft TAR.

This Chapter is organized to provide a complete description of the cost, effectiveness, and application of the technologies considered by the agencies in this technical assessment. We have included a brief review of the technology assessment used in the FRM as well as a summary of all the research that has been performed since the FRM to inform the Draft TAR. Finally, we discuss how we synthesized all of the various inputs to inform the final cost, effectiveness, and application conclusions.

Section 5.2 presents the agencies' joint assessment of the current state of technologies and the advancements that have occurred since the FRM. The agencies have reexamined every technology considered in the FRM, as well as assessing some technologies that are currently

[B] For more information see http://energy.gov/eere/bioenergy/co-optimization-fuels-engines.

commercially available but did not play a significant role in the FRM analysis, as well as emerging technology for which enough information is known that it may be included in this Draft TAR. The categories of technologies discussed in Section 5.2 include: engines, transmissions, electrification, aerodynamics, tires, mass reduction, and other vehicle technologies, such as improved accessories and low drag brakes. In addition, Section 5.2.9 provides an overview of the air conditioning efficiency and leakage credits, updates on test evaluations for the Idle Test and the AC17 air conditioning performance test, and a summary of the situation regarding low global warming potential (GWP) refrigerant. Section 0 concludes with a summary of the off-cycle credit program and an overview of how off-cycle credits have been used by manufacturers in their current compliance with the GHG program. This section also details how off-cycle credits have been considered in the Draft TAR analysis.

The final two sections of this chapter are devoted to presenting the details of the approaches, assumptions, and technology inputs used in the agencies' independent assessments; beginning in Section 5.3 with the technology assessment that forms the basis of the analysis of the GHG standards, followed by the technology assessment for the CAFE program in Section 5.4.

The particular details of the technology assessment for the GHG analysis begin in Section 5.3.1 with a description of the fundamental assumptions for fuels, performance neutrality, and cost and effectiveness measurement that underpin the technical analysis.

Section 5.3.2 focuses on the overall costing methodologies used in the GHG analysis which include the determination of both direct and indirect costs, as well as the application of learning and maintenance and repair costs. The methodologies used to develop technology costs remain largely unchanged from the FRM. However, all of the technology cost inputs have been reevaluated based on any new information available since the FRM. In some cases, the costs used in the FRM were determined to remain the most appropriate; in other cases, cost values have been updated, including transmissions due to updates to the teardown results used in the FRM, and battery costs due to updates to the model upon which the FRM's battery costs were based. Further, we have updated the costs for 24-bar turbocharged packages to include additional costs associated with variable geometry turbochargers, as well as updating mass reduction costs based on teardown studies completed since the FRM. Importantly, we have also added new technologies that were not considered in the FRM, notably a direct injection Atkinson Cycle engine and a 48 Volt mild-hybrid.

Section 5.3.3 describes the approach used for determining technology effectiveness in the GHG analysis. Vehicle benchmarking is at the foundation of the EPA's analysis for technology effectiveness and a description of the benchmarking testing conducted by the EPA can be found in Section 5.3.3.1. The benchmarking data have been used largely to inform EPA's full vehicle simulation model, ALPHA, and information regarding vehicle modeling is provided in Section 5.3.3.2. EPA has also estimated the effects of adding technology to existing powertrains using Gamma Technology's GT Power model and the results of this investigation can be found in Section 5.4.1. Finally, EPA continues to apply the Lumped Parameter Model (LPM) to efficiently estimate the overall effectiveness of technology packages, and the updates to the LPM and its application in the Draft TAR is described in Section 5.3.3.4.

In Section 5.3.4, EPA describes the specific data and assumptions for individual technologies that are used in the GHG analysis in this Draft TAR. Informed by all of the information on the state of technologies described in Section 5.2, these inputs and assumptions for cost, effectiveness, and technology application are used in the OMEGA model determination of the cost-minimizing compliance pathway presented in Chapter 12.

Section 5.4 presents the approaches, methodologies, and inputs used in the technology assessment for the CAFE analysis.

Section 5.4.1 describes the methodologies for estimating technology costs in the CAFE analysis, and particular cost assumptions for individual technologies.

Section 5.4.2 provides detail on NHTSA's evaluation of technology effectiveness based on vehicle benchmarking, engine simulation using the GT Power model and full vehicle simulation modeling using Argonne National Laboratory's Autonomie model.

Some of the technologies considered for this Draft TAR for which there are notable updates from the FRM analysis are summarized below. The full discussion of these updates is provided throughout the remaining sections of this chapter.

- Direct Injection Atkinson Cycle Engine
    - In the FRM, the use of Atkinson Cycle engines was primarily considered in HEV applications. In the last few years, a new generation of naturally-aspirated SI Atkinson Cycle engines applicable outside of HEVs have been introduced into light-duty vehicle applications. The most prominent application of this technology is the Mazda SKYACTIV-G® system. It combines direct injection, an ability to operate over an Atkinson Cycle with increased expansion ratio, wide-authority intake camshaft timing, and an optimized combustion process. This type of engine operation is not limited to naturally aspirated engines and when applied to boosted engines is referred to as "Miller Cycle," as described below.

- Turbocharged, Downsized Engines
    - In the FRM, turbocharged, downsized engines were anticipated to be a prominent technology applied by vehicle manufacturers to improve vehicle powertrain efficiency.
    - The penetration rate of turbo-downsized engines into the light-duty fleet has increased from 3 percent in 2008 to 16 percent in 2014.[1]
    - Turbocharged, downsized engines are beginning to adopt head-integrated exhaust manifolds or separate, water-cooled exhaust manifolds. These systems also use separate coolant loops for the head/manifold and for the engine block. The changes allow faster warmup, improved temperature control of critical engine components, further engine downspeeding, and reduce the necessity for commanded enrichment for component protection. The net result is improved efficiency over the regulatory cycles and during real world driving. Engine downspeeding also has synergies with recently developed, high-gear-ratio spread transmissions that may result in further drive cycle efficiency improvements.

- Direct Injection Miller Cycle Engine
    - This new generation of turbocharged GDI engine combines direct injection, the ability to operate over a Miller Cycle (boosted Atkinson Cycle) with increased

expansion ratio, wide-authority intake camshaft timing, and an optimized combustion process.

- Turbocharger Improvements
  - Newer turbochargers have been developed that reduce both turbine and compressor inertia allowing faster turbocharger spool-up.
  - Improvements have been made to broaden the range of compressor operation before encountering surge and to improve compressor efficiency at high pressure ratios.
  - The introduction of head-integrated exhaust manifolds or separate, water-cooled exhaust manifolds reduces exhaust turbine inlet temperatures under high-load conditions and improves exhaust temperature control. This allows the use of less expensive, lower temperature materials for the turbine housing and exhaust turbine. Reduced turbine inlet temperatures also allow the introduction of turbochargers with variable nozzle turbines into SI engine applications, similar to those used in light-duty diesel applications.
  - Twin-scroll turbochargers are finding broad application in turbocharged, downsized GDI engines. Twin-scroll turbochargers improve turbocharger spool-up and improve torque output at lower engine speeds, allowing further engine downspeeding.
  - Turbochargers with variable nozzle turbines (VNT) are now common in light-duty diesel applications and are under development for gasoline spark ignition engines, particularly those that use cooled EGR and head-integrated exhaust manifolds.

- Cylinder Deactivation
  - Cylinder deactivation applied to engines with less than six cylinders was not analyzed as part of the FRM. Further developments in NVH (noise, vibration, and harshness) abatement, including the use of dual-mass dampening systems, has resulted in the recent introduction of a 4-cylinder/2-cylinder engine into the European light-duty vehicle market.
  - The development of rolling or dynamic cylinder deactivation systems allows a further degree of cylinder deactivation for odd-cylinder (e.g., 3-cylinder, 5-cylinder) inline engines than was possible with previous cylinder deactivation system designs.
  - Both 3-cylinder/2-cylinder and 3-cylinder/1.5-cylinder (rolling deactivation) designs are at advanced stages of engine development

- Variable Geometry Valvetrain Systems
  - In the FRM, variable geometry valvetrain systems, including those that vary valve timing and/or valve lift, were anticipated in the FRM to be a major technology for reducing engine pumping losses.

- Continuously Variable Transmissions (CVT)

  - A new generation of CVTs has been introduced into the LD market by several major OEMs. These new CVTs have significant improvements in the areas of efficiency, integration, and customer acceptance over the previous generation.
  - Early CVTs had various customer acceptance issues mainly due to lack of positive shift feel typical in a conventional automatic transmission. Recent changes to transmission control strategies include an index shift, providing the consumer with an experience that more closely resembles a conventional automatic transmission. These changes in shift strategies may or may not result in a small decrease in overall powertrain efficiency; however, the bulk of the customer acceptance issues have been addressed and CVTs have become very popular.

- Dual Clutch Transmissions (DCT)
  - Initial implementation of DCTs, mostly in non-performance vehicles, were accepted in Europe but were not widely accepted in the North American market. Launch and shift characteristics differed from conventional automatic transmission performance affecting some consumer acceptance in the United States. However, strategies have been developed to improve overall DCT operational characteristics.
  - Damp Dual Clutch Transmission (DCT)
    - The Damp Clutch DCT combines the improved durability and drivability of the Wet Clutch DCT with the efficiency of a Dry Clutch DCT.
  - Torque Converter Dual Clutch Transmission
    - The addition of a torque converter as a launch device greatly improves operational characteristics and eliminates the need for complex crankshaft dampers and other NVH technologies. The elimination of these NVH technologies approximately offsets the additional cost of the torque converter.
  - HEV or Mild Hybrid
    - Integrating a DCT into either HEV or low-voltage, 48V P2 drive systems provides improved launch assist, low-speed creep capability, and torque between shifts comparable to the driving characteristics of a torque-converter/planetary gear-set automatic transmission.

- Vehicle Electrification
  - The sales of hybrid products have been negatively impacted by lower fuel prices and improvements in the efficiency of conventional vehicles that are, in many cases, closing the fuel economy gap between hybrid and conventional vehicles.
  - While stop-start has been in production for a considerable amount of time in Europe (a predominantly manual transmission market), some of the initial product offerings had consumer feedback concerns. Recent vehicles introduced with stop-start that were specifically designed for the U.S. market, such as the Chevrolet Malibu, have been met with very good reviews. Indications from suppliers are that further improvements, including the use of continuously engaged starters, are under development.
  - Low Voltage Mild Hybrid

- A new generation of Mild Hybrid technologies has been introduced into the LD market using a nominal 48 volt electrical system that features the elimination of costly high voltage safety requirements and leverages the use of lower cost battery technologies. An effectiveness close to that of higher-voltage mild hybrids can be achieved by significantly reducing battery pack weight, and by eliminating active battery pack cooling hardware and heavy 3-phase AC cables.

5.2 State of Technology and Advancements Since the 2012 Final Rule

Since the 2017-2025MY GHG standards were established in 2012, efficiency technologies have been developed further and steadily implemented by manufacturers over a broad range of vehicles. Many of these are key technologies that factored prominently in the FRM analysis, such as direct injection, turbocharging and downsizing, and higher gear count transmissions. The goal of improving cost-effectiveness is a consistent driver of innovation, and the resulting advancement that is occurring for even previously established technologies necessitates a re-evaluation of cost, effectiveness, and implementation for this analysis. For example, the light-weight materials, aerodynamic features, and dual-clutch transmissions applied initially to high-performance and luxury vehicles are requiring more cost-effective implementations and different consumer considerations for their successful adoption in mass-market vehicles.

Other technologies that were known, but not included previously, have continued to evolve and are now being applied in ways that were not expected or considered at the time of the FRM analysis. Direct injection Atkinson Cycle engines have been applied to non-hybrids successfully, and continuously variable transmissions are contributing to high powertrain efficiencies in applications that have been well-received by consumers and expert reviewers.

Still other technologies have emerged since the FRM analysis which were previously thought to be beyond the 2017-2025MY timeframe, but now appear promising or even likely due to further innovation and development. Mild hybrid electric vehicles with 48 volt electrical systems are one example that have undergone substantial testing and development by multiple suppliers, and have demonstrated significant efficiency benefits with lower complexity and system cost compared to strong hybrid systems or higher voltage mild hybrid systems.

5.2.1 Individual Technologies and Key Developments

The technologies considered for this Draft TAR are briefly described below. They fit generally into four broad categories: engine, transmission, vehicle, and electrification technologies. A more detailed description of each technology, and the technology’s costs and effectiveness, is described in greater detail later in this section. These technologies were also considered in the FRM unless otherwise noted.

Types of engine technologies applied in this Draft TAR analysis to improve fuel economy and reduce CO_2 emissions include the following:

- *Low-friction lubricants* – low viscosity and advanced low friction lubricants oils are now available with improved performance and better lubrication.
- *Reduction of engine friction losses* – can be achieved through low-tension piston rings, roller cam followers, improved material coatings, more optimal thermal management, piston surface treatments, cylinder wall treatments and other

improvements in the design of engine components and subsystems that improve engine operation.

- *Second level of low-friction lubricants and engine friction reduction* – As technologies advance between now and the rulemaking timeframe, there will be further developments enabling lower viscosity and lower friction lubricants and more engine friction reduction technologies available, including the use of roller bearings for balance shaft systems and further improvements to surface treatment coatings.
- *Cylinder deactivation* – deactivates the intake and exhaust valves and prevents fuel injection into some cylinders during light-load operation. The engine runs temporarily as though it were a smaller displacement engine with fewer cylinders which substantially reduces pumping losses.
- *Variable valve timing* – alters the timing or phase of the intake valve, exhaust valve, or both, primarily to reduce pumping losses, increase specific power, and control residual gases.
- *Discrete variable valve lift* – increases efficiency by optimizing air flow over a broader range of engine operation which reduces pumping losses. Accomplished by controlled switching between two or more cam profiles.
- *Continuous variable valve lift* – an electromechanically controlled system in which cam period and phasing is changed as lift height is controlled. This yields a wide range of performance optimization and volumetric efficiency, including enabling the engine to be valve throttled.
- *Stoichiometric gasoline direct-injection technology* – injects fuel at high pressure directly into the combustion chamber to improve cooling of the air/fuel charge within the cylinder, which allows for higher compression ratios and increased thermodynamic efficiency.
- *Turbocharging and downsizing* – increases the available airflow and specific power level, allowing a reduced engine size while maintaining performance. This reduces pumping losses at lighter loads in comparison to a larger engine. In this Draft TAR, the agencies considered two levels of boosting, 18 bar brake mean effective pressure (BMEP) and 24 bar, as well as four levels of downsizing, from I4 to smaller I4 or I3, from V6 to I4 and from V8 to V6 and I4. 18 bar BMEP is applied with 33 percent downsizing and 24 bar BMEP is applied with 50 percent. To achieve the same level of torque when downsizing the displacement of an engine by 50 percent, approximately double the manifold absolute pressure (2 bar) is required. Engine downsizing to 27 bar BMEP used in the 2017-2025 FRM was not considered in this Draft TAR.
- *Atkinson Cycle Engines* - combine a substantial increase in geometric compression ratio[C] (in the range of 12.5 - 14:1) and alters intake valve event timing to provide

[C] Geometric compression ratio is a ratio of the piston clearance volume + displacement swept volume to the displacement swept volume in a reciprocating piston engine. The actual effective compression ratio and expansion ratio must also take into account valve events governing the actual flows involved in the combustion process. Effective compression ratio and expansion ratios for typical Otto-cycle engines are nearly equivalent and governed by the chosen geometric compression ratio. Atkinson and Miller Cycle engines lower the trapped air or air-fuel charge volume during intake via either late intake valve closing or early intake valve closing to reduce effective compression ratio while simultaneously increasing effective expansion ratio. This is done by reducing the piston clearance volume and thus increasing the geometric compression ratio.

much later intake valve closing (LIVC). This lowers the trapped air charge, effectively lowering actual compression ratio to reduce knock limited operation while maintaining the expansion ratio for improved efficiency. Although producing lower torque at low engine speeds for a given displacement, this engine has specific high efficiency operating points and is capable of significant CO_2 reductions when properly matched to a strong hybrid system. Electric motor/generators produce high torque at low speeds are thus are capable offsetting low engine speed torque deficiencies with Atkinson Cycle engines.

- *Direct Injection Atkinson Cycle Engines* - combine direct injection, a substantial increase in geometric compression ratio (in the range of 13 - 14:1), wide authority intake camshaft timing, variable exhaust camshaft timing and an optimized combustion process enabling significant reductions in CO_2 as compared to a standard direct injected engine. This engine is capable of changing the effective compression ratio (i.e., varying the degree of Atkinson operation) by varying intake valve events. The ability to reduce pumping losses over a large area of operation may allow avoidance of the additional cost of higher gear count transmissions. The Mazda SKYACTIV-G engine is one example of this technology. This technology was not considered in the FRM.
- *Miller Cycle Engines* - combine direct injection, a substantial increase in geometric compression ratio relative to other boosted engines, wide authority intake camshaft timing, and variable exhaust camshaft timing, and an optimized combustion process enabling significant reductions in CO_2 as compared to a standard direct injected engine. This is essentially Atkinson Cycle with the addition of a turbocharger boosting system. The addition of a turbocharger improves volumetric efficiency and broadens the areas of high-efficiency operation. The ability to reduce pumping losses over a large area of operation may allow avoidance of the additional cost of higher gear count transmissions. This technology was not considered in the FRM.
- *Exhaust-gas recirculation with boost* – increases the exhaust-gas recirculation used in the combustion process to increase thermal efficiency and reduce pumping losses. Peak levels of exhaust gas recirculation approach 25 percent by volume in these highly boosted engines (this, in turn raises the boost requirement by approximately 25 percent). This technology is only applied to 24 bar BMEP and Miller cycle engines in this Draft TAR. The 27 bar BMEP engine used in the FRM was not considered for this Draft TAR.
- *Diesel Engines* – have several characteristics that give superior fuel efficiency, including reduced pumping losses due to lack of (or greatly reduced) throttling, and a combustion cycle that operates at higher compression ratio and expansion ratios, with a very lean air/fuel mixture, than an equivalent-performance gasoline engine. This technology requires additional enablers, such as use of NOx adsorption exhaust catalyst (NAC), selective catalytic reduction (SCR) of NOx, or a combination of both NAC and SCR NOx catalytic after-treatment.

Transmission technologies considered in this Draft TAR include:

- *Improved automatic transmission controls* – optimizes shift schedule to maximize fuel efficiency under wide ranging conditions, and minimizes losses associated with torque converter slip through lock-up or modulation.

- *Six, seven, and eight-speed automatic transmissions* – the gear ratio spacing and transmission ratio are optimized to enable the engine to operate in a more efficient operating range over a broader range of vehicle operating conditions.
- *Dual clutch transmission (DCT)* - are similar to a manual transmission, but the vehicle controls shifting and launch functions. A dual-clutch automated shift manual transmission uses separate clutches for even-numbered and odd-numbered gears, so the next expected gear is pre-selected, which allows for faster, smoother shifting.
- *Continuously Variable Transmission (CVT)* – uses a belt between two variable ratio pulleys allowing an infinite set of gear ratios to enable the engine to operate in a more efficient operating range over a broad range of vehicle operating conditions.
- *Shift Optimization* – targets engine operation at the most efficient point for a given power demand. The shift controller emulates a traditional Continuously Variable Transmission by selecting the best gear ratio for fuel economy at a given required vehicle power level to take full advantage of high BMEP engines. The shift controller also incorporates boundary conditions to prevent undesirable operation such as shift busyness and NVH issues.
- *Manual 6-speed transmission* – offers an additional gear ratio, often with a higher overdrive gear ratio, than a 5-speed manual transmission.
- *High Efficiency Gearbox (automatic, DCT, CVT, CVT, or manual)* – continuous improvement in seals, bearings and clutches, super finishing of gearbox parts, and development in the area of lubrication, all aimed at reducing frictional and other parasitic load in the system for an automatic, DCT or manual type transmission.

Types of vehicle technologies applied in this Draft TAR analysis include:

- *Low-rolling-resistance tires* – have characteristics that reduce frictional losses associated with the energy dissipated in the deformation of the tires under load, thereby reducing the energy needed to move the vehicle. There are two levels of rolling resistance reduction considered in this Draft TAR analysis targeting at 10 percent and 20 percent rolling resistance reduction respectively.
- *Low-drag and zero drag brakes* – reduce the sliding friction of disc brake pads on rotors when the brakes are not engaged because the brake pads are pulled away from the rotors.
- *Secondary axle disconnect for four-wheel drive systems* – provides a torque distribution disconnect between front and rear axles when torque is not required for the non-driving axle. This results in the reduction of associated parasitic energy losses.
- *Aerodynamic drag reduction* – is achieved by changing vehicle shapes, reducing frontal area, sealing gaps in body panels, or adding additional components including side trim, air dams, underbody covers, and more aerodynamic side view mirrors. There are two levels of aerodynamic drag reduction considered in this Draft TAR analysis targeting 10 percent and 20 percent aerodynamic drag reduction respectively.
- *Mass reduction* – encompasses a variety of techniques ranging from improved design and better component integration to application of lighter and higher-strength materials. Mass reduction can lead to collateral fuel economy and GHG benefits due

to downsized engines and/or ancillary systems (transmission, steering, brakes, suspension, etc.).

Types of electrification/accessory and hybrid technologies considered in this Draft TAR include:

- *Electric power steering (EPS)* - An electrically-assisted steering system that has advantages over traditional hydraulic power steering because it replaces a continuously operated hydraulic pump, thereby reducing parasitic losses from the accessory drive.
- *Improved accessories (IACC)* – There are two levels of IACC applied in this Draft TAR analysis. The first level may include high efficiency alternators, electrically driven (i.e., on-demand) water pumps and cooling systems. This excludes other electrical accessories such as electric oil pumps and electrically driven air conditioner compressors. The second level of IACC includes alternator regenerative braking on top of what are included in the first level of IACC.
- *Air Conditioner Systems* – These technologies include improved hoses, connectors and seals for leakage control. They also include improved compressors, expansion valves, heat exchangers and the control of these components for the purposes of improving tailpipe CO_2 emissions and fuel economy when the A/C is operating.
- *Non-hybrid 12-volt Stop-Start* – Also known as idle-stop or 12V micro hybrid and is the most basic system that facilitates idle-stop capability. This system typically includes an enhanced performance starter and battery.
- *Mild Hybrid* – Provides idle-stop capability and launch assistance and uses a higher voltage battery with increased energy capacity over typical automotive batteries. The higher system voltage allows the use of a smaller, more powerful electric motor and reduces the weight of the motor, inverter, and battery wiring harnesses. This system replaces a standard alternator with an enhanced power, higher voltage, higher efficiency belt-driven starter-alternator which can recover braking energy while the vehicle slows down (regenerative braking). An example of a 100 volt system is the GM Chevrolet Malibu eAssist system. Next generation mild hybrid systems scheduled for production starting in 2017 include versions running at 48 volts that significantly reduce cost by using lower cost batteries, lower cost electrical components, and eliminating high voltage safety systems.
- *P2 Hybrid* – P2 hybrid is a hybrid technology that uses a transmission integrated electric motor placed between the engine and a gearbox or CVT, with a wet or dry separation clutch which is used to decouple the motor/transmission from the engine. In addition, a P2 Hybrid would typically be equipped with a larger electric machine than a mild hybrid system but smaller than a power-split hybrid architecture. Disengaging the clutch allows all-electric operation and more efficient brake-energy recovery. Engaging the clutch allows efficient coupling of the engine and electric motor and based on simulation, when combined with a DCT transmission, provides similar efficiency to other strong hybrid systems.
- *Power-split Hybrid (PSHEV)* –A hybrid electric drive system that replaces the traditional transmission with a single planetary gear-set and two motor/generators.

The smaller motor/generator uses the engine to either charge the battery or supply additional power to the drive motor. The second, more powerful motor/generator is permanently connected to the vehicle's final drive and always turns with the wheels, as well as providing regenerative braking capability. The planetary gear-set splits engine power between the first motor/generator and the output shaft to either charge the battery or supply power to the wheels. The Power-split hybrid provides similar efficiency to other strong hybrid systems.

- *Plug-in hybrid electric vehicles (PHEV)* – Are hybrid electric vehicles with the means to charge their battery packs from an outside source of electricity (usually the electric grid). These vehicles have larger battery packs than non-plug-in hybrid electric vehicles with more energy storage and a greater capability to be discharged. They also use a control system that allows the battery pack to be substantially depleted under electric-only or blended mechanical/electric operation, allowing for reduced fuel use during "charge depleting" operation.
- *Battery electric vehicles (BEV)* – Are vehicles with all-electric drive and with vehicle systems powered by energy-optimized batteries charged from an outside source of electricity (usually the electric grid). BEVs with 75 mile, 100 mile and 200 mile ranges have been included as potential technologies.

5.2.2 Engines: State of Technology

Internal combustion engine improvements continue to be a major focus in improving the overall efficiency of light-duty vehicles. While the primary type of light-duty vehicle engine in the United States is a gasoline fueled, spark ignition (SI), port-fuel-injection (PFI) design, it is undergoing a significant evolution as manufacturers work to improve engine brake thermal efficiency (BTE) from what has historically been approximately 25 percent to BTE of 37 percent and above. This focus on improving gasoline SI engines has resulted in the adoption of technologies such as gasoline direct injection (GDI), turbo-charging and downsizing, Atkinson Cycle, Miller Cycle, increased valve control authority through variable valve timing and variable valve lift, integrated exhaust manifolds, reduced friction, and cooled EGR. Vehicle manufacturers have more choices of technology for internal combustion engines than at any previous time in automotive history and more control over engine operation and combustion. In addition, manufacturers have access to improved design tools that allow them to investigate and simulate a wide range of technology combinations to allow them to make the best decisions regarding the application of technology into individual vehicles. Despite the access to improved tools and simulation, EPA believes that manufacturers have not yet explored the entire design space of modern powertrain architectures and that innovation will continue resulting in improvements in efficiency that are beyond what is currently being demonstrated in the new car fleet.

As discussed in Chapter 3, the use of many of the major powertrain technologies analyzed in the 2012 FRM, including engine technologies such as VVT, direct injection, turbocharging, and cylinder deactivation have increased since the publication of the FRM and appear to be trending towards EPA projections of technology penetration levels from the 2017-2025 FRM analysis (see Chapter 3). Engines equipped with GDI are projected to achieve a 46 percent market share in MY2015. Approximately 18 percent of new vehicles are projected to be equipped with turbochargers for MY2015. Use of cylinder deactivation has grown to capture a projected 13 percent of light-duty vehicle production for MY2015. Light duty diesel vehicles are projected to increase to a projected 1.5 percent of new vehicle production for MY2015, which is the highest level since MY1984. Recently introduced light-duty diesels in the U.S. include several new pickup truck (2015 Ram 1500, 2016 Chevrolet Colorado, 2016 GMC Canyon) and SUV (2015 Jeep Grand Cherokee, 2016 Land Rover Range Rover, Mercedes GLE300 and GLE350) models.

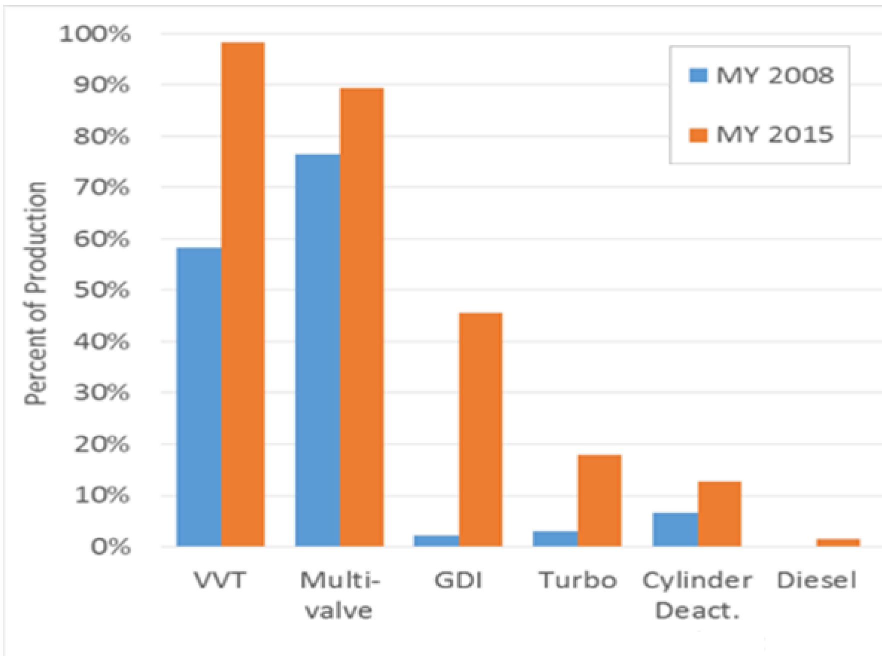


Figure 5.1 Light-duty Vehicle Engine Technology Penetration since the 2012 Final Rule

5.2.2.1 Overview of Engine Technologies

Since the FRM, the agencies have continued to meet with automobile manufacturers, major Tier 1 automotive suppliers and major automotive engineering services firms to review both public and confidential data on the development of advanced internal combustion engines for MY2022 and later. A considerable amount of new work has been completed both within the agencies and within industry and academia that is available for consideration for the Draft TAR. The agencies have completed several engine benchmarking programs that have produced detailed engine maps. These engine maps represent some of the best performing engines available today and have been used in the ALPHA and Autonomie models to directly estimate the effectiveness of modern powertrain technology being applied to a wide spectrum of vehicle applications. In addition, industry and academia regularly publishes similar levels of detail with regard to engine operation in the public domain, and the agencies have also used this information to either directly inform or to compare effectiveness estimations.

In addition to creating detailed engine maps for full vehicle simulation, the agencies conducted proof-of-concept, applied research to investigate the potential for further engine improvements. This includes the use of both computer-aided engineering tools and the development and analysis of advanced engine technologies via engine dynamometer testing. Further details are provided in Section 5.4.

In meetings with automobile manufacturers and Tier 1 suppliers, we learned about both convergent and divergent engine technologies trends. In many cases, it was difficult to obtain information on specific engine technologies beyond MY2022. Through MY2022, with few exceptions, gasoline direct injection and VVT will be applied to most engines. Significant attention will be placed on reducing engine friction and accessory parasitic loads. In passenger car and smaller light-duty truck segments, there will be considerable diversity of engine technologies, including turbocharged GDI engines with up to 25-bar BMEP, both turbocharged and naturally aspirated GDI engines with external cooled EGR, and engines that combine GDI with operation over the Atkinson Cycle and use of Atkinson Cycle outside of HEV applications. With respect to larger, heavier vehicles, including full-size SUVs and pickup trucks with significant towing utility, some manufacturers will be relying on naturally aspirated GDI engines with cylinder deactivation, some will be relying more on turbocharged-downsized engines, and others will be using a variety of engine technologies, including light-duty diesels. Vehicle manufacturers are at advanced stages of research with respect to:

- Stratified-charge, lean-burn combustion
- Multi-mode combustion approaches
  - homogenous charge, compression ignition, lean-burn operation at light loads
  - stratified-charge, lean-burn spark ignition at moderate loads
  - stoichiometric homogenous charge, spark ignition at high loads
- Variable-compression ratio (VCR) engines
- Engines exceeding 24-bar BMEP

While the introduction of variable compression ratio engines and highly boosted GDI engines above 24-bar BMEP is expected within the 2022-2025 timeframe, these technologies will most likely be introduced into relatively low-volume, high performance applications. Manufacturers and suppliers are finding that turbocharged engines can achieve lower CO_2 emissions over the regulatory drive cycles and improved real-world fuel economy at more moderate (24 bar and below) BMEP levels. While there are both performance and efficiency advantages to VCR at high BMEP levels, both Atkinson Cycle and Miller Cycle with VVT are technologies that compete with VCR and that have a comparable ability to vary effective compression ratio but with reduced cost and complexity.

We also learned from manufacturers and suppliers that specific engine technologies have synergies with other CO_2-reduction technologies. For example, measures to reduce engine friction, particularly friction at startup, help reduce the motor torque necessary for restart in 12V start/stop systems. GDI and electric cam phasing systems can be used for combustion assistance of engine restart. There are also synergies between Miller Cycle, IEM, cooled-EGR, and the use of VNT turbochargers which are described in more detail in Section 5.2.2.7.

Despite recent EPA and California ARB compliance actions with respect to light-duty diesel NOx emissions, diesel engines remain a technology for the reduction of GHG emissions from light-duty vehicles. Advances in NOx and PM emissions control technology are bringing light-duty diesels fully into compliance with Federal Tier 3 and California LEV III emissions standards at a cost that is competitive with the cost-effectiveness other high efficiency, advanced engine technologies. In the FRM, diesel powertrains were not expected to be a significant technology for improving vehicle efficiency, however, since then many new light-duty vehicles have been introduced to the U.S. market with diesel engines, including the Ram 1500 full-size pickup truck, the Chevrolet Colorado mid-size pickup truck, the Jeep Grand Cherokee SUV, and the Chevrolet Cruze. In addition, diesel engines are continuing to evolve using technologies similar to those being introduced in new light-duty gasoline engines and heavy-duty diesel truck engines, including the use of advanced friction reduction measures, increased turbocharger boosting and engine downsizing, engine "downspeeding," the use of advanced cooled EGR systems, improved integration of charge air cooling into the air intake system, and improved integration of exhaust emissions control systems for criteria pollutant control. The best BTE of advanced diesel engines under development for light duty applications is now 46 percent and thus is approaching that of heavy-duty diesel truck engines.[2]

In addition to a reevaluation all the cost and effectiveness values of the technologies that were considered in the FRM, this assessment includes evaluations of technologies where substantial new information has emerged since the FRM, including Atkinson and Miller cycle engines, and application of cylinder deactivation operation to 3-cylinder, 4-cylinder, and turbocharged engines.

5.2.2.2 Sources of Engine Effectiveness Data

In addition to the sources of engine CO_2 effectiveness data used in the 2017-2025 LD GHG FRM, the agencies also used engine data from a wide range of sources to update engine effectiveness for this assessment:

- Newly available, public data (e.g., peer-reviewed journals, peer-reviewed technical papers, conference proceedings)
- Data directly acquired by EPA via engine dynamometer testing at EPA-NVFEL or at contract laboratories
- Benchmarking and simulation modeling of current and future engine configurations
- Confidential data from OEMs, Tier 1 suppliers, and major automotive engineering services firms
- Data from the U.S. Department of Energy Vehicle Technologies Program

A considerable amount of brake-specific fuel consumption (BSFC), brake-thermal efficiency (BTE) and chassis-dynamometer drive cycle fuel consumption data for advanced powertrains has been published in journals, technical papers and conference proceedings since the publication of the 2012 FRM. In some cases, published data includes detailed engine maps of BSFC and/or BTE over a wide area of engine operation. In addition, these publications provide a great deal of information regarding the specific design changes made to an engine which allow the engine to operate at an improved BSFC and vehicles to operate with improved fuel consumption. These design details often include changes to engine friction, changes to valvetrain and valve control, combustion chamber design and combustion control, boosting components and boosting control, and exhaust system modifications. This information provides the agency an indication of which technologies to investigate in more detail and offer the opportunity to correlate testing and simulation results against currently available and future designs.

Since 2012, many examples of advanced engine technologies have gone into production for the U.S., European and Japanese markets. EPA has acquired many vehicles for chassis dynamometer testing and has developed a methodology for conducting detailed engine dynamometer testing of engines and engine/transmission combinations. Engine dynamometer testing was conducted both at the EPA-NVFEL facility in Ann Arbor, MI and at other test facilities under contract with EPA. Engine dynamometer testing of production engines outside of the vehicle chassis required the use of a vehicle-to-engine (or vehicle-to-engine/transmission) wiring tether and simulated vehicle feedback signals in order to allow use of the vehicle manufacturer's engine management system and calibrated control parameters. NHTSA conducted engine dynamometer testing of light-duty truck engines at Southwest Research Institute. In addition to fuel consumption and regulated emissions, many of the engines were also instrumented with piezo-electric cylinder pressure transducers and crankshaft position sensors to allow calculation of the apparent rate of heat release and combustion phasing. Engines with camshaft-phasing were also equipped with camshaft position sensors to allow monitoring of the timing of valve events. Engine dynamometer testing also incorporated hardware-in-the-loop simulation of drive cycles so that vehicle packages with varying transmission configurations and road-loads could be evaluated.

While the confidential data provided by vehicle manufacturers, suppliers and engineering firms cannot be published in the Draft TAR, these sources of data were important as they allowed the EPA to perform quality and rationality checks against the data that we are making publically available. In each case where a specific technology was benchmarked, EPA met with the vehicle manufacturer. In cases where expected combinations of future engine technologies were not available for testing from current production vehicles, a combination of proof-of-concept engine dynamometer testing and engine and vehicle CAE simulations were used to determine drive cycle effectiveness. For example, use of cooled EGR and an increased geometric compression ratio was modeled using Gamma Technologies GT-Power simulations of combustion and gas dynamics with subsequent engine dynamometer validation conducted using a prototype engine management system, a developmental external low-pressure cooled EGR system, and a developmental dual-coil offset ignition system. Finally, several of these benchmarking activities were the subject of technical papers published by SAE and included a peer review of the results as part of the publication process.

5.2.2.3 Low Friction Lubricants (LUB)

One of the most basic methods of reducing fuel consumption in gasoline engines is the use of lower viscosity engine lubricants. More advanced multi-viscosity engine oils are available today with improved performance in a wider temperature band and with better lubricating properties. This can be accomplished by changes to the oil base stock (e.g., switching engine lubricants from a Group I base oils to lower-friction, lower viscosity Group III synthetic) and through changes to lubricant additive packages (e.g., friction modifiers and viscosity improvers). The use of 5W-30 motor oil is now widespread and auto manufacturers are introducing the use of even lower viscosity oils, such as 5W-20 and 0W-20, to improve cold-flow properties and reduce cold start friction. However, in some cases, changes to the crankshaft, rod and main bearings and changes to the mechanical tolerances of engine components may be required. In all cases, durability testing is required to ensure that durability is not compromised. The shift to lower viscosity and lower friction lubricants also improve the effectiveness of valvetrain technologies such as cylinder deactivation, which rely on a minimum oil temperature (viscosity) for operation.

5.2.2.4 Engine Friction Reduction (EFR1, EFR2)

In addition to low friction lubricants, manufacturers can also reduce friction and improve fuel consumption by improving the design of engine components and subsystems. Approximately 10 percent of the energy consumed by a vehicle is lost to friction, and just over half is due to frictional losses within the engine. Examples include improvements in low-tension piston rings, piston skirt design, roller cam followers, improved crankshaft design and bearings, material coatings, material substitution, more optimal thermal management, and piston and cylinder surface treatments. Additionally, as computer-aided modeling software continues to improve, more opportunities for evolutionary friction reductions may become available.

All reciprocating and rotating components in the engine are potential candidates for friction reduction, and minute improvements in several components can add up to a measurable fuel economy improvement.

5.2.2.5 Cylinder Deactivation (DEAC)

In conventional spark-ignited engines throttling the airflow controls engine torque output. At partial loads, efficiency can be improved by using cylinder deactivation instead of throttling. Cylinder deactivation (DEAC) can improve engine efficiency by disabling or deactivating cylinders when the load is significantly less than the engine's total torque capability – the valves are kept closed, and no fuel is injected – as a result, the trapped air within the deactivated cylinders is simply compressed and expanded as an air spring, with reduced friction and heat losses. The active cylinders combust at additional loads to compensate for the deactivated cylinders. Pumping losses are significantly reduced as long as the engine is operated in this "part-cylinder" mode.

Cylinder deactivation control strategy relies on setting maximum manifold absolute pressures or predicted torque within which it can deactivate the cylinders. Noise and vibration issues reduce the operating range to which cylinder deactivation is allowed, although manufacturers continue exploring vehicle changes that enable increasing the amount of time that cylinder deactivation might be suitable. Some manufacturers have adopted active engine mounts and/or active noise cancellations systems to address NVH concerns and to allow a greater operating range of activation.

5.2.2.6 Variable Valve Timing (VVT) Systems

Variable valve timing (VVT) is a family of valve-train designs that alter the timing of the intake valve, exhaust valve, or both, primarily to reduce pumping losses, increase specific power, and control the level of residual gases in the cylinder. VVT reduces pumping losses when the engine is lightly loaded by controlling valve timing closer to an optimum needed to sustain horsepower and torque. VVT can also improve volumetric efficiency at higher engine speeds and loads. Additionally, VVT can be used to alter (and optimize) the effective compression ratio where it is advantageous for certain engine operating modes (e.g., in the Atkinson Cycle).

VVT has now become a widely adopted technology. In MY2015, more than 98 percent of light-duty vehicles sold in the U.S. are projected to use some form of VVT. The three major types of VVT are listed in the sub-sections below.

Each of the three implementations of VVT uses a cam phaser to adjust the camshaft angular position relative to the crankshaft position, referred to as "camshaft phasing." The phase adjustment results in changes to the pumping work required by the engine to accomplish the gas exchange process. The majority of current cam phaser applications use hydraulically-actuated units, powered by engine oil pressure and managed by a solenoid that controls the oil pressure supplied to the phaser. Electric cam phasing allows a wider range of camshaft phasing, faster time-to-position, and allows adjustment of camshaft phasing under conditions that can be challenging for hydraulic systems, for example, during and immediately after engine startup.

5.2.2.6.1 Intake Cam Phasing (ICP)

Valvetrains with ICP can modify the timing of the inlet valves by phasing the intake camshaft while the exhaust valve timing remains fixed. This requires the addition of a cam phaser on each bank of intake valves on the engine. An in-line 4-cylinder engine has one bank of intake valves, while V-configured engines have two banks of intake valves.

5.2.2.6.2 Coupled Cam Phasing (CCP)

Valvetrains with coupled (or coordinated) cam phasing can modify the timing of both the inlet valves and the exhaust valves an equal amount by phasing the camshaft of a single overhead cam (SOHC) engine or a cam-in-block, overhead valve (OHV) engine. For overhead cam engines, this requires the addition of a cam phaser on each bank of the engine. Thus, an in-line 4-cylinder engine has one cam phaser, while SOHC V-engines have two cam phasers. For overhead valve (OHV) engines, which have only one camshaft to actuate both inlet and exhaust valves, CCP is the only VVT implementation option available and requires only one cam phaser.

5.2.2.6.3 Dual Cam Phasing (DCP)

The most flexible VVT design is dual (independent) cam phasing, where the intake and exhaust valve opening and closing events are controlled independently. This option allows the option of controlling valve overlap, which can be used as an internal EGR strategy. At low engine loads, DCP creates a reduction in pumping losses, resulting in improved fuel consumption/reduced CO_2 emissions. Increased internal EGR also results in lower engine-out NOx emissions. The amount by which fuel consumption is improved and CO_2 emissions are reduced depends on the residual tolerance of the combustion system and on the combustion phasing achieved. Additional improvements are observed at idle, where low valve overlap could result in improved combustion stability, potentially reducing idle fuel consumption.

5.2.2.6.4 Variable Valve Lift (VVL)

Controlling the lift of the valves provides a potential for further efficiency improvements. By optimizing the valve-lift profile for specific engine operating regions, the pumping losses can be reduced by reducing the amount of throttling required to produce the desired engine power output. By moving the throttling losses further downstream of the throttle valve, the heat transfer losses that occur from the throttling process are directed into the fresh charge-air mixture just prior to compression, delaying the onset of knock-limited combustion. Variable valve lift control can also be used to induce in-cylinder mixture motion, which improves fuel-air mixing and can result in improved thermodynamic efficiency. Variable valve lift control can also potentially reduce overall valvetrain friction. At the same time, such systems may incur increased parasitic losses associated with their actuation mechanisms. A number of manufacturers have already implemented VVL into all (BMW) or portions of their fleets (Toyota, Honda, and GM), but overall this technology is still available for application to most vehicles. There are two major classifications of variable valve lift, discrete variable valve lift (DVVL) and continuous variable valve lift (CVVL).

DVVL systems allow the selection between two or three discrete cam profiles by means of a hydraulically-actuated mechanical system. By optimizing the cam profile for specific engine operating regions, the pumping losses can be reduced by reducing the amount of throttling required to produce the desired engine power output. This increases the efficiency of the engine. These cam profiles may consist of a low and a high-lift lobe or other combinations of cam profiles, and may also include an inert or blank lobe to incorporate cylinder deactivation (in the case of a 3-step DVVL system). DVVL is normally applied together with VVT control. DVVL is also known as Cam Profile Switching (CPS). DVVL is a mature technology with low technical risk.

In CVVL systems, valve lift is varied by means of a mechanical linkage, driven by an actuator controlled by the engine control unit. The valve opening and phasing vary as the lift is changed and the relation depends on the geometry of the mechanical system. BMW has considerable production experience with CVVL systems and has versions of its "Valvetronic" CVVL system since 2001. CVVL allows the airflow into the engine to be regulated by means of intake valve opening reduction, which improves engine efficiency by reducing pumping losses from throttling the intake system further upstream as with a conventionally throttled engine. CVVL provides greater effectiveness than DVVL, since it can be fully optimized for all engine speeds and loads, and is not limited to a two or three step compromise. There may also be a small reduction in valvetrain friction when operating at low valve lift, resulting in improved low load fuel consumption for cam phase control with variable valve lift as compared to cam phase control only. Most of the fuel economy effectiveness is achieved with variable valve lift on the intake valves only. CVVL is only applicable to double overhead cam (DOHC) engines.

5.2.2.7 GDI, Turbocharging, Downsizing and Cylinder Deactivation

Between 2010 and 2015, automotive manufacturers have been adopting advanced powertrain technologies in response to GHG and CAFE standards (see 3.2 Technology Penetrations). Just over 45 percent of MY2015 light-duty vehicles in U.S. were equipped with gasoline direct injection (GDI) and approximately 18 percent of MY2015 light-duty vehicles were turbocharged. Nearly all vehicles using turbocharged spark-ignition engines also used GDI to improve suppression of knocking combustion. GDI provides direct cooling of the in-cylinder charge via in-cylinder fuel vaporization.[3] Use of GDI allows an increase of compression ratio of approximately 0.5 to 1.5 points relative to naturally aspirated or turbocharged engines using port-fuel-injection (e.g., an increase from 9.9:1 for the 5.3L PFI GM Vortec 5300 to 11:1 for the 5.3L GDI GM Ecotec3 with similar 87 AKI gasoline octane requirements).

Figure 5.2 shows a comparison of brake thermal efficiency (BTE) versus engine speed and load between a high-volume, MY2008 2.4L I4 engine equipped with PFI and a MY2013 GM Ecotec™ 2.5L I4 equipped with GDI. The GDI engine has a significantly higher compression ratio, (11.3:1 vs 9.6:1), higher efficiency throughout its range of operation, and achieves higher BMEP levels (approximately 12.5 bar vs 11.3 bar), allowing a significant increase in power per displacement. The incremental effectiveness at approximately 2-bar BMEP and 2000 rpm was

17 percent but varied from approximately 3 percent to approximately 11 percent at other speed and load points of importance for the regulatory drive cycles.

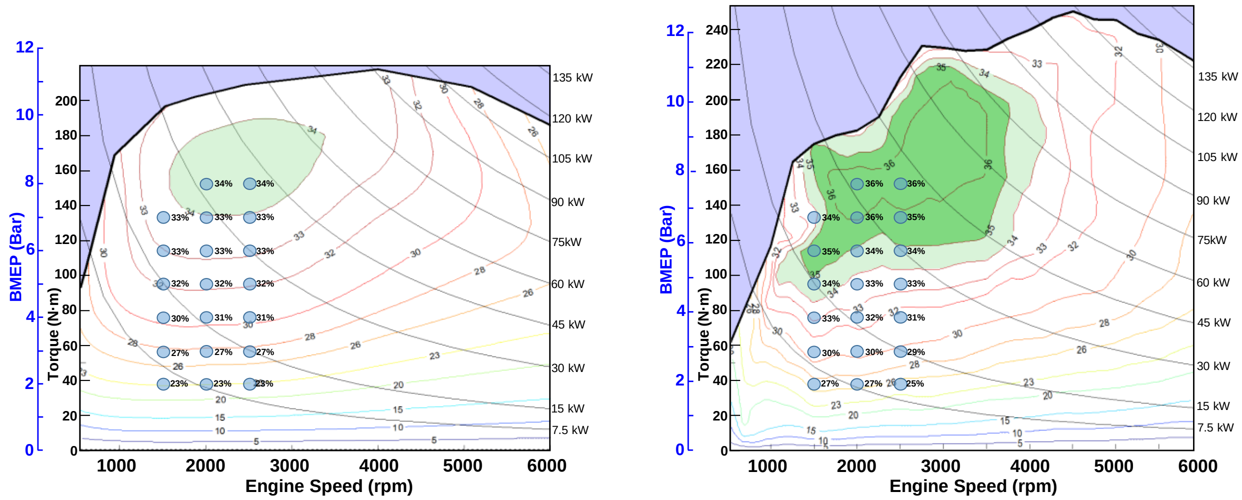


Figure 5.2 Comparison of BTE for A Representative MY2008 2.4L I4 NA DOHC PFI 4-valve/cyl. Engine with Intake Cam Phasing (Left)[D] and a GM Ecotec 2.5L NA GDI Engine with Dual Camshaft Phasing (Right).[E]

Area of Operation > 34% BTE is Shown in Light Green. Area of Operation >35% BTE is Shown in Dark Green.

Toyota's D-4S system combines GDI and PFI systems, with two injectors per cylinder (one directly in-cylinder and one immediately upstream of the intake port).[4,5,6] As of 2015, all Toyota vehicles in the U.S. with GDI appear to be using a variation of the D-4S dual GDI/PFI fuel injection system. This system increases peak BMEP, provides additional flexibility with respect to calibration of the EMS for improved cold-start emissions and offers an efficiency improvement over GDI alone. Based on certification data and EPA confirmatory test data, Toyota vehicles using engines equipped with the D4S system have relatively low PM emissions over the FTP75 cycle that are roughly comparable to PFI-equipped vehicles (<0.60 mg/mi).[7] A comparison of the Toyota 2GR-FSE engine is shown compared to a 3.5L PFI engine in Figure 5.3. The 2GR-FSE achieves a very high BMEP for a naturally aspirated engine (13.7 bar). Although both engines have comparable displacement, they are not directly comparable because the higher BMEP attained by the 2GR-FSE would allow further engine downsizing for a similar application, with potential for further improvement in BTE at light load relative to the 3.5L PFI engine. The area greater than 34 percent BTE is significantly larger for the Toyota 2GR-FSE due to a combination of factors, including a higher compression ratio enabled by GDI and reduced pumping losses through use of a dual camshaft phasing system that enables internal EGR at light loads.

[D] Based on engine dynamometer test data provided to EPA as part of "Light Duty Vehicle Complex Systems Simulation," EPA Contract No. EP-W-07-064, work assignment 2-2, with PQA and Ricardo.
[E] Based on EPA engine dynamometer test data.

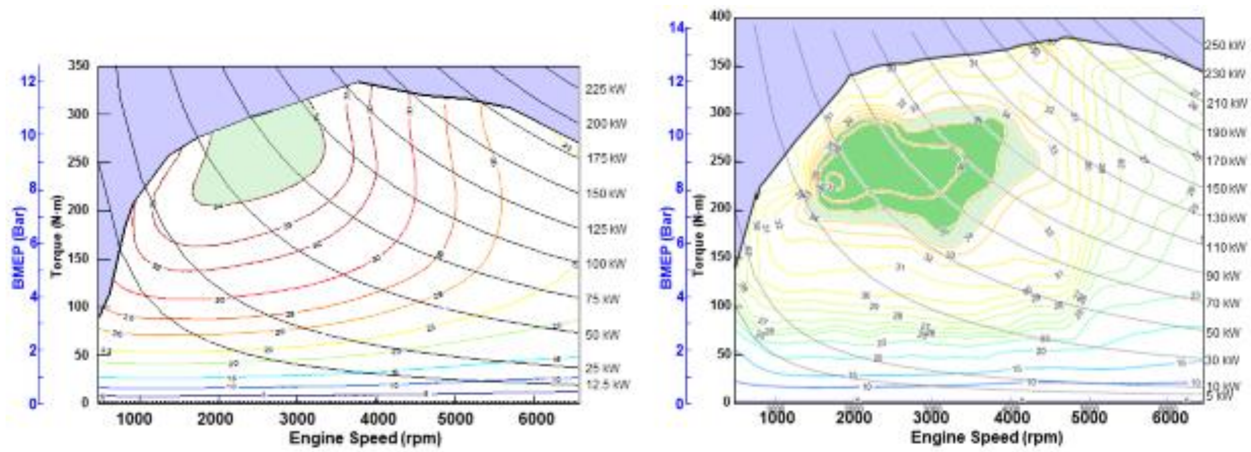


Figure 5.3 Comparison of BTE for A Representative MY2010 3.5L V6 NA PFI 4-valve/cyl. Engine[F] (Left) and a Toyota 2GR-FSE GDI/PFI Engine with Dual Camshaft Phasing[G] (Right).

Note: Area of Operation > 34% BTE is Shown in Light Green.

The recently redesigned Ford turbocharged 3.5L "EcoBoost™" engine in the 2017 Ford F150 also uses a dual GDI/PFI injection system to increase power, reduce emissions, and improve efficiency,[8] but other engines in Ford's EcoBoost lineup use GDI. In MY2015, Ford offered a version of the EcoBoost turbocharged GDI engines as standard or optional engines in nearly all of models of light-duty cars and trucks. Ford's world-wide production of EcoBoost engines exceeded 200,000 units per month during CY2015.[9]

Approximately 13 percent of MY2015 light-duty vehicles used cylinder deactivation, primarily in light-duty truck applications. In MY2015, General Motors introduced their "Ecotec3" line of OHV V6 and V8 engines across their entire lineup of light-duty pickups and truck-based SUVs. These engines are equipped with GDI, coupled-cam-phasing, and cylinder deactivation. Both the V6 and V8 EcoTec3 engines are capable of operation on 4-cylinders under light-load conditions. Application of GDI has synergies with cylinder deactivation. The higher BMEP achievable with GDI also increases the BMEP achievable once cylinders have been deactivated, thus increasing the range of operation where cylinder deactivation is enabled.

Cylinder deactivation operates the remaining, firing cylinders at higher BMEP under light load conditions. This moves operation of the remaining cylinders to an area of engine operation with less throttling and thus lower pumping losses (Figure 5.4) and reduced BSFC.

[F] Based on engine dynamometer test data provided to EPA as part of "Light Duty Vehicle Complex Systems Simulation," EPA Contract No. EP-W-07-064, work assignment 2-2, with PQA and Ricardo.
[G] Based on EPA engine dynamometer test data.

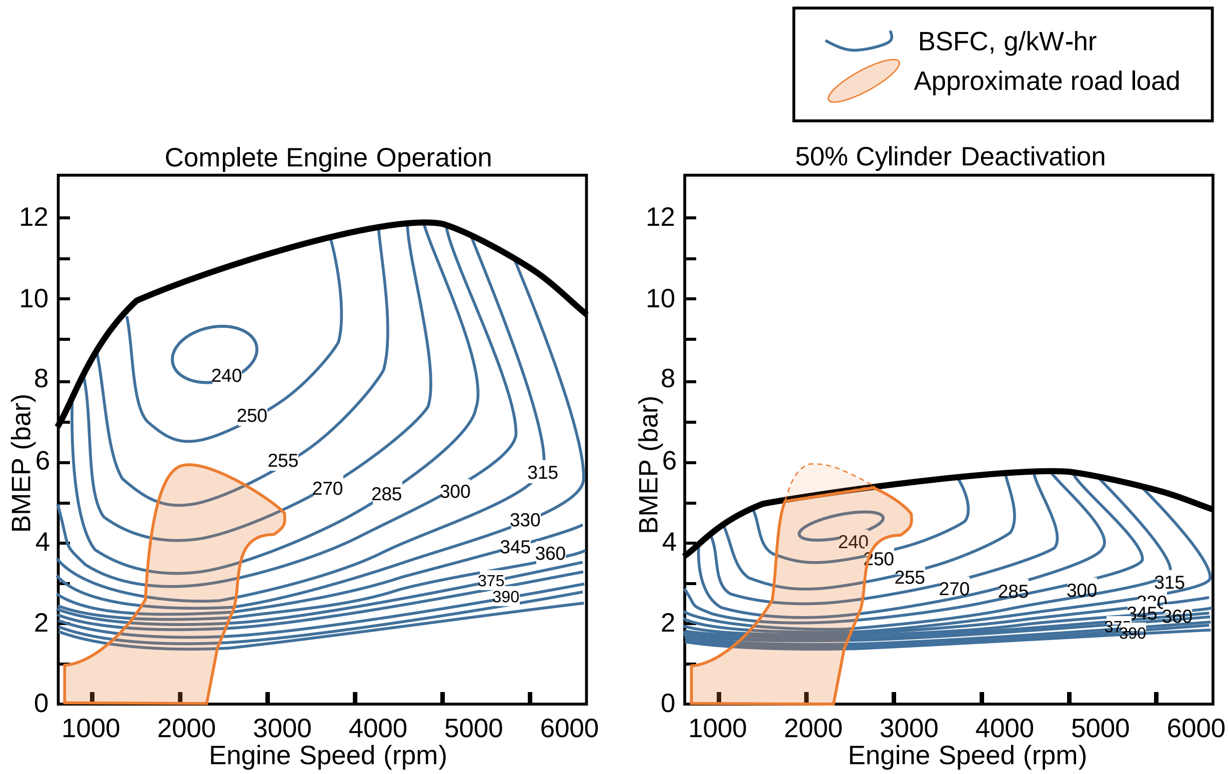


Figure 5.4 Graphical Representation Showing How Cylinder Deactivation Moves Engine Operation to Regions of Operation with Improved Fuel Consumption over the UDDS Regulatory Drive Cycle (shaded area).

In the 2017-2025 LD GHG FRM, EPA limited its analysis of cylinder deactivation to engines with six or more cylinders. At the time, there were concerns that application of cylinder deactivation to 3 or 4-cylinder engines would result in unacceptable NVH. Since 2012, improvements in crankshaft dampening systems have extended the application of cylinder deactivation to four cylinder engines. Volkswagen introduced their 1.4L TSI EA 211 turbocharged GDI engine with "active cylinder management" in Europe for MY2013.[10] This engine is the first production application of cylinder deactivation to an I4 engine and can deactivate 2 cylinders via cam-shifting under light load conditions. VW recently introduced a Miller Cycle variant of the same EA211 engine family with cylinder deactivation.[11] Schaeffler has developed a dynamic cylinder deactivation system for I3 and I5 engines that alternates or "rolls" the deactivated cylinders. This system allows all cylinders to be deactivated after every ignition cycle and reactivated during the next cycle. Cylinder deactivation thus alternates within a single deactivation phase and not each time a new deactivation mode is introduced. The net result is that engines with an odd number of cylinders can operate, on average, with half their cylinder displacement (i.e., I3 can drop to 1.5 cylinders on average or an I5 can drop to 2.5 cylinders on average). Ford and Schaeffler investigated both rolling cylinder deactivation and a system to deactivate one cylinder with Ford's EcoBoost 1.0L I3 engine and found that, with appropriate vibrational dampening, either strategy could be implemented with no NVH deterioration and with 3 percent or greater improvement in both real-world and EU drive cycle fuel economy.[12] Tula Technology has demonstrated a system with the capability of deactivating any cylinder that they refer to as "Dynamic Skip Fire."[13] Tula found a combined-cycle fuel economy improvement of approximately 14 percent for an unspecified vehicle equipped with a 6.2L PFI V8 and approximately 6 percent for an application equipped with the GM Active Fuel Management 4/8 cylinder deactivation system. It should be noted that engines with more opportunity for pumping loss reduction over the regulatory drive cycles (e.g., larger displacement, naturally aspirated, PFI) generally have higher CO_2 effectiveness when equipped with cylinder deactivation.

Many automotive manufacturers have launched a third or fourth generation of GDI engines since their initial introduction in the U.S. in 2007. Turbocharged, GDI engines are in now in volume production at between 21-bar and 25-bar BMEP. Most recent turbocharged engine designs now use head-integrated, water-cooled exhaust manifolds and coolant loops that separate the cooling circuits between the engine block and the head/exhaust manifold(s). Head-integrated exhaust manifolds (IEM) are described further in the section on thermal management in 5.2.2.11. The use of IEM was assumed within the EPA analysis of 27-bar BMEP turbocharged GDI engines for the FRM. The benefits, including increased ability to downspeed the engine without pre-ignition and the potential for cost savings in the design of the turbocharger turbine housing appear to extend to lower BMEP-level turbocharged GDI engines and will likely be incorporated into many future turbocharged light-duty vehicle applications. The application of IEM's does effect cooling system design and manufacturers will be required to provide sufficient cooling system capacity if they adopt this technology.

The 2.7L Ford Ecoboost engine was introduced in the MY2015 Ford F150. This engines uses one turbocharger per bank, IEM and dual camshaft phasing. Peak BMEP is approximately 24-bar and the maximum towing capacity of the F150 equipped with this engine is 13,300 lbs. when used with a 3.73:1 final drive ratio in the 2016 Ford F150. Figure 5.5 shows a comparison of BMEP and torque vs. engine speed and BTE between a conventional MY2010 5.4L OHC V8 light-duty pickup truck engine and the MY 2015 2.7L Ford Ecoboost engine. This comparison thus represents 50 percent engine downsizing using turbocharging and GDI. The 2.7L Ecoboost engine has bother higher peak torque and power, higher peak BTE, and approximately double the area above 34 percent BTE.

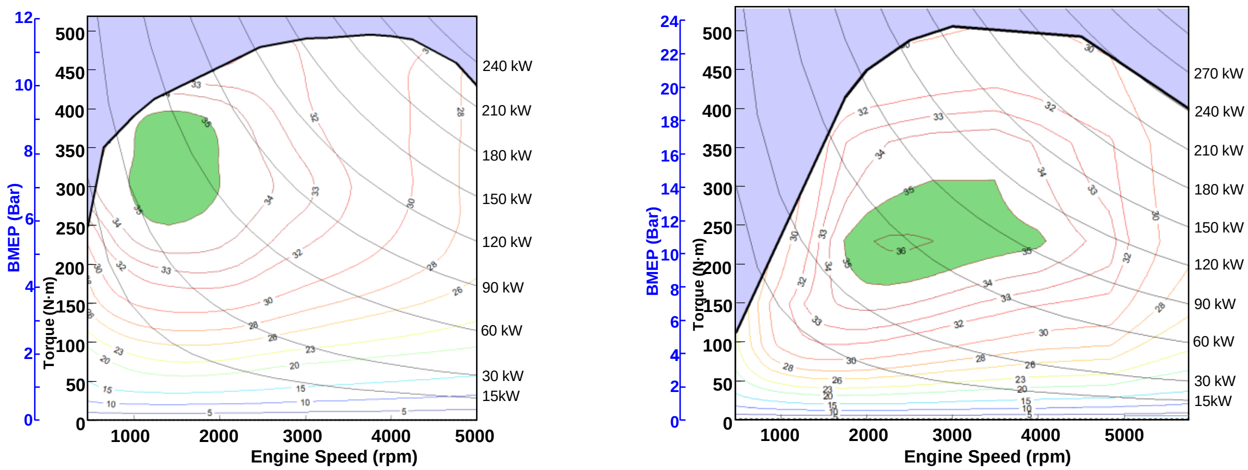


Figure 5.5 Comparison of BTE for A Representative MY2010 5.4L V8 NA PFI 3-valve/cyl. Engine[H] (Left) and a Ford 2.7L V6 Ecoboost Turbocharged, GDI Engine With Dual Camshaft Phasing[I] (Right).

Note: Area of Operation > 35% BTE is Shown in Green.

Figure 5.6 shows maps of BMEP and torque vs. engine speed and BTE for a representative MY2010 2.4L PFI engine with intake camshaft phasing and a MY2012 1.0L Ford EcoBoost turbocharged, GDI, engine with an integrated exhaust manifold (IEM) and dual camshaft phasing.[14] The 1.0L EcoBoost engine features turbocharging to a peak BMEP of 25-bar, GDI with center-mounted, spray-guided injection, a cylinder-head integrated exhaust manifold, and dual camshaft phasing. While not a direct comparison for purposes of engine downsizing (the 1.0L EcoBoost is more comparable to a 1.8 – 2.0L NA PFI engine based on torque characteristics and rated power), this comparison of BTE does demonstrate the manner that turbocharging and downsizing can be used to expand regions of high thermal efficiency to cover a larger portion of engine operation. For example, the EcoBoost engine exceeds 30 percent BTE above 6-bar BMEP/50 N-m torque over most of the engine's range of engine speeds while the area above 30 percent BTE for the NA PFI engine is considerably smaller.

[H] Based on engine dynamometer test data provided to EPA as part of "Light Duty Vehicle Complex Systems Simulation," EPA Contract No. EP-W-07-064, work assignment 2-2, with PQA and Ricardo.

[I] Based on EPA engine dynamometer test data.

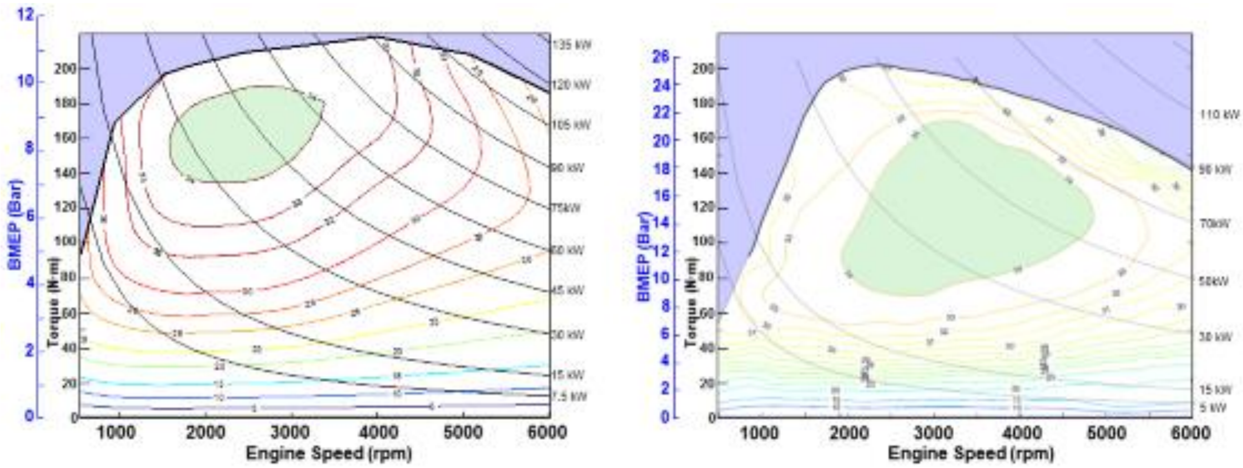


Figure 5.6 Comparison of BTE for A Representative MY2010 2.4L NA PFI Engine[J] (Left) and A Modern, 1.0L Turbocharged, Downsized GDI Engine[K] (Right).

Note: Area of Operation > 34% BTE is Shown in Light Green.

A comparison of the same 2.4L PFI engine with a more recent, MY2017 Honda 1.5L Turbocharged GDI engine with IEM is shown in Figure 5.7.[15,16] The torque characteristics of the Honda engine are a closer match to the 2.4L PFI engine and the Honda engine represents approximately 37 percent downsizing relative to the 2.4L PFI engine due to turbocharging and includes other improvements (friction reduction, dual cam phasing, higher rates of internal EGR). The Honda 1.5L turbocharged GDI engine has significantly improved efficiency when comparing BTE across 20 speed and load points of significance for the regulatory drive cycles (1500 -2500 rpm and 2-bar to 8-bar BMEP as referenced to the 2.4l ENGINE). The BTE of the Honda 1.5L turbocharged engine showed an incremental effectiveness of 6 percent to 30 percent across this entire range of operation. The difference was more pronounced at lighter loads. Incremental effectiveness was 16 percent to 30 percent below 6-bar BMEP relative to the 2.4L engine (~112 N-m of torque).

[J] Based on engine dynamometer test data provided to EPA as part of "Light Duty Vehicle Complex Systems Simulation," EPA Contract No. EP-W-07-064, work assignment 2-2, with PQA and Ricardo.
[K] Adapted from Ernst et al. 2011.[14]

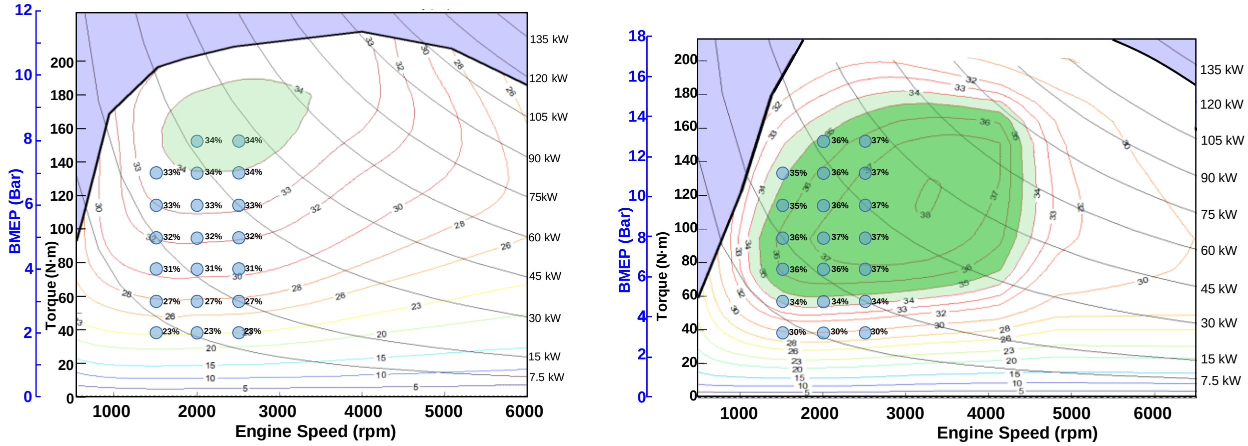


Figure 5.7 Comparison of BTE for A Representative MY2010 2.4L NA PFI Engine[J] (Left) and A Modern, 1.5L Turbocharged, Downsized GDI Engine[L] (Right).

Note: Area of Operation > 34% BTE is Shown in Light Green. Area of Operation >35% BTE is Shown in Dark Green. BTE Was Also Compared Across 20 Operational Points of Significance for Regulatory Drive Cycles between 1500 and 2500 RPM.

Recent turbocharger improvements have included use of lower-mass, lower inertia components and lower friction ball bearings to reduce turbocharger lag and enable higher peak rotational speeds. Improvements have also been made to turbocharger compressor designs to improve compressor efficiency and to expand the limits of compressor operation by improving surge characteristics (see Figure 5.8).

[L] Adapted from Wada et al. 2016 and Nakano et al 2016.[15,16]

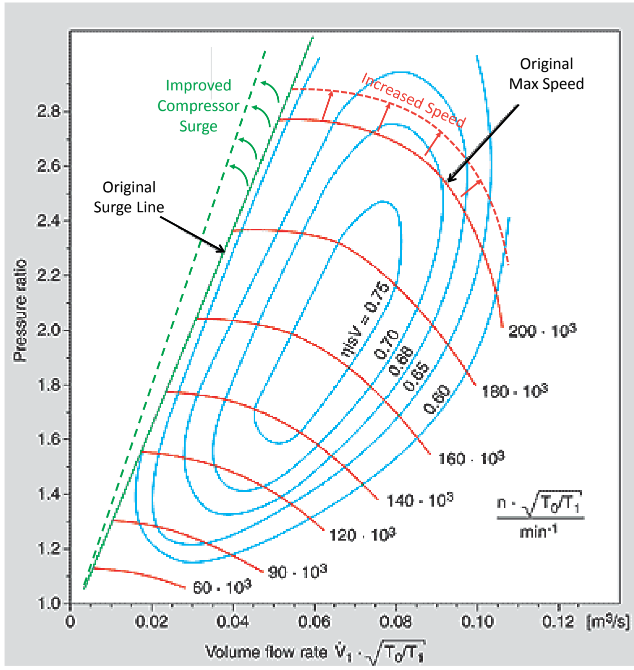


Figure 5.8 Typical Turbocharger Compressor Map Showing How Pressure And Flow Characteristics Can Be Matched Over a Broader Range of Engine Operation Via Surge Improvement and Higher Operational Speed.

Turbochargers with variable nozzle turbines (VNT) use moveable vanes within the turbocharger to allow adjustment of the effective exhaust turbine aspect ratio, allowing the operation of the turbocharger to be better matched across the entire speed and load range of an engine. VNT turbochargers are commonly used in modern light-duty and heavy-duty diesel engines. The use of head-integrated exhaust manifolds (IEM) and split-coolant loops within the engine and the use of cooled EGR (Sections 5.2.2.8 and 5.2.2.11) can reduce peak exhaust temperatures sufficiently to allow lower cost implementation of VNT turbochargers in spark ignition engines. There are also synergies between the application of VNT and Miller cycle (increased low-speed torque, improved torque response).[11]

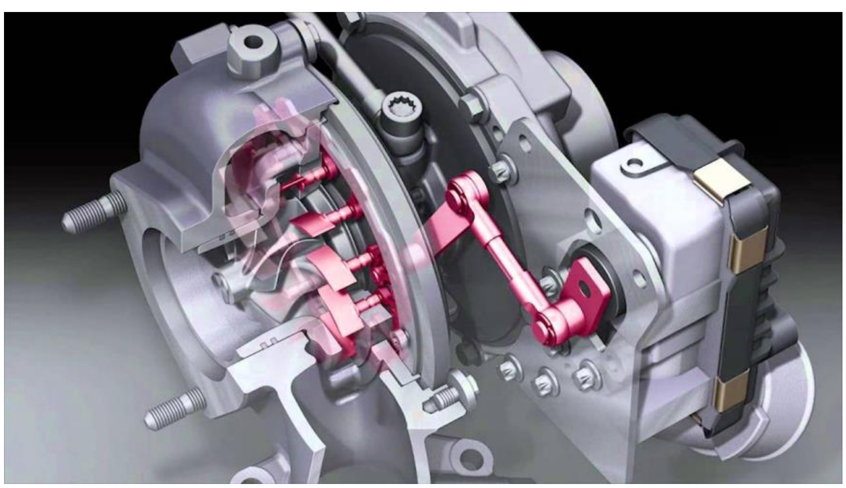


Figure 5.9 Cross Sectional View of a Honeywell VNT Turbocharger. The Moveable Turbine Vanes And Servo Linkage Are Highlighted In Light Red.

5.2.2.8 EGR

Exhaust gas recirculation (EGR) is a broad term used for systems that control and vary the amount of inert, residual exhaust gases left in cylinder during combustion. EGR can improve efficiency at part-load by reducing pumping losses due to engine throttling. EGR also reduces combustion temperatures and thus reduces NOx formation. The use of cEGR can reduce knocking combustion, thus allowing compression ratio and/or turbocharger boost pressure to be increased or spark timing to be advanced. EGR also slows the rate of combustion, so its use is often accompanied by other changes to the engine (e.g., inducing charge motion and turbulent combustion) to shorten combustion duration and allow improved combustion phasing. Internal EGR uses changes in independent cam-phasing to vary the overlap between intake and exhaust valve timing events, thus changing the amount of residual gases trapped in cylinder after cylinder scavenging. External EGR recirculates exhaust gases downstream of the exhaust valve back into the air induction system. With turbocharged engines, there are variants of external EGR that use a low pressure loop, a high pressure loop or combinations of the two system types (see Figure 5.10). External EGR systems can also incorporate a heat-exchanger to lower the temperature of the recirculated exhaust gases (e.g., cooled EGR or cEGR), improving both volumetric efficiency and enabling higher rates of EGR. Nearly all light-duty diesel engines are equipped with cEGR as part of their NOx emission control system. Some diesel applications also use relatively large amounts (>25 percent) of cEGR at light- to part-load conditions to enable dilute low-temperature combustion (see Section 5.2.2.11 for a more detailed description of light-duty diesel technologies). Research is also underway to apply similar forms of low-temperature combustion using high EGR rates to gasoline engine applications. This includes lean-homogenous compression auto ignition (see Section 5.2.2.14) and other homogenous charge compression ignition concepts (see Section 5.2.2.11).

The use of cEGR was analyzed as part of EPA's technology packages for post-2017 light-duty vehicles with engines at 24-bar BMEP, primarily as a means to prevent pre-ignition at the high turbocharger boost levels needed at 24-bar BMEP and above. The analysis did take into account efficiency benefits from the use of cEGR with turbocharged engines due primarily to part-load reductions in pumping losses and the reduction or elimination of commanded fuel enrichment under high-load conditions.

Prior to 2012, there were no examples of production vehicles equipped with turbocharged GDI engines using cEGR. The PSA 1.2L EB PureTech Turbo engine was recently launched in the MY2014 Peugeot 308 in Europe as the first high-volume production application of cEGR on a turbocharged GDI engine. This engine has over 24-bar BMEP and also operates using Miller Cycle (see Section 5.2.2.10 for a more detailed description of Miller-Cycle). The MY2016 Mazda CX-9 2.5L SKYACTIV Turbo engine similarly combines the use of Miller Cycle with cEGR.

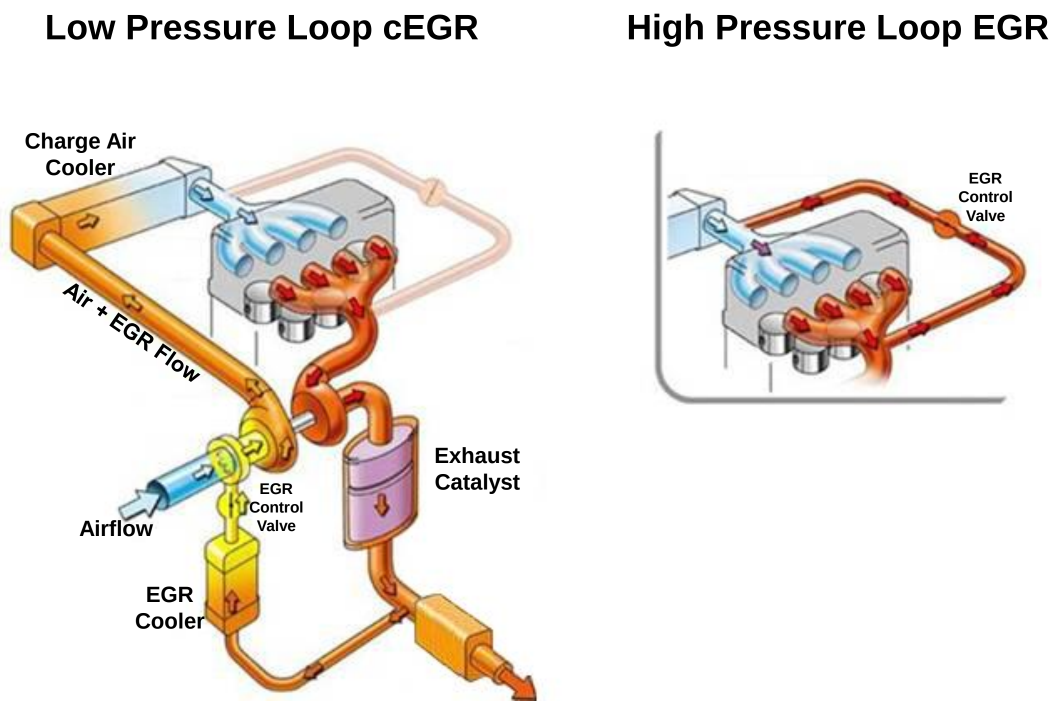


Figure 5.10 A Functional Schematic Example of a Turbocharged Engine Using Two Variants of External EGR.

Note: The Schematic On The Left Shows The Details Of A Low Pressure Loop (Post-Turbine To Pre-Compressor) Cegr System. The Schematic Inset on the Right Shows High Pressure Loop (Pre-Turbine to Post-Compressor) EGR.[17] In The FRM Analysis, Some TDS24 Packages And All TDS27 Packages Used Dual-Loop (Both High And Low Pressure) EGR.

5.2.2.9 Atkinson Cycle

Typical 4-cycle internal combustion engines have an effective compression ratio and effective expansion ratio that are approximately equivalent. Current and past production Atkinson Cycle engines use changes in valve timing (e.g., late-intake-valve-closing or LIVC) to reduce the effective compression ratio while maintaining the expansion ratio (see Figure 5.11 and Figure 5.12). This approach allows a reduction in top-dead-center (TDC) clearance ratio (e.g., increase in "mechanical" or "physical" compression ratio) to increase the effective expansion ratio without increasing the effective compression ratio to a point that knock-limited operation is encountered. Increasing the expansion ratio in this manner improves thermal efficiency but also lowers peak brake-mean-effective-pressure (BMEP), particularly at lower engine speeds.[M] Depending on how it is implemented, some Atkinson Cycle engines may also have sufficient cam-phasing authority to widely vary effective compression ratio and can use this variation as a

[M] BMEP is defined as torque normalized by cylinder displacement. It allows for emissions and efficiency comparisons between engines of different displacement.

means of load control without use of the standard throttle, resulting in additional pumping loss reductions.

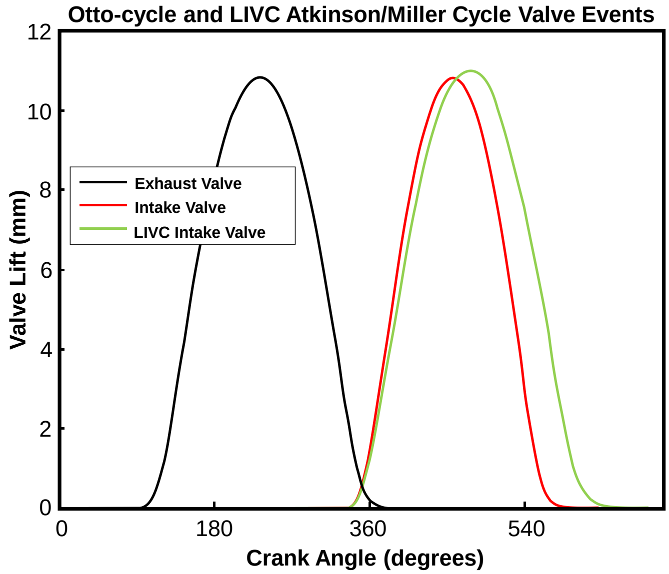


Figure 5.11 Comparison of the Timing of Valve Events for Otto-Cycle (black and orange lines) and LIVC Implementations of Atkinson- Or Miller-Cycle (black and green lines).

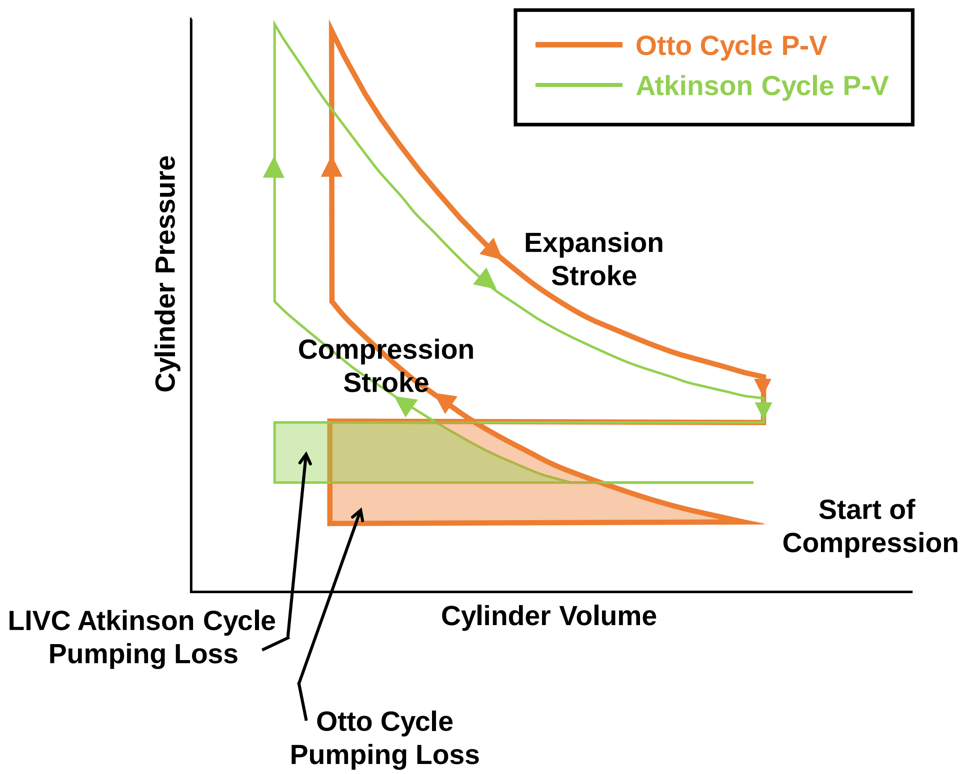


Figure 5.12 Diagrams Of Cylinder Pressure Vs. Cylinder Volume For A Conventional Otto-Cycle SI Engine (orange line) Compared To A LIVC Implementation of Atkinson Cycle (green line) Highlighting the Reduction in Pumping Losses.

Prior to 2012, the use of naturally-aspirated Atkinson Cycle engines has been limited to HEV and PHEV applications where the electric machine could be used to boost torque output, particularly at low engine speeds. Because of this, EPA's analyses for the FRM did not include the use of Atkinson Cycle outside of HEV and PHEV applications. Nearly all HEV/PHEV applications in the U.S. use Atkinson Cycle, including the Honda Insight, Toyota Prius, Toyota Camry Hybrid, Lexus 400h, Hyundai Sonata Hybrid and Chevrolet Volt. The Toyota 2ZR-FXE used in the third-generation Toyota Prius and Lexus 200h uses a combination of LIVC Atkinson Cycle, cooled EGR, and port-fuel-injection (PFI) to achieve a peak BTE of 38.5 percent, the highest BTE achieved to date for a production spark-ignition engine. Further refinements to this engine, including increased tumble to increase both the speed of combustion and EGR tolerance, have resulted in peak BTE of 40 percent.[18]

Since 2012, Atkinson Cycle engines have been introduced into non-hybrid applications. These applications use camshaft-phasing with a high degree of authority together with either GDI (e.g., Mazda SKYACTIV-G 1.5L, 2.0L and 2.5L engines, Toyota 2GR-FKS engine), PFI (MY2017 Hyundai Elantra "Nu" 2.0-liter PFI Atkinson) or a combination of PFI with cooled EGR (Toyota 1NR-FKE and 2NR-FKE engines). As of MY2017, all of Mazda's engines for the U.S. market are either Atkinson Cycle or Miller Cycle (boosted Atkinson). Toyota's 2GR-FKS engine became an optional engine offered in the Toyota Tacoma pickup truck beginning in

MY2016. The Tacoma is currently the mid-size pickup truck segment sales leader in the U.S. The Toyota Tacoma equipped with the 2GR-FKS Atkinson Cycle engine has an SAE J2807 tow rating of 6,800 pounds. The Hyundai "Nu" 2.0-liter PFI Atkinson Cycle engine is the base engine offering in the Hyundai Elantra. The Hyundai Elantra is currently within the top 5 in sales within the compact car segment in the U.S.

The effective compression ratio of Atkinson Cycle engines can be varied using camshaft phasing to increase BMEP and the use of GDI (Mazda) or cEGR (Toyota) are used, in part, for knock mitigation. These engines from Mazda and Toyota also incorporate other improvements, such as friction reduction from valvetrain and piston design enhancements. The Toyota 1NR-FKE 1.3L I3 and 2NR-FKE 1.5L I4 engines achieve a peak BTE of 38 percent, very close to the BTE achieved with the 2ZR-FXE engine used in the Toyota Prius.[18,19] EPA testing of 2.0L and 2.5L variants of the Mazda SKYACTIV-G engine achieved peak BTE of 37 percent while using either 88AKI (91 RON) or 92 AKI (96 RON) fuel. More important from a standpoint of drive-cycle fuel economy and CO_2 emissions was the very large “island” of more than 32 percent BTE (Figure 5.13) which, depending on the transmission and road load, would cover most operation over the UDDS and HwFET regulatory drive cycles depending on the specific vehicle application (e.g., road loads, final drive, gear-ratio spread). In the case of the Mazda SKYACTIV-G engines, the use of GDI and cam-phasing resulted in increased BMEP and rated power relative to the previous PFI, non-Atkinson versions of this engine and allowed a small degree of engine downsizing (e.g., replacement of the previous 2.5L PFI engine with the 2.0 SKYACTIV-G) on some Mazda platforms with equal or improved performance. In the case of the Toyota 1NR-FKE, the use of cEGR and cam-phasing allowed BMEP to be maintained relative to peak BMEP of the Non-Atkinson Cycle engine it replaced and allowed the use of a lower cost PFI fuel system. Both the Mazda and Toyota Atkinson Cycle engines use electro-mechanical systems for camshaft phasing on the intake camshaft.

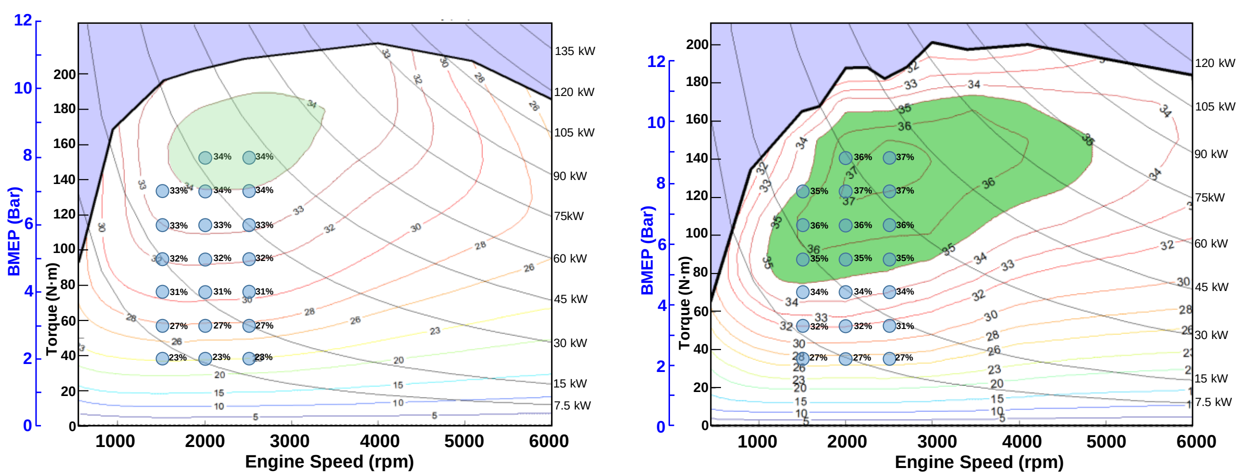


Figure 5.13 Comparison of BTE for a Representative MY2010 2.4L NA PFI Engine[N] (left) and a 2.5L NA GDI LIVC Atkinson Cycle Engine (right) tested by EPA.[O,20]

[N] Based upon engine dynamometer data provided to EPA under a contract with PQA and Ricardo, "Light Duty Vehicle Complex Systems Simulation" EPA Contract No. EP-W-07-064, work assignment 2-2.
[O] Derived from EPA engine dynamometer data first presented by Lee et al. 2016. [20]

A recent benchmarking analysis by EPA of a 2014 Mazda SKYACTIV-G naturally aspirated (NA) gasoline direct injection (GDI) engine showed a peak BTE of approximately 37 percent, relatively high for SI engines.[O,21] This was in part due to an ability to use late-intake-valve-closing (LIVC) Atkinson-cycle operation to decouple the knock-limited effective CR from the expansion ratio available from a very high 13:1 geometric CR. The Mazda SKYACTIV-G is one of the first implementations of a naturally-aspirated, LIVC Atkinson-cycle engine in U.S. automotive applications outside of hybrid electric vehicles (HEV) and also appears to be the first Atkinson-cycle engine to use GDI. Port-fuel-injected (PFI) Atkinson-cycle engines have been used in hybrid electric vehicle applications in the U.S. for over a decade. PFI/Atkinson-cycle engines have demonstrated peak BTE of approximately 39 percent in the 2015 Honda Accord HEV and 40 percent in the 2016 Toyota Prius HEV. While NA/Atkinson-cycle engines can achieve comparable or better peak BTE in comparison with downsized, highly boosted, turbocharged GDI engines like the Ricardo EGRB configuration, modern turbocharged GDI engines often have relatively high BTE across a broader range of engine speed and torque as well as improved BTE and fuel consumption at light loads, as shown in Figure 5.14. Based on EPA's initial engineering analysis of the Mazda SKYACTIV-G engine, it appeared that another reasonable, alternative technological path to both high peak BTE and a broad range of operation with high BTE might be possible through the application of cooled-EGR (cEGR), a higher compression ratio, and cylinder deactivation to a naturally-aspirated GDI/Atkinson-cycle engine like the SKYACTIV-G.

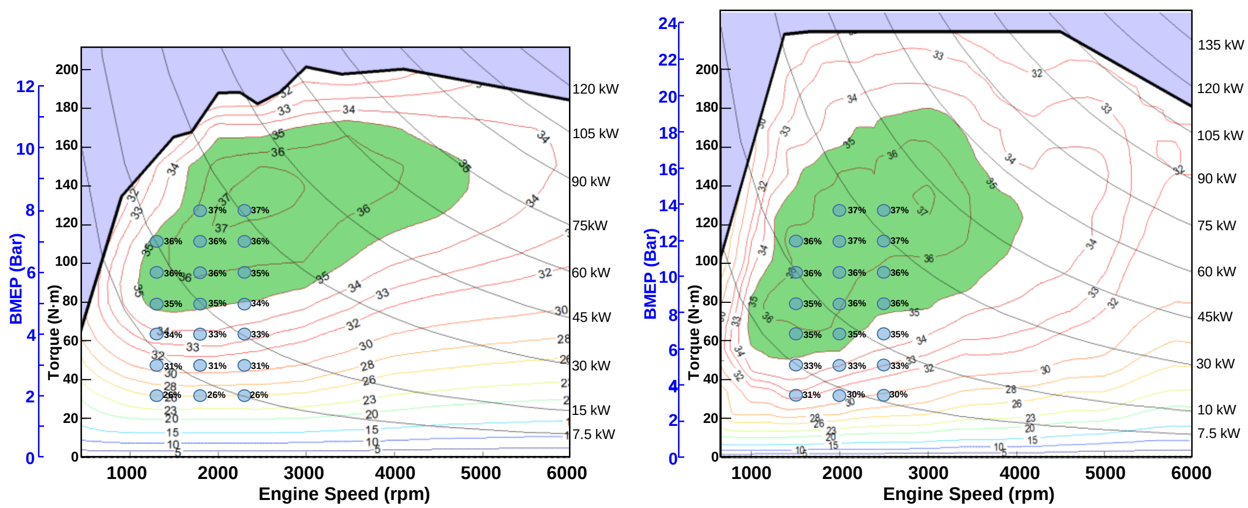


Figure 5.14 A Comparison of BSFC Maps Measured For The 2.0L 13:1CR SKYACTIV-G Engine[O] (left) and Modeled For A 1.0L Ricardo "EGRB Configuration"[N] (right).

5.2.2.10 Miller Cycle

Like Atkinson Cycle, Miller Cycle engines use changes in valve timing to reduce the effective compression ratio while maintaining the expansion ratio. Automakers have investigated both early intake valve closing (EIVC) and LIVC variants. There is some disagreement over the application of the terms Atkinson or Miller Cycle to EIVC and LIVC valve event timing and sometimes the terms are used interchangeably. For the purpose of EPA's analyses, Miller Cycle is a variant of Atkinson cycle with intake manifold pressure boosted by a either a turbocharger and/or a mechanically or electrically driven supercharger. It is simply an extension of Atkinson Cycle to boosted engines. The first production vehicle offered using Miller Cycle was the MY1995 Mazda Millenia S, which used the KJ-ZEM 2.3L PFI engine with a crankshaft-driven Lysholm compressor for supercharging. Until recently, no Miller Cycle gasoline SI engines were in mass production after 2003, and Miller Cycle was not evaluated as a potential gasoline engine technology as part of the 2017-2025 GHG FRM.

As with Atkinson Cycle engines, the use of GDI and camshaft-phasing with a high degree of authority have significant synergies with Miller Cycle. Modern turbocharger and after cooler systems allow Miller Cycle engines to attain BMEP levels approaching those of other modern, downsized, turbocharged GDI engines. The 1.2L I3 PSA "EB PureTech Turbo" Miller engine recently launched in Europe, N. Africa and S. America in the MY2014 Peugeot 308[22]. In addition to Miller Cycle, the engine also uses cEGR. This engine has a maximum BMEP of 24-bar and is similar in many respects to the Ford 1.0L I3 EcoBoost but achieves 35 percent BTE over a slightly broader area of operation vs. 34 percent BTE for the EcoBoost (see Figure 5.15).

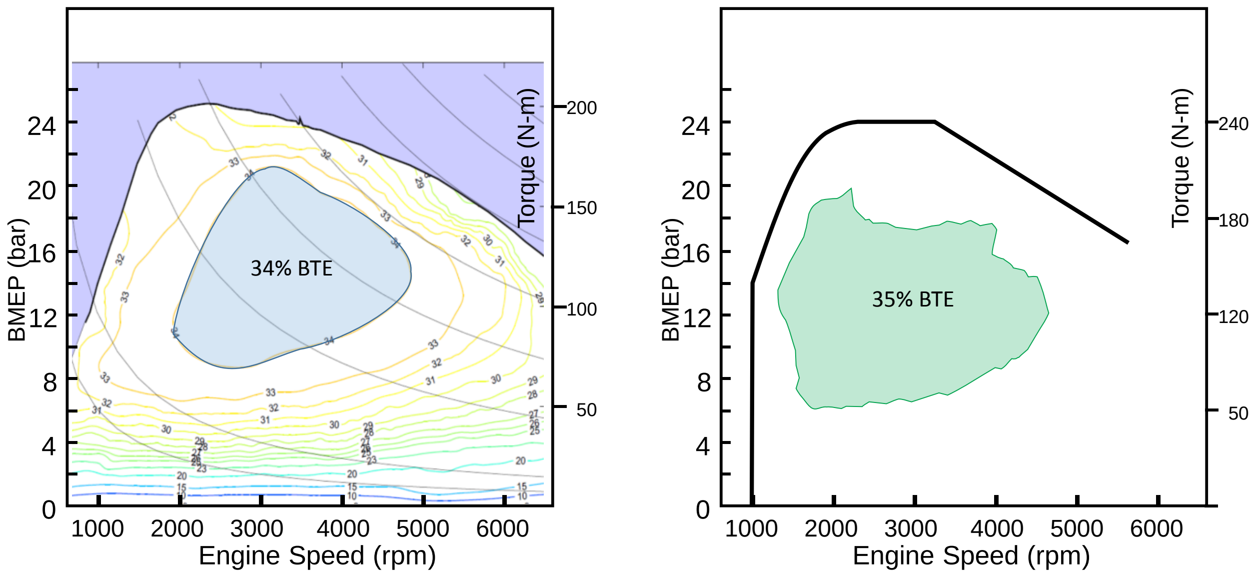


Figure 5.15 Comparison of BTE for Downsized, Turbocharged GDI Engines.

Note: Ford 1.0L EcoBoost Engine Is On The Left And A 1.2L Miller Cycle PSA EB Puretech Engine Is On The Right. A More Detailed BTE Map Is Not Yet Available For The PSA Engine.

In MY2016, VW will be launching a Miller Cycle variant of the 2.0L EA888 turbocharged GDI engine in the U.S. The VW implementation of Miller Cycle has a second Miller Cycle cam profile and uses camshaft lobe switching on the intake cam to go into and out of an EIVC version of Miller Cycle.[23,24] The peak BTE of 37 percent is higher than that of the PSA Miller cycle engine, in part due to a higher expansion ratio (11.7:1 for the VW engine vs. 10.5:1 for the PSA engine). Like the PSA engine, the VW uses high-pressure cEGR. Peak BTE is comparable to the Mazda SKYACTIV-G engines but is available over a broader range of speed and load conditions. Both Atkinson and Miller Cycle engines show broad areas of operation at greater than 32 percent BTE. Figure 5.16 shows a comparison between a MY2010 3.5L NA PFI DOHC V6 and the VW 2.0L EA888 Miller Cycle engine with comparable torque delivery. The area of operation at greater than 32 percent BTE is approximately double for the Miller Cycle engine relative to the DOHC PFI engine. BTE is improved by approximately 40 percent at light load for the Miller Cycle engine and peak BTE is improved approximately 6 percent.

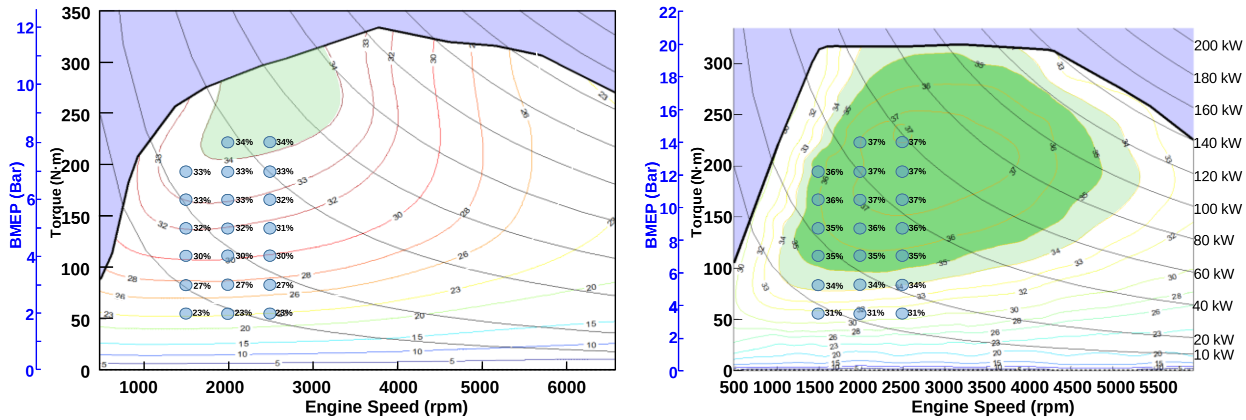


Figure 5.16 Comparison of BTE for A Representative MY2010 3.5L NA PFI V6 Engine[P] (Left) And A Downsized 2.0L I4 Miller Cycle Engine[Q] (Right).

Note: The Light Green Area Shows Regions of >34% BTE. The Dark Green Area Shows a Region >35% BTE.

Since VW has published detailed data for both Miller Cycle and a turbocharged GDI (non-Miller) variants of the EA888 series of engines, a more direct comparison between turbocharged, downsized GDI and Miller Cycle engines is possible. Figure 5.17 shows BTE for both variants of the 2.0L I4 VW EA888 engine. When comparing BTE at comparable BMEP, there is a 6-10 percent incremental improvement for the Miller Cycle engine relative to the turbocharged GDI engine over a broad area of operation from 1500-2500 rpm and from 2-bar to 12-bar BMEP (i.e., below 55 - 60 percent of peak BMEP - areas of importance for the regulatory drive cycles).[R] Comparing BTE of the 2.0 Miller cycle variant to the smaller displacement, 1.8L version of the same engine family (similar 22-bar BMEP to the 2.0L turbocharged GDI, but equivalent torque to the 2.0L Miller Cycle engine) lowers the incremental effectiveness for Miller Cycle to approximately 4-7 percent relative to a turbocharged GDI engine and comparable partial load operation from 1500-2500 rpm. Confidential business information from a Tier 1 automotive supplier provided an estimate of approximately 5 percent CO_2 combined-cycle incremental benefit for Miller Cycle relative to a 24-bar BMEP turbocharged, downsized engine and a loss of approximately 8-12 percent peak BMEP due to reduced volumetric efficiency for Miller Cycle. This is consistent relative to the data published by VW.

[P] Based upon engine dynamometer data provided to EPA under a contract with PQA and Ricardo, "Light Duty Vehicle Complex Systems Simulation" EPA Contract No. EP-W-07-064, work assignment 2-2.

[Q] Adapted from Wurms et al. 2015.[538]

[R] Note that VW did not significantly change the turbocharging system when applying Miller Cycle to this engine family, so the Miller Cycle variant has a peak BMEP of 20-bar instead of 22-bar due to the reduced induction from LIVC. Turbocharger improvements (e.g., higher pressure ratio and different flow characteristics) would be necessary to maintain the 2.0L Miller Cycle engine at 22-bar BMEP, thus comparisons in this case are limited to 20-bar BMEP and below.

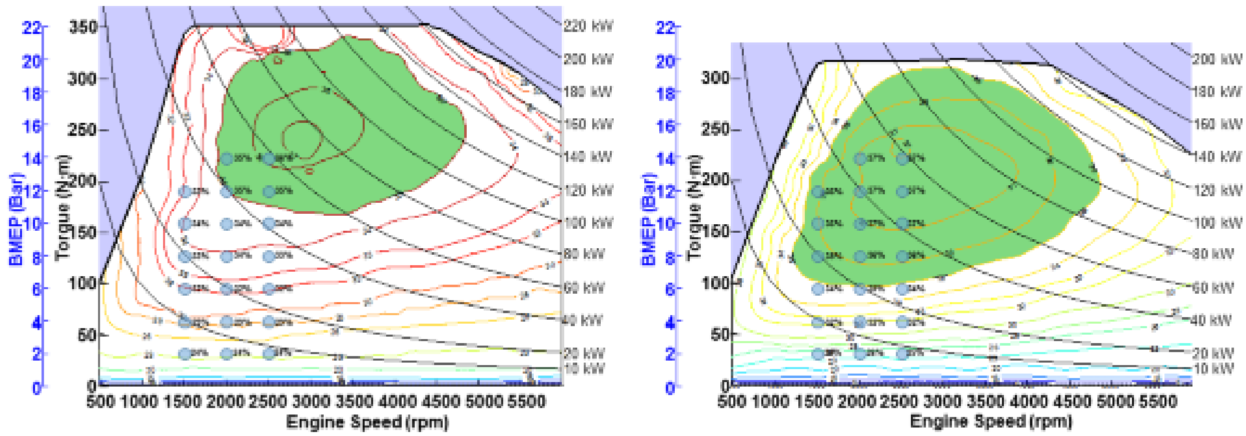


Figure 5.17 Comparison of BTE for 2015 Turbocharged, Downsized GDI (left) and 2017 Miller Cycle (right) variants of the same engine family, the 2.0L VW EA888.[Q]

Note: Green area shows region of high (35%) BTE.

5.2.2.11 Light-duty Diesel Engines

Diesel engines have characteristics that differ from gasoline spark ignition (SI) engines and allow improved fuel efficiency, particularly at part-load conditions. These include reduced pumping losses due to lack of (or greatly reduced) throttling, and a combustion cycle that operates at a higher compression ratio and at very lean air/fuel ratio when compared with an equivalent-performance gasoline engine. Operating with a lean-of-stoichiometric air/fuel ratio poses challenges with respect to NOx control, requiring either a NOx adsorption catalyst (NAC), urea or ammonia-based selective catalytic reduction (SCR) or some combination of NAC and SCR in order to meet Federal Tier 3 and California LEV III NOx emissions standards. Beginning with Federal Tier 2 emission standards, it has also been necessary to equip light-duty diesels with catalyzed diesel particulate filters (CDPFs) in order to comply with light duty PM emission standards.

Detailed analysis of the vehicle simulation results used within the FRM uncovered some shortcomings within the MSC EASY5 vehicle simulations used as light-duty diesel vehicle GHG effectiveness inputs into the Ricardo Surface Response Model. The modeled light-duty diesel technology packages did not operate in the most efficient regions of engine operation. This may have been in part due to inconsistencies in the application of the optimized shift strategy and in part due to an oversight that resulted in the apparent oversizing of light-duty diesel engine displacements. For example, plotting the average engine speed and load operating points over the regulatory drive cycles for the MSC EASY5 diesel simulations on top of the diesel engine maps showed that there was significant potential for improvement in the choice of selected gear. As a result, additional analyses using the ALPHA vehicle simulation model have been conducted for light-duty diesel engine technology packages in order to update GHG effectiveness from these packages.

Light-duty diesel engines have also evolved considerably over the last five years, particularly in Europe. Modern light-duty diesel engine designs appear to be following similar trends to those of turbocharged GDI engines and, in some cases, heavy-duty diesel engine designs, including:

1) Engine downsizing (increased peak BMEP)
2) Engine down-speeding
3) Advanced friction reduction measures
4) Reduced parasitics
5) Improved thermal management
6) Use of a combination of both low- and high-pressure-loop cooled EGR
7) Advanced turbocharging, including the use of VNT and sequential turbocharging
8) Incorporation of highly-integrated exhaust catalyst systems with high NOx and PM removal efficiencies
9) Adoption high-pressure common rail fuel injection systems with higher injection pressures and increased capability (i.e., multiple injections per firing cycle)

The highest BMEP engines currently in mass-production for high-volume light-duty vehicle applications are all diesel engines. MY2016-2017 light-duty diesel engines are available from Honda, BMW and Mercedes Benz in the EU with approximately 26-bar to 29-bar BMEP and peak cylinder pressures at or above 200-bar. [25,26,27] The light-duty diesel technology packages used in the FRM analyses relied on engine data with peak BMEP in the range of 18 - 20 bar. These were engine configurations using single-stage turbocharging with electronic wastegate control, high-pressure or low-pressure (single-loop) cooled EGR, and common-rail fuel injection with a 1800 bar peak pressure. The cost analysis in the FRM for advanced light-duty diesel vehicles assumed use of using a DOC+DPF+SCR system for meeting emissions standards for criteria pollutants.

In response to EPA Heavy Duty GHG emissions standards, large Class 8 heavy-duty truck engine designs have exceeded 50 percent BTE.[28,29] Despite their inherent differences, there now appears to be a significant transfer of technology from heavy-duty diesel engines to much smaller bore, higher speed light-duty diesel engines underway, particularly for engines with high BMEP. Use of CAE tools to design complex, stepped-geometry steel piston crowns and the use of carefully designed piston oil-cooling galleries result in remarkably similar approaches when comparing recent approaches to heavy-duty truck piston designs to recent light-duty diesel engine piston designs such as that of the Mercedes-Benz OM654.[28,30] The Mercedes-Benz OM654 engine incorporates other design elements that are similar to current heavy-duty diesel engine designs, including driving the camshaft and some auxiliaries off of the rear of the engine, the use of a high pressure common rail (HPCR) fuel injection systems with 2050 bar peak pressure and the use of a VNT turbocharger. BMW's B57 light-duty diesel engine used in the MY2017 BMW 730d and 740d uses an HPCR fuel injection system currently with 2500 bar peak pressure and with capability to expand peak pressures to 3000-bar. Driving injection pressures higher allows more flexibility for use of multiple injections and allows better optimization of combustion phasing. Modern, high BMEP light-duty diesel engines using conventional diffusional combustion are capable of peak BTE of approximately 42 percent (see Figure 5.18).[31]

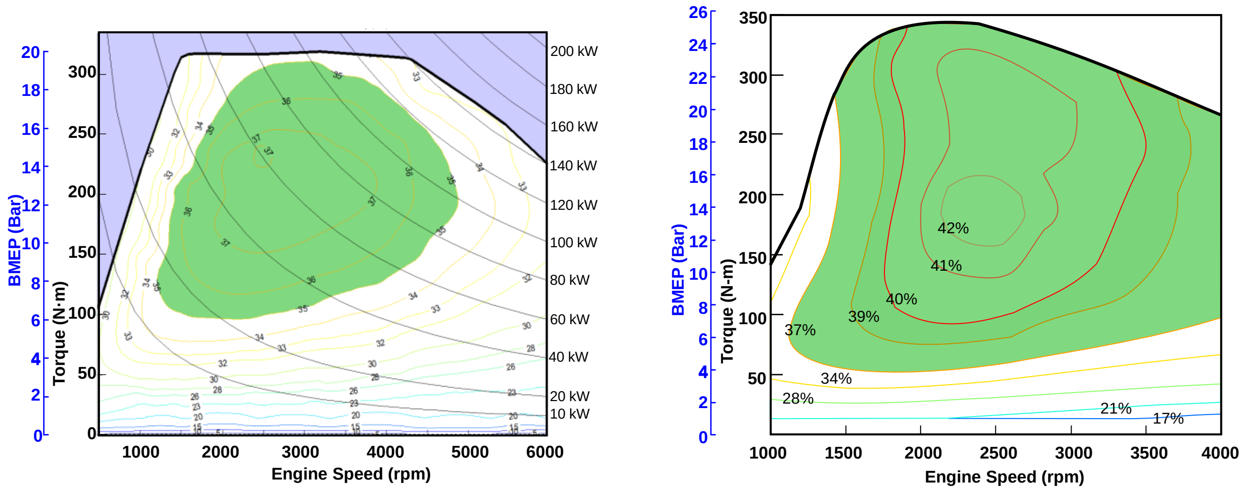


Figure 5.18 Comparison Of BTE For A Downsized SI 2.0L I4 Miller Cycle Engine (Left)[S] And A 1.7L I4 Turbocharged Diesel Engine With HPCR, Low And High Pressure Loop Cegr, And VNT Turbocharger (Right)[T].

Note: Green area shows region of high (35%) BTE.

Advanced turbocharging and cooled EGR systems allow higher rates of EGR to be driven and, when combined with more capable, higher pressure (2000-3000 bar) HPCR systems can allow a degree of operation at light loads using pre-mixed charge compression ignition (PCCI) or other low-temperature modes of combustion with inherently low NOx and PM emissions and reduced thermal losses over a broader area of engine operation. Cummins "Light-duty Efficient, Clean Combustion" engine development program for the U.S. DOE used mixed-mode, part-load PCCI/high-load diffusional combustion approach and achieved a 20 percent improvement in uncorrected city-cycle fuel economy (e.g., from 20.3 mpg to 24.5 mpg) when compared to a more conventional diesel in a 5000 lb. inertial test weight SUV at Tier 2, Bin 5 emissions levels. Peak BTE for the PCCI combustion mode was approximately 46 percent compared with 42 percent peak BTE for conventional diffusional diesel combustion. Cummins developed a similar dual-mode combustion approach as part of the Advanced Technology Powertrains for Light-Duty (ATP-LD) and the Advanced Technology Light Automotive Systems (ATLAS) engine development programs for the U.S. DOE.[32,33] The engines developed as part of this program combined dual-mode PCCI/diffusional combustion together with further improvements to the turbocharger and charge air cooler systems, improved integration of the catalytic CDPF and urea-SCR systems and addition of a NAC system for storage of cold-start NOx emissions. Developmental engines and emissions control systems were integrated into Nissan Titan full-size 2-wheel-drive pickup trucks and achieved emissions consistent with Tier 3 Bin 30 compliance and 21.8/34.3/26.0 City/Highway/Combined (uncorrected) fuel economy at a 5500 lb. inertial test weight. A similar engine used in the mid-size Nissan Frontier 4-wheel drive pickup at reduced peak BMEP (21.3 bar vs. 23.4 bar in the Titan demonstration) achieved a 35 percent

[S] Adapted from Wurms et al. 2015.[538]
[T] Adapted From Busch Et Al. 2015.[31]

combined cycle fuel economy improvement relative to the MY2015 4.0L PFI V6 Nissan Frontier.[34]

5.2.2.12 Thermal Management

Most recent turbocharged engine designs now use head-integrated, water-cooled exhaust manifolds and coolant loops that separate the cooling circuits between the engine block and the head/exhaust manifold(s) (Figure 5.19). Examples include the head-integrated exhaust manifolds (IEM) and split-coolant loops used with the Ford 1.0L I3, 1.5L I4, 2.0L I4 and 2.7L V6 EcoBoost engines, the 2.0L VW EA888 engine, the GM EcoTec SGE 1.0L 3-cylinder and 1.4L 4 cylinder engines, and the PSA 1.2L EB PureTech Turbo. The use of IEM and split-coolant-loops is now also migrating to some naturally aspirated GDI and PFI engines, including the GM 3.6L V6 LFX and EcoTec 1.5L engines and the 1.0L 3-cylinder Toyota 1KR-FE ESTEC. These types of thermal management systems were included in the FRM analysis of turbocharged GDI engines at BMEP levels of 24-bar and above but were not considered for turbocharged engines at lower BMEP levels or for naturally aspirated engines. Benefits include:

- Improved under-hood thermal management (reduced radiant heat-load)
- Reduced thermal gradients across the cylinder head
- Reduction in combustion chamber hot spots that can serve as pre-ignition sources
- Improved knock limited operation
- Reduce or eliminate enrichment required for component protection, particularly at low-speed/high-load conditions
    - Enable additional engine “down-speeding” without encountering enrichment
- Improved control of turbine inlet temperature (turbocharged engines only)
    - Enable use of lower-cost materials turbine and turbine housing materials
    - Enable use of variable-geometry turbines similar to light-duty diesel applications
- Improved catalyst durability
- Shorter time to catalyst light-off after cold-start
- Improved coolant warmup after cold start
- Reduced noise
- Lower cost and parts count
    - Improved durability (fewer gaskets to fail)
- Reduced weight (savings of approximately 1 kg/cylinder)

Figure 5.19 Exhaust Manifold Integrated Into a Single Casting with the Cylinder Head

5.2.2.13 Reduction of Friction and Other Mechanical Losses

In urban driving, approximately 60 percent of engine losses are due to mechanical losses, including engine friction.[35] Piston and cylinder friction from the piston rings and piston skirts account for 35 percent or more of engine friction in modern light-duty gasoline engines and approximately 50 percent of engine friction in modern light-duty diesels engines.[35,36,37] The remaining frictional losses are primarily due to crankshaft, connecting rod, valvetrain and balance shaft friction. Piston skirt friction accounts for approximately 30 percent of piston friction. Molybdenum disulfide (MoS_2) and Diamond-like carbon (DLC) piston skirt coatings have demonstrated part-load engine friction reductions of approximately 16 percent and 20 percent, respectively.[36] Improvements in cylinder bore surface treatments such as plasma coatings[26,27,38] and laser roughening[39] have also been introduced in recent engine designs to reduce engine friction and improve cylinder bore wear characteristics.

Offsetting the crankshaft from the bore centerline, sometimes referred to as a désaxé cylinder arrangement, can be used to reduce side forces on the piston and piston rings during the power stroke, reducing friction piston/liner friction and reducing component wear.[40] For example, the 2ZR-FXE engine used in the 2009-2015 Toyota Prius and the 2ZR-FE engine in the 2009-2016 Toyota Corolla have the crankshaft centerline shifted 8 mm towards the intake side of the engine to reduce friction.[41]

Schaeffler has developed roller bearings that can be applied to the first and last crankshaft main bearings without the added complexity of using built crankshafts or split main bearings to reduce crankshaft friction and increase front journal load bearing capability when used with higher power P0 mild hybrid systems. Roller bearing balance shafts for 3- and 4-cylinder engines have also been developed by Schaeffler, BMW and others that can reduce balance shaft friction by approximately 50 percent.

In addition to reducing engine mechanical losses, engine friction reduction also improves engine restart when combined with stop/start systems. Reducing engine friction can also allow additional engine downspeeding while maintaining idle and off-idle engine NVH characteristics.

Hyundai and Delphi used a MY2011 2.4L 4-cylinder GDI engine to demonstrate a combined-cycle fuel economy improvement of 4 percent by using a combination of a MoS_2 piston skirt coating, CrN physical vapor-deposition coated piston rings, low tension oil control rings and engine downspeeding.[42] They also achieved a further 2.9 percent combined-cycle fuel economy improvement through use of a 2-stage variable displacement oil pump.

5.2.2.14 Potential Longer-Term Engine Technologies

In addition to the engine technologies considered for this Draft TAR, and discussed above, there are many other engine technology development efforts underway that may be fruitful in the longer-term. While introduction of engines using these combustion concepts may occur prior to 2025, EPA and NHTSA do not expect significant penetration of these technologies into the light-duty vehicle fleet in the 2022-2025 timeframe.

Homogenous charge compression ignition (HCCI), gasoline compression ignition and other dilute, low-temperature compression ignition gasoline combustion concepts are topics of considerable automotive research and development due to the potential for additional pumping loss improvements at light and partial load conditions and reduced thermal losses. Challenges remain with respect to combustion control, combustion timing, and, in some cases, compliance with Federal Tier 3 and California LEV3 NMOG+NO_X standards.

Engines using variable compression ratio (VCR) appear to be at a production-intent stage of development, but also appear to be targeted primarily towards limited production, high performance and very high BMEP (27-30 bar) applications. At lower BMEP levels, other concepts (e.g., Atkinson Cycle for NA applications, Miller Cycle for boosted applications) provide a similar means to vary effective compression ratio for knock mitigation with reduced cost and complexity with some tradeoffs with respect to volumetric efficiency.

One vehicle manufacturer recently entered production with a water injection system for knock mitigation. Injection of water and water/methanol or water/ethanol mixtures into the intake systems of turbocharged and/or mechanically supercharged engines for knock mitigation is not a new concept. Aircraft engines predating World War II and some of the first turbocharged automobile applications for the U.S. market in the 1960's used such systems for knock mitigation. Water injection systems compete with other means of knock mitigation (EGR, Atkinson Cycle, Miller Cycle, and IEM/split-cooling) that do not require fluid replenishment. Current and near term applications appear to be limited to low-volume production, high performance vehicles.

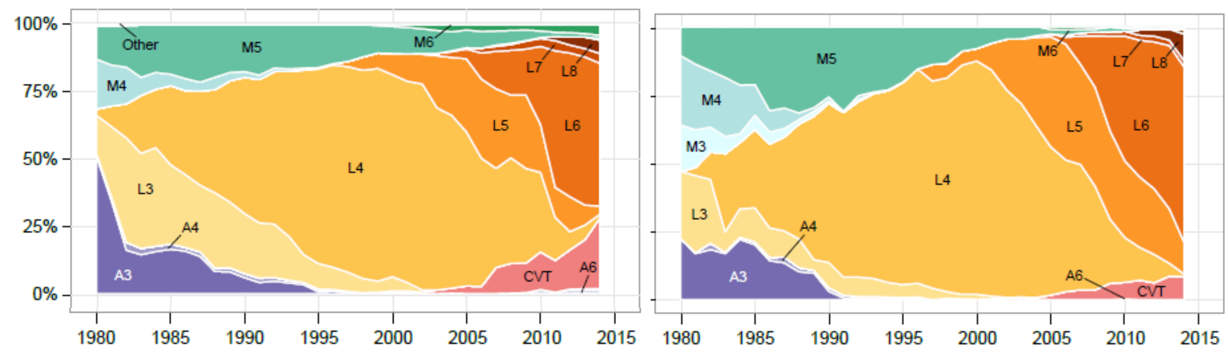
The DOE Co-Optimization of Fuels and Engines (Co-Optima) initiative aims to improve near-term efficiency of spark-ignition (SI) and compression ignition engines through the identification of fuel properties and design parameters of existing base engines that maximize performance.

According to DOE, Co-Optima is a first-of-its-kind effort brings together multiple DOE offices, national laboratories, and industry stakeholders to simultaneously conduct tandem fuel and engine R&D and deployment assessment in order to maximize energy savings and on-road vehicle performance, while also reducing long-term transportation-related petroleum consumption and GHG emissions. Two parallel research tracks focus on: 1) improving near-term efficiency of spark-ignition (SI) engines through the identification of fuel properties and design parameters of existing base engines that maximize performance. The efficiency target represents a 15% fuel economy improvement over state-of-the-art, future light-duty SI engines with a market introduction target of 2025; and 2) simultaneous testing of new fuels with existing CI engines (as well as advanced compression ignition [ACI] combustion technologies as they are developed) to enable a longer-term, higher-impact series of synergistic solutions. The fuel economy target represents a 20% improvement over state-of-the-art, future light-duty SI engines with a market introduction target of 2030. By using low-carbon fuels, such as biofuels, GHGs and petroleum consumption can be further reduced. EPA and NHTSA will continue to closely follow the Co-Optima program and provide input to DOE, including through EPA's technical representative on the Co-Optima External Advisory Board, as this program has the potential to provide meaningful data and ideas for GHG and fuel consumption reductions in the light-duty vehicle fleet for 2026 and beyond.

5.2.3 Transmissions: State of Technology

5.2.3.1 Background

The function of a transmission system is to reduce the relatively high engine speed and increase the torque, so that the power output of the engine can be coupled to the wheels. The complete drivetrain includes a differential (integral to the transmission on front-wheel-drive vehicles; separate on rear-wheel-drive vehicles) which provides further speed reduction, and often a hydraulic torque converter which provides significant torque multiplication at low speed conditions. The complete drivetrain – torque converter, transmission, and differential – is designed as a set to best match the power available from the engine to that required to propel the vehicle.



Car

Truck

Transmission	Lockup?	Number of Gears	Key
Automatic Semi-Automatic Automated Manual	No	3	A3
		4	A4
		5	A5
		6	A6
	Yes	2	L2
		3	L3
		4	L4
		5	L5
		6	L6
		7	L7
		8	L8

Transmission	Lockup?	Number of Gears	Key
Continuously Variable	–	–	CVT
Manual	–	3	M3
		4	M4
		5	M5
		6	M6
Other	–	–	Other

Figure 5.20 Transmission Technology Production Share, 1980 – 2014[43]

Different transmission architectures are available for use in light duty vehicles. Conventional automatic transmissions (ATs) are the most popular type, and still dominate the light-duty fleet, as seen in Figure 5.20. Manual transmissions (MTs), although less popular than in the past, are also still part of the fleet. Both ATs and MTs have, among other improvements, seen an increase in the number of gears employed. Figure 5.20 shows the recent gains in six, seven, and eight-speed transmissions in both the car and light truck segment. Two other transmission types have also seen an increase in market share. These are dual-clutch transmissions (DCTs), which have significantly lower parasitic losses than ATs, and continuously variable transmissions (CVTs), which can vary their ratio to target any place within their overall spread. Each of these four types of transmissions is discussed in more detail in the sections below.

5.2.3.2 Transmissions: Summary of State of Technology and Changes since the FRM

In the analysis conducted for the 2017-2025MY FRM, the agencies estimated that DCT transmissions would be very effective in reducing fuel consumption and CO_2 emissions, less expensive than current automatic transmissions, and thus a highly likely pathway used by manufacturers to comply with the regulation. However, DCTs thus far, have been used in only a small portion of the fleet as some OEMs have reported in meetings with the agencies have indicated and some vehicle owners have cited drivability concerns for DCT.[44] On the other hand, the 2017-2025MY FRM analysis also predicted a low effectiveness associated with CVTs (due to the high internal losses and small ratio spans of CVTs in the fleet at that time), and thus CVTs were not included in the FRM fleet modeling. However, internal losses in current CVTs have been much reduced and ratio spans have increased from their predecessors, leading to increased effectiveness and further adoption rates in the fleet, particularly in the smaller car segments. The new CVT's also tend to give the best effectiveness for their cost.

Again in the 2017-2025MY FRM, the agencies estimated that step transmissions with higher numbers of gears (e.g., AT8s) would be slowly phased into the fleet. However, AT8s have been "pulled ahead," appearing in substantial numbers even before 2015MY. In addition, manufacturers have introduced (and/or have plans to introduce) transmissions with even higher numbers of gears (e.g., AT9s and AT10s), a technology that was not considered in the 2017-2025MY FRM.

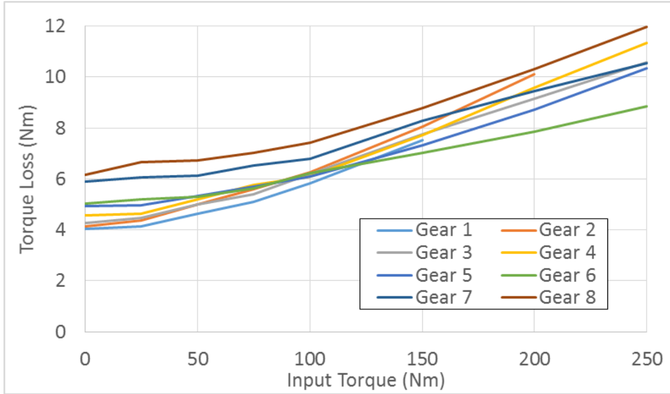
Thus, as highlights of transmission technology analysis in this Draft TAR, (a) the technology packages and vehicle classes where DCTs are applicable have been re-evaluated to reflect manufacturer's current choices, (b) the effectiveness of CVTs has been re-examined and increased to reflect current vintage CVTs and their use in the fleet, and (c) nine and ten-speed transmissions were considered (since they are or will be in the fleet) when determining the effectiveness of future transmissions in the fleet.

5.2.3.3 Sources of Transmission Effectiveness Data

In addition to the sources of transmission effectiveness data cited in the 2017-2025 LD FRM, the agencies also used data from a wider range of available sources to update and refine transmission effectiveness for this analysis. These sources included:

1) Peer-reviewed journals, peer-reviewed technical papers, and conference proceedings presenting research and development findings
2) Data obtained from transmission and vehicle testing programs, carried out at EPA-NVFEL, ANL, and other contract laboratories
3) Modeling results from simulation of current and future transmission configurations
4) Confidential data obtained from OEMs and suppliers on transmission efficiency

For transmission testing programs, EPA contracted with FEV Engine Technologies to test specific transmissions in a transmission component test stand. The testing program was primarily designed to determine transmission efficiency and torque loss over a range of input speeds, input loads, and temperatures. In addition, other driveline parameters, such as transmission rotational inertia and torque converter K-factor were characterized. Two automatic transmissions have been characterized in this test program, which is still on-going. Torque loss maps were generated for both a six-speed 6T40 GM automatic transmission and an eight-speed 845RE FCA automatic transmission (see Figure 5.21).



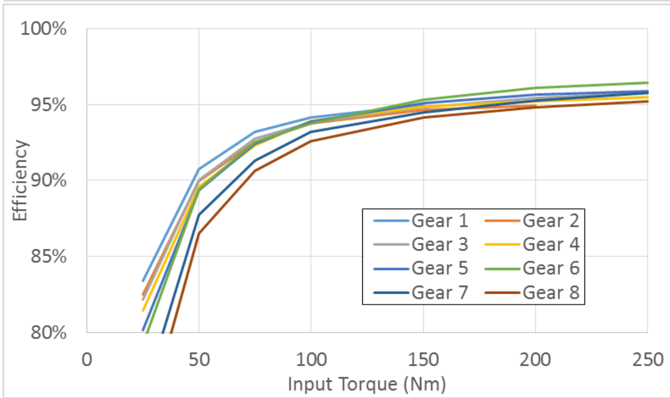


Figure 5.21 Average Torque Losses (Left) And Efficiency (Right) In Each Gear For An Eight-Speed 845RE Transmission From A Ram, Tested At 100 °C And With Line Pressures Matching Those Measured In-Use In The Vehicle. Torque Losses Were Averaged Over 1000 Rpm - 2500 Rpm. This Transmission Is A Clone of the ZF 8HP45.

In addition to contracting to test specific transmission, EPA has obtained torque loss maps and/or operational strategies for current generation transmissions from manufacturers and suppliers. These maps are CBI, but have been used to inform EPA on the effectiveness of transmissions currently on the market. Maps obtained from manufacturers and suppliers include examples of both CVTs and DCTs.

To characterize transmission and torque converter operation strategies, EPA has also performed multiple chassis dynamometer tests of current-generation vehicles equipped with a range of transmission technologies. The transmission gear and torque converter state (as well as other vehicle parameters) were recorded over the FTP, HWFET, and US06 cycles. The recorded data were used to determine the drive strategy for the engine-transmission pair in the vehicle.

The transmission losses and shifting strategy were used as modeling inputs to EPA's full-vehicle ALPHA model.[45] The shifting strategy was parameterized to allow sufficient flexibility to maintain reasonable shift strategies while changing other vehicle attributes.[46]

EPA also performed a study using chassis dynamometer testing to determine effectiveness of transmissions. In particular, two Dodge Chargers, one with a five-speed transmission and one with an eight-speed transmission, were tested on the dynamometer. Other than the transmission, these vehicles had identical powertrains, and so provided an ideal opportunity to test the effect of different transmissions in the vehicle.[47] Multiple repetitions of the FTP and HWFET, cycles were run, with the result that the Charger equipped with the eight-speed transmission exhibited on average a 6.5 percent reduction in fuel consumption over the five-speed Charger on the combined FTP/HWFET cycle. The eight-speed Charger also exhibited an increase in acceleration performance, according to tests by *Car and Driver,* with, for example, a 0.5 second improvement in 0-60 time.[48,49]

NHTSA has leveraged work performed over the past 15 years by Argonne National Laboratory with Autonomie under funding from the U.S. Department of Energy. Leveraging vehicle test data for a large number of vehicles measured at Argonne's Advanced Powertrain Research Facility (APRF), shifting algorithms were developed and validated for multiple transmission technologies (i.e., automatic, CVT, DCT) and gear number (i.e., 6 vs 8 speeds).[50] Detailed instrumentation was also critical in developing component models and controls for advanced transmissions such as Dual Clutch.[51] While specific transmission gear ratios and shifting algorithms were used during the validation process, a different approach was used to design the transmission gear ratios to properly quantify the effectiveness of the technology. Argonne used an algorithm published by Naunheimer along with a range of constraints to design their transmission gear ratios.[52] A set of efficiencies for each gear was selected to represent today's leading technologies across all transmission types to ensure proper comparison. Calibration of the shifting algorithms was performed within a set of constraints to ensure proper driving quality. The constraints were defined based on vehicle test data.

5.2.3.4 Sources of GHG Emission Improvements: Reduction in Parasitic Losses, Engine Operation, and Powertrain System Design

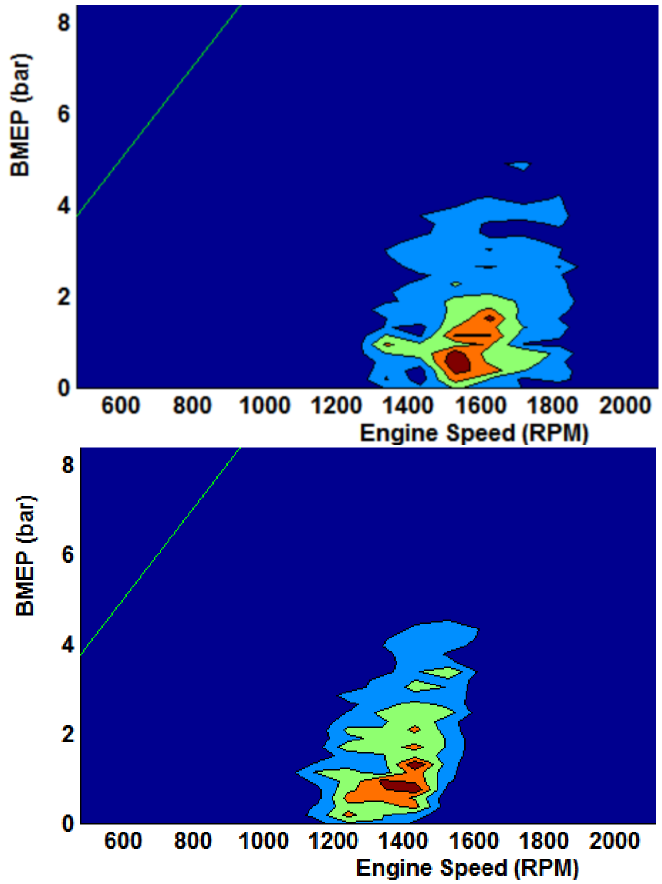
The design of the transmission system can affect vehicle GHG emissions in two ways. First, reducing the energy losses within the transmission (and/or torque converter) reduces the energy required from the engine, which also reduces GHG emissions. Reducing transmission losses can be accomplished by increasing gearing efficiency, reducing parasitic losses, altering the torque converter lockup strategy, or other means. A more in-depth discussion of internal energy loss reduction is included in the "Transmission Parasitic Losses" and "Torque Converter Losses and Lockup Strategy" sections below.

Another method to decrease GHG emissions is to design the entire powertrain system - the engine and transmission - to keep the engine operating at the highest available efficiency for as much time as possible. Transmissions with more available gears (or, at the extreme, continuously variable transmissions) can maintain engine operation within a tighter window, and thus maintain operation nearer the highest efficiency areas of the engine map. Likewise, transmissions with a wider ratio spread can maintain engine operation nearer the highest efficiency areas of the engine map for a wider range of vehicle speeds, in particular lowering the engine speed at highway cruise for reduced GHG emissions.

In addition, the highest engine efficiencies for a given power output tend to be at lower speeds, so transmission control strategies that allow very low engine speeds (i.e., "downspeeding") also reduce GHG emissions. Shifting strategies are discussed in the "Transmission Shift Strategies" section below.

As a practical matter, transmissions with an increased number of gears tend also to have a wider ratio. For example, the ZF 8HP eight-speed RWD transmission has a spread of 7.07,[53] the Aisin eight-speed FWD transmission has a spread of 7.58,[54] the Mercedes 9G-TRONIC nine-speed transmission has a ratio spread of 9.15,[55] and the ZF 9HP48 nine-speed FWD transmission has a spread of 9.8.[56]

The effects of additional gears and a wider ratio can be seen in Figure 5.23, which compares engine operation of the same engine when coupled with a six-speed transmission and with an eight-speed transmission. Compared to the six-speed transmission, the eight-speed transmission allows the engine to operate over a narrower speed range and at lower speeds, both of which tend to reduce GHG emissions.



(a) Six-speed (b) Eight-speed

Figure 5.22 Engine Operating Conditions for Six-Speed (Left) and Eight-Speed (Right) Automatic Transmissions on the FTP-75 Drive Cycle[57]

The dominant trends in transmissions have been toward a larger number of gears and a wider ratio spread. However, it is recognized, including by the 2015 NAS Report, that above certain values, additional gearing and ratio spread provide minimal additional fuel economy benefits.[58] [59] [60] Thus, increasing the number of gears (except when going to effectively infinite the case of CVT transmissions) and ratio spread beyond that exhibited by the current market leaders is unlikely to result in significant fuel consumption benefits, although other vehicle attributes such as acceleration performance and shift smoothness may benefit.

In fact, it is well-understood that typical implementations of high-gear transmissions provide both fuel consumption and acceleration performance benefits. Performance benefits come from two factors: first, the gear ratio spread of transmissions with higher number of gears will typically "straddle" the ratio spread of the lower number of gear transmission they replace (i.e., first gear is a numerically higher ratio and the final gear is a numerically lower ratio). This provides more launch torque and quicker acceleration from stop. Second, the gear ratios of sequential gears tend to be closer together in transmissions with a higher number of gears. This not only narrows the on-cycle operation range of the engine for improved fuel economy (as in Figure 5.23), but also maintains engine performance nearer the maximum power point in high power demand situations for better acceleration performance at higher vehicle speeds.

To determine the relative cost-effectiveness of different technologies, it is important to account for *all* technology benefits where possible. As the NAS point out, "objective comparisons of the cost-effectiveness of different technologies for reducing FC can be made only when vehicle performance remains equivalent."[61] This is particularly relevant for advanced transmissions, which do affect performance when coupled with the same engine as transmissions with a lower number of gears. In evaluating information on measured or modeled fuel consumption effects of advanced transmissions, it is important to consider both reported fuel consumption benefits and any simultaneous acceleration performance benefits, so that transmission effectiveness can be objectively and fairly estimated.

Transmission design parameters that substantially affect engine operation - gearing ratios, ratio spread, and shift control strategy - are all used to optimize the engine operation point, and thus the effectiveness of these transmission parameters depend in large part on the engine it is coupled with. Advanced engines incorporate new technologies, such as variable valve timing and lift, direct injection, and turbocharging and downsizing, which improve overall fuel consumption and broaden the area of high-efficiency operation. With these more advanced engines, the benefits of increasing the number of transmission gears (or using a continually variable transmission) diminish as the efficiency remains relatively constant over a wider area of engine operation. For example, the NAS estimated that the benefit of an eight-speed transmission over a six-speed transmission is reduced by approximately 15 percent when added to a modestly turbocharged, downsized engine instead of a naturally aspirated engine.[62] Thus, the effectiveness of transmission speeds, ratio, and shifting strategy should not be considered as an independent technology, but rather as part of a complete powertrain.

Additionally, because the engine and transmission are paired in the powertrain, the most effective design for the engine-transmission pair is where the entire powertrain is running at the highest combined efficiency. This most effective point may not be at the highest engine efficiency, because a slightly different operation point may have higher transmission efficiency, leading to the best combined efficiency of the entire powertrain.

5.2.3.5 Automatic Transmissions (ATs)

Conventional planetary automatic transmissions remain the most numerous type of transmission in the light duty fleet. These transmissions will typically contain at least three or four planetary gear sets, which are connected to provide the various gear ratios. Gear ratios are selected by activating solenoids which engage or release multiple clutches and brakes. A cutaway of a modern RWD transmission (in this case the ZF 8HP70) is shown in Figure 5.23.

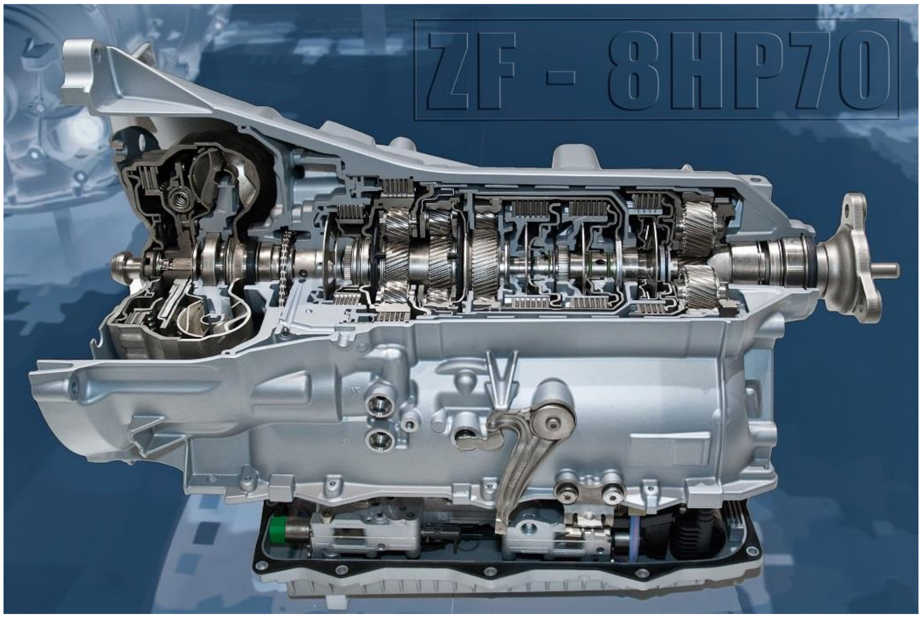


Figure 5.23 ZF 8HP70 Automatic Transmission[63]

Automatic transmissions are packaged with torque converters which provide a fluid coupling between the engine and the driveline, and provide a significant increase in launch torque. When transmitting torque through this fluid coupling, energy is lost due to the churning fluid. These losses can be eliminated by engaging ("locking up") the torque convertor clutch to directly connect the engine and transmission. A discussion of torque converter lockup is continued in the "Torque Converter Losses and Lockup Strategy" section below.

In general, ATs with a greater number of forward gears (and the complementary larger ratio spread) offer more potential for CO_2 emission reduction, but at the expense of higher control complexity. Transmissions with a higher number of gears offer a wider speed ratio and more opportunity to operate the engine near its most efficient point (as shown in the previous section).

In the past few years, manufacturers have taken advantage of this fact. Four- and five-speed automatic transmissions, which dominated the market in 2005, have substantially declined in number, being replaced by six-speed and higher transmissions (see Figure 5.20 above). In fact, the average number of AT gears in the fleet has rapidly increased, and in 2014 was above six for both cars and trucks (see Figure 5.24 below).

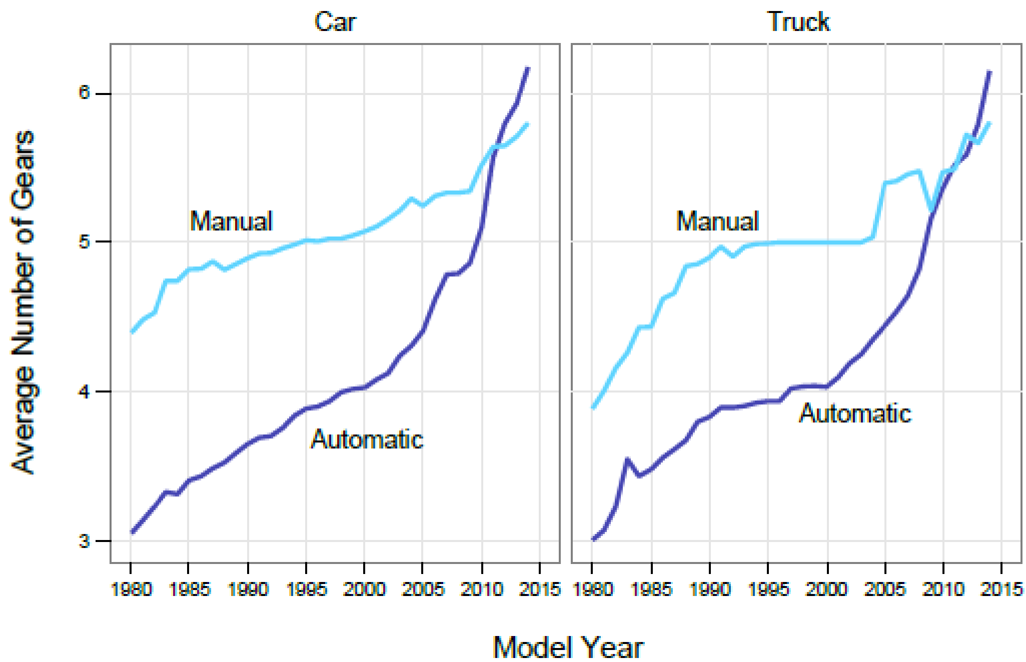


Figure 5.24 Average Number of Transmission Gears for New Vehicles (excluding CVTs)[64]

As six-speed ATs have supplanted the four-and five-speeds, seven- and eight-speed transmissions have also appeared on the market. In the FRM, eight speed ATs were not expected to be available in any significant number until approximately 2020. However, even as of 2014 seven- and eight-speed transmissions occupy a significant and increasing portion of the market.

Seven-speed transmissions currently available include the RWD 7G-Tronic from Mercedes and the JATCO JR710E available in Nissan products. RWD eight-speed transmissions available include offerings from General Motors and Hyundai, as well as transmission suppliers Aisin and ZF. The ZF 8HP, introduced in 2009, has been incorporated into offerings from a range of manufacturers, including Fiat/Chrysler, Jaguar/Land Rover, and Volkswagen. ZF has begun production of a second generation of 8HP transmissions (the 8HP50), which features a higher ratio spread, lower drag torque, and improved torsional vibration absorption compared to the first generation.[65] Aisin also offers a FWD eight-speed used by multiple manufacturers. This includes use in the compact 2016 Mini Cooper Clubman,[66] a vehicle smaller than those assumed eligible for eight-speed transmissions in the FRM.

In the FRM, the agencies limited their consideration of the effect of additional gears to eight-speed transmissions. However, some ATs with more than eight gears are already in production, and more examples are in development. At this time, nine-speed transmissions are being manufactured by ZF[67] (which produces a FWD nine-speed incorporated into Fiat/Chrysler, Honda, and Jaguar/Land Rover vehicles[68]) and Mercedes[69] (which produces a RWD nine-speed). In addition, Ford and General Motors have announced plans to jointly design and build nine-speed FWD transmissions and ten-speed RWD transmissions (2017 F150 and 2017 Camaro ZL1), and Honda is developing a ten-speed FWD transmission.[70]

Manufacturers have claimed substantial fuel consumption benefits associated with newer transmissions. ZF claims its first generation 8HP can reduce fuel consumption by 6 percent on the NEDC compared to a circa 2005 ZF 6HP, using the same engine, along with improving vehicle acceleration performance.[71] ZF also outlined a series of potential improvements to the first generation 8HP that could provide an additional 5 to 6 percent fuel consumption reduction on the U.S. combined cycle.[72] The second generation ZF eight-speed[73] is expected to achieve up to 3 percent efficiency gain on the NEDC due to the improvements noted above; ZF also outlined additional potential savings associated with a third generation eight-speed transmission.[74] Likewise, Mercedes clamed a 6.5 percent fuel consumption improvement on the NEDC with its nine-speed transmission compared to the previous seven-speed.[75] It should also be noted that the percent fuel consumption reported on the NEDC drive cycle will be different from the U.S. combined cycles.

In FWD vehicles, ZF claims its nine-speed FWD transmission reduces fuel consumption by 10 percent - 16 percent compared to an early- 2000s six-speed transmission.[76] Aisin claims its new FWD eight-speed transmission decreases fuel consumption 16.5 percent compared to an early generation six-speed, and nearly 10 percent compared to the previous generation six-speed.[77] In addition, the new eight-speed improves acceleration performance. BMW, using the Aisin FWD transmission, reports a 14 percent fuel consumption reduction on the NEDC over the previous six-speed transmission.[78]

These efficiency improvements are due to a range of design changes in the transmissions. In addition to improving the engine operation efficiency through changing the number of gears, overall ratio, and shift points, these transmissions also reduce parasitic losses, change torque converter behavior, and/or shift to neutral during idle. Mercedes claims a total of 6.5 percent fuel economy improvement on the NEDC by using its nine-speed 9G-TRONIC in place of the earlier generation seven-speed.[79] Of this, 2 percent is due to the change in the number of gears, ratio spread, and shift strategy, with the remainder due to transmission efficiency improvements.

With the positive consumer acceptance, higher effectiveness, and increasing production of transmissions with up to ten forward gears, it may be possible that transmissions with even more gears will be designed and built before 2025. Researchers from General Motors have authored a study showing that there is some benefit to be gained from transmissions containing up to 10 speeds.[80] However this appears to be near the limit for improved fuel consumption, and studies have shown that there is no added potential for reduction in CO_2 emissions beyond nine or ten gears.[81] [82] In fact, ZF CEO Stefan Sommer has stated that ZF would not design transmissions with more than nine gears: "We came to a limit where we couldn't gain any higher ratios. So the increase in fuel efficiency is very limited and almost eaten up by adding some weight and friction and even size of the transmission."[83] Although manufacturers may continue to add gears in response to consumer preference for other performance attributes, it is unlikely that further increases will provide CO_2 emissions benefits beyond that of optimized eight, nine or ten-speeds.

5.2.3.6 Manual Transmissions (MTs)

In a manual transmission, gear pairs along an output shaft and parallel layshaft are always engaged. Gears are selected via a shift lever, operated by the driver. The lever operates synchronizers, which speed match the output shaft and the selected gear before engaging the gear with the shaft. During shifting operations (and during idle) a clutch between the engine and transmission is disengaged to decouple engine output from the transmission.

Manual transmissions are in general lighter, cheaper to manufacture, and have lower parasitic losses than automatic transmissions. The 2015 NAS report found the overall energy loss in a manual transmission to be only about 4 percent, as compared to a 13 percent loss in automatic transmissions.[84]

As with ATs, the average number of gears in MTs has increased (Figure 5.24), albeit at a reduced rate compared to ATs. As in ATs, the higher number of gears and associated increase in ratio spread increases potential fuel savings.

However, manual transmissions have only a small market share, estimated at only 3.7 percent in 2014.[85] Automatic transmissions (ATs, CVTs, and DCTs) are more popular at least in part because customers prefer not to manually select gears.

5.2.3.7 Dual Clutch Transmissions (DCTs)

Dual clutch transmissions are similar in their basic construction to manual transmissions, but use two coaxial input shafts with two clutches to shift between the two shafts. By simultaneously opening one clutch and closing the other, the DCT "hands off" power from one shaft to the other, and thus to sequential gears. Unlike the MT, the DCT selects the appropriate gear automatically (as in an AT). DCTs offer an efficiency advantage over a typical automatic because their parasitic losses are significantly lower. In addition, DCTs in general do not require a torque converter, as gradually engaging the clutch (much like with a manual transmission) provides the application of launch torque.

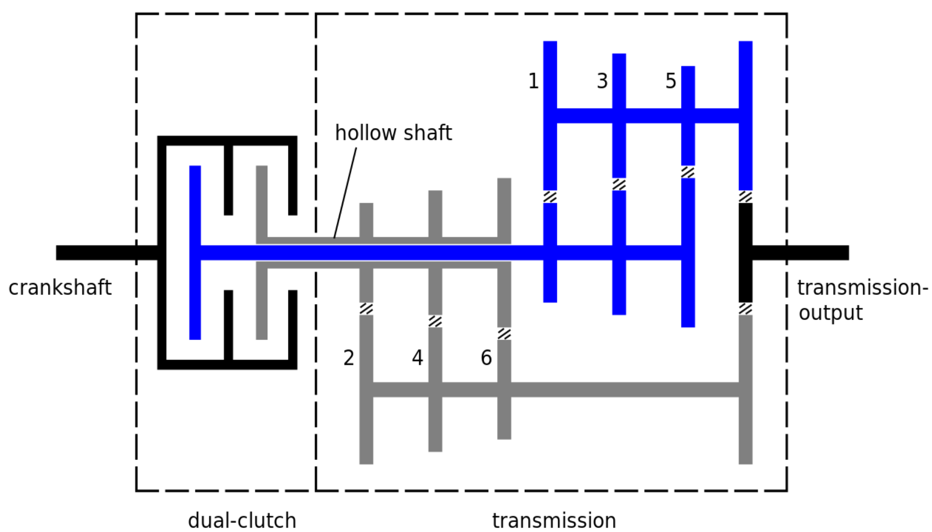


Figure 5.25 Generic Dual Clutch Transmission[86]

Multiple DCTs have been introduced into the marketplace, primarily in six- and seven-speed versions. Volkswagen has used multiple generations of DCTs in their products. Ford has used six-speed DCTs jointly developed with Getrag. Fiat has another version of a six-speed DCT, while both Honda and Hyundai have developed seven-speed versions. Honda introduced an eight-speed DCT with a torque converter on the 2015 Acura TLX.[87]

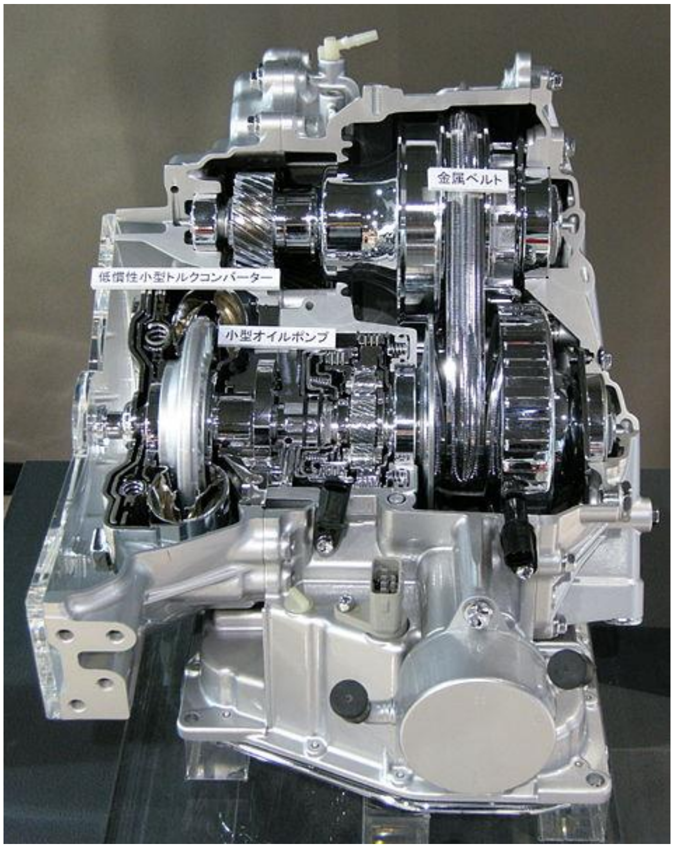
However, DCTs have encountered issues with customer acceptance, and, as the NAS stated in its 2015 report, "are not likely to reach the high penetration rates predicted by EPA/NHTSA ... primarily due to customer acceptance issues."[88] As noted by the NAS in their 2015 report, “This difference in drivability and consumer acceptance [between wet and dry clutch DCTs] can be seen in the comparison of two of Volkswagen's MY2015 vehicles, the VW Golf and the VW Polo. The Golf, with a wet-clutch DCT, has received many positive reviews and awards, while the Polo, with a dry-clutch DCT, has received poor reviews for transmission-related drivability."[89]

Getrag announced the 7DCT300 which has a wet clutch with lubrication on demand (we refer to these as damp clutch DCTs), equaling the efficiency of a dry DCT. The "damp" clutch is also smaller and has a higher tolerance for engine irregularities.[90] Wet/damp clutch DCTs tend to have better consumer acceptance than dry clutch DCTs. The 7DCT300 is available in Europe on the 2015 Renault Espace.

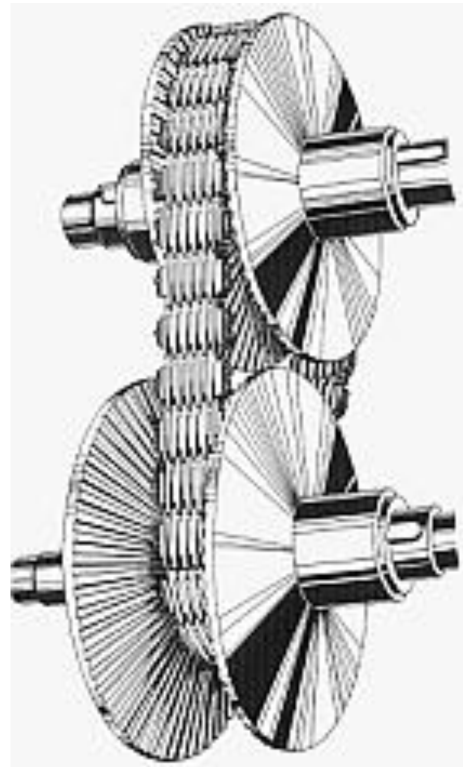
As in ATs, it is expected that additional gears above the current maximum will not significantly decrease fuel consumption and resulting GHG emissions. A 2012 study by DCT manufacturer Getrag indicated that additional gears above seven and additional ratio spread above 8.5 provided minimal additional fuel economy benefits.[91]

5.2.3.8 Continuously Variable Transmissions (CVTs)

Conventional continuously variable transmissions consist of two cone-shaped pulleys, connected with a belt or chain. Moving the pulley halves allows the belt to ride inward or outward radially on each pulley, effectively changing the speed ratio between the pulleys. This ratio change is smooth and continuous, unlike the step changes of other transmission varieties. CVTs were not chosen in the fleet modeling for the 2017-2025MY FRM analysis because of the predicted a low effectiveness associated with CVTs (due to the high internal losses and narrow ratio spans of CVTs in the fleet at that time). However, improvements in CVTs in the current fleet have increased their effectiveness, leading to rapid adoption rates in the fleet. In their 2015 report, the NAS recommended CVTs be added to the list of considered technologies, and the agencies are re-evaluating the cost and effectiveness numbers for this technology.



(a)



(b)

Figure 5.26 (a) Toyota CVT[92] (b) Generic CVT sketch[93]

One advantage of CVT's is that CVT's continue to transmit torque during ratio changes. During a ratio change or shift the energy from the engine is wasted on ATs and some DCTs. ATs and some DCT have a hesitation during shifts caused by the torque disruption during gear changes. This shift feeling is well known to consumers and in some cases comforting to drivers (they miss it when driving a vehicle with a CVT). As mentioned in the AT section ATs efficiency peaks with 9 to 10 gears, while going to a CVT (with an effectively "infinite" number of gear steps) adds a new level of efficiency to the overall system. This is in part due to the fact that CVTs do not need to stop transmitting torque to change ratios.

Another advantage of a CVT is that, within its ratio range, it can maintain engine operation close to the maximum efficiency for the required power. However, CVTs were not considered in the FRM because at the time CVTs had a ratio range of near 4.0, limiting the range where the engine operation could be optimized. In addition, the CVTs were less than 80 percent efficient [94], and thus required more total output energy from the engine. These limitations overwhelmed the CVT’s inherent advantage compared to conventional ATs.

However, in the recent past, manufacturers and suppliers have intensified development of CVTs, reducing the parasitic losses and increasing the ratio spread. The current generation of CVT are now nearly 85 percent efficient, with ongoing work by suppliers to push that number to 90 percent.[95] Ratio spreads for new CVTs from Honda, Toyota, and JATCO now range between 6.0 and 7.0.[96] [97] [98] JATCO has introduced a very small CVT what has a two speed output with take a CVT with a small ratio spread and doubles it for an overall ratio spread of 7.3[99] in the base version and 8.7 in the "wide range" version.[100] As in ATs and DCTs, it is expected that additional increase in ratio range above the current maximum will not significantly decrease fuel consumption and resulting GHG emissions.[101]

Reducing losses in CVTs has been a particular focus of manufacturers. The JATCO CVT8 featured a 40 percent reduction in mechanical losses compared to their earlier generation CVT.[102] The losses were reduced by decreasing the size of the oil pump, implementing a new, higher efficiency belt, and reducing the fluid churning losses. Honda's new compact car CVT increased efficiency 1.0 percent to 1.5 percent at higher vehicle speeds compared to their previous generation CVT.[103] The increased efficiency was primarily due to a reduction in oil pump losses and bearing friction. Honda's new midsize CVT increased efficiency up to 5 percent compared to the earlier generation CVT, primarily by reducing the required hydraulic pressure (by up to 38 percent).[104] Toyota's new K114 CVT reduced torque losses by 22 percent, compared to the earlier generation of CVTs, primarily by reducing the losses associated with the oil pump, and reducing the size of the bearings.[105]

The decreased transmission losses (5 - 10 percent) and increased ratio spread (from 4 to between 6 and 8.7) of CVTs has made them more effective in CO_2 reduction than estimated in the FRM, and thus CVTs are anticipated to be used in an increasing share of the fleet (see Figure 5.20). The supplier JATCO supplies CVTs to Nissan, Chrysler, GM, Mitsubishi, and Suzuki[106] In addition, other manufacturers' – Audi, Honda, Hyundai, Subaru, and Toyota – all make their own CVTs.

The JATCO CVT8 demonstrated a 10 percent improvement in fuel economy for both the highway and city cycles compared to earlier generation CVTs.[107] Honda's new compact car CVT increased fuel economy approximately 7 percent compared to the earlier generation CVT over both the U.S. test cycle and the Japanese JC08 test cycle.[108] Honda's new midsize CVT increased fuel economy 10 percent over the earlier generation 5AT on the U.S. cycle, and 5 percent compared to the earlier generation CVT on the Japanese JC08 test cycle.[109] Toyota's new K114 CVT increased fuel economy by 17 percent on the Japanese JC08 test cycle compared to the earlier generation CVT.[110]

Initial introductions of CVTs suffered from consumer acceptance issues, where customers complained of the “rubber band” feel of the transmission, due to the indirect connection between the driver’s throttle input and the vehicle’s acceleration response. To combat this perception, vehicle manufacturers have added a shift feel calibration to the CVT control strategy, which mimics the feel of a conventional AT.[111] This calibration, although having a slight effect on fuel economy, has improved consumer acceptance.[112]

In this document, only conventional belt or chain CVTs are considered. At least two other technologies – toroidal CVTs and Dana’s VariGlide® technology[113] – are under development and may be available in the 2020-2025 timeframe. The Dana VariGlide is considered a CVP (Continuously Variable Planetary) with the major design difference being it using balls to transmit torque and vary the ratio. Dana has stated that it is currently in development with an OEM. Targeted production could be as early as 2020. These technologies hold promise for increased efficiency compared to current design belt or chain CVTs.

5.2.3.9 Transmission Parasitic Losses

Reducing parasitic loses in the transmission improves drivetrain efficiency and lowers the required energy output from the engine. In general, parasitic losses can come from (a) the oil supply, (b) electricity requirements, (c) drag torque, (d) gearing efficiency, and (e) creep (idle) torque.[114]

5.2.3.9.1 Losses in ATs

A study by ZF suggests that the largest sources of losses over the combined city/highway cycle in conventional automatic transmissions are the oil supply and the drag torque.[115] This is followed by the creep torque (on the city cycle), with the electrical requirements and gearing efficiency being relatively minor.

For conventional ATs, power required to supply oil to the transmission is one of the largest sources of parasitic loss. An oil pump is required for lubrication and for hydraulic pressure for clamping the clutches. A baseline transmission would typically use a gerotor-type pump driven off the torque converter. Replacing or resizing the oil pump can result in a substantial decrease in torque losses. For example, Aisin claims a 33 percent reduction in torque loss in its new generation transmission from optimizing the oil pump,[116] and Mercedes claims a 2.7 percent increase in fuel economy on the NEDC by changing the pumping system.[117] Pump-related losses can be reduced by substituting a more efficient vane pump for the gerotor. Losses can be further reduced with a variable-displacement vane pump, and by reducing the pressure of the system. Losses can be further decreased by using an on-demand electric pump: Mercedes claims an additional 0.8 percent increase in fuel economy on the NEDC by implementing a lubrication on demand system.[118] Another way to reduce losses from the pump is by reducing leakage in the system. Reducing leakage reduces parasitic losses by reducing the amount of fluid that needs to be pumped through the system to maintain the needed pressure.

A second large source of parasitic loss in ATs is the drag torque in the transmission from the clutches, brakes, bearings, and seals. These components have the potential to be redesigned for lower frictional losses. New clutch designs offer potential reductions in clutch drag, promising up to a 90 percent reduction in drag.[119] Replacing bearings can reduce the associated friction by 50 to 75 percent. New low-friction seals for can reduce friction by 50 percent to provide an overall reduction in bearing friction loss of approximately 10 percent.[120]

Optimizing shift elements improved fuel economy on the Mercedes 9G-TRONIC by 1 percent over the NEDC.[121]

Drag torque can be further reduced by decreasing the viscosity of the automatic transmission fluid used to lubricate the transmission. A study of transmission losses indicate that about a 2 percent fuel consumption reduction was obtained on the FTP 75 cycle by switching to the lowest viscosity oil.[122] However, reduction of transmission fluid viscosity may have an adverse effect on long-term reliability.

Transmission efficiency may also be improved through superfinishing the gear teeth to improve meshing efficiency.

5.2.3.9.2 Losses in DCTs

Advanced DCTs typically have lower losses than ATs, largely due to having an on-demand pump, splash lubrication, and fewer open clutches. The primary losses in DCTs are load-independent drag and splash losses. Unlike ATs, DCTs typically depend on splash lubrication for their internal components rather than forced lubrication. This eliminates the losses associated with oil supply pumps, but adds churning losses due to rotating components moving through the oil. Churning losses can be minimized by keeping oil levels low and warming up the lubrication oil.

A primary consideration in DCT losses is the use of wet or dry clutches.[123] Dry clutches do not require oil cooling flow, and therefore do not contribute to oil churning losses that are incurred with wet clutch systems; this has traditionally meant that dry clutch reduced GHG emissions by an additional 0.5 to 1 percent over wet clutch DCTs. However, dry clutches have a limited maximum torque capacity, and have suffered from customer acceptance issues. In response, so-called "damp" clutches have been introduced, where on-demand cooling flow has substantially reduced the parasitic losses associated with wet clutches.

DCTs also may benefit from the same improvements in bearing and seal drag and gear finishing that are outlined in the AT section above.

5.2.3.9.3 *Losses in CVTs*

CVTs tend to have higher losses than either ATs or DCTs, in large part due to the high oil pressures required to keep the belt and pulleys securely clamped. These losses increase significantly at high input torques, as even higher pressures are required to maintain the clamping force.[124]

A study by JATCO suggests that losses in the CVT are dominated by oil pump torque and losses in the belt-pulley system, with fluid churning losses as the next largest player.[125] By reducing leakage in the oil system and reducing line pressure when possible, JATCO's CVT8 was able to run with a reduced size oil pump and considerable reduction in oil pump torque loss. JATCO also redesigned the belt for lower loss, and reduced the oil level and viscosity to reduce churning losses. The overall result was a 40 percent reduction in mechanical losses compared to the earlier generation CVT.

Honda developed a new CVT using a comparable strategy.[126] They decreased the required pulley thrust by refining the control strategy and by using a fluid with increased coefficient of friction, which combined for a transmission efficiency increase of 2.8 percent. They also altered the belt trajectory around the pulley for an added 0.4 percent efficiency increase.

Another opportunity for reduced losses in CVT's is Dana's VariGlide System. Dana’s VariGlide system can provide more favorable system losses than traditional belt or chain technologies. The VariGlide system eliminates the requirement for a high pressure pump, using instead a fully passive mechanical clamping mechanism. The unique coaxial configuration, similar to a planetary gearset coupled with high power density, allows for simple integration into traditional transmission architectures and makes it uniquely suited for RWD applications.

5.2.3.9.4 *Neutral Idle Decoupling*

An additional technology that has been implemented in some transmissions, which was not considered in the FRM, is the application of a "neutral idle." In this strategy, a neutral clutch is opened when the vehicle is at a stop, which effectively reduces the creep torque required from the engine.[127,128] BMW demonstrated a reduction in fuel consumption of 2 - 3 percent on the NEDC for an optimized neutral idle decoupling system on an eight-speed transmission.[129] Similarly, ZF calculated that implementing a neutral idle decoupling system on its eight-speed transmission would reduce fuel consumption by 0.5 percent to 1.4 percent on the U.S. combined cycle, depending on the K-factor of the torque converter.[130] It should be noted, of course, that the neutral idle decoupling simply reduces idling losses, and implementing stop-start system would eliminate the effectiveness of this technology.

5.2.3.10 Transmission Shift Strategies

The transmission shift schedule can strongly influence the fuel consumption over a drive cycle. A more aggressive shift schedule will downshift the transmission earlier and upshift later (i.e., at lower engine speeds). This moves engine operation, for a particular required power, to lower speeds and higher torques where engine efficiency tends to be higher. Along with this, reducing time between shifts (i.e., allowing more shifts), reducing the minimum gear where fuel cutoff is used, and altering torque converter slip (covered in the next section) will also decrease fuel consumption. Applying an aggressive shift strategy can reduce fuel consumption by about 5 percent in a generic six-speed transmission or 1-3 percent in a generic nine-speed transmission.[131] Similarly, BMW showed about a 2 percent reduction in CO_2 from downspeeding the engine, comparing their current generation six-speed transmission to an earlier generation.[132]

However, the application of the strategy is limited by NVH and drivability concerns, as lower engine speeds produce more significant driveline pulses and allowing more shifts may increase a shift busyness perception. Manufacturers reduce the NVH impact by using allowing partial lockup, adding a torque convertor dampener, and/or adding a pendulum dampener. These changes along with decreasing the ratio between gears has made higher gear numbers and increased shifting more acceptable. Reducing the ratio between gears allows shifting to be less perceptible due to the smaller change in engine speed.

5.2.3.11 Torque Converter Losses and Lockup Strategy

Torque converters are typically associated with conventional ATs and CVTs, although they have appeared on Honda's newest eight-speed DCT. Torque converters provide increased torque to the wheels at launch, and serve as a torsional vibration damper at low engine speeds. However, this comes at the cost of energy loss in the torque converter fluid, and modern torque converters typically have a lockup clutch that mechanically locks the impeller and turbine together, bypassing the fluid coupling.

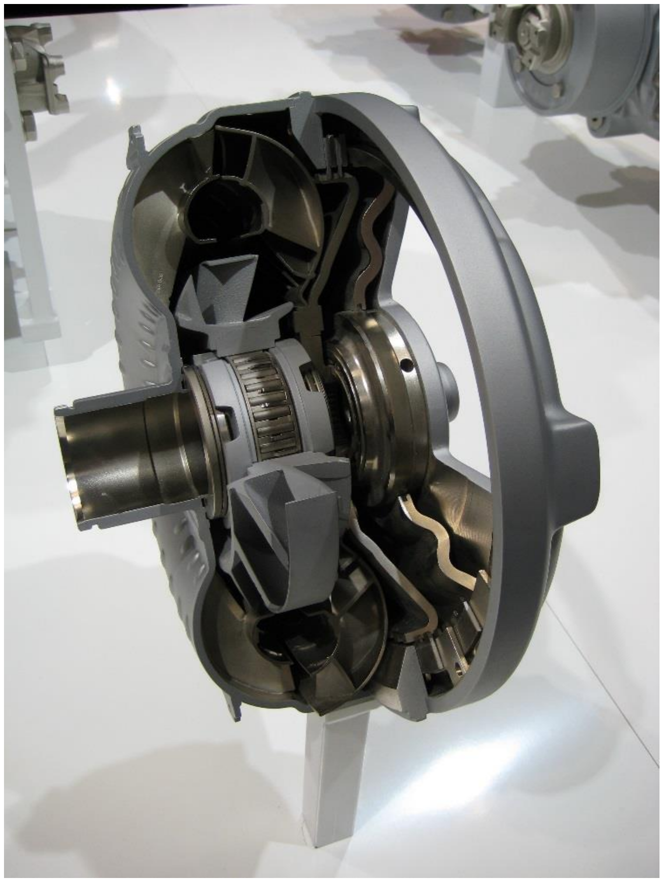


Figure 5.27 ZF Torque Converter Cutaway[133]

Although in the past torque converters remained unlocked up to high vehicle speeds, recent trends are to lock up at much lower speeds. Improvements in torsional vibration dampers, and the ability to utilize micro-slip across the lockup clutch has enabled lower lockup speeds. Mazda, for example, claims torque converter lockup as low as 5 mph for its SKYACTIV-Drive AT.[134] Although not as aggressive, BMW claims a 1 percent reduction in CO_2 from an early torque converter lockup.[135]

5.2.4 Electrification: State of Technology

Electrification includes a large set of technologies that share the common element of using electrical power for certain vehicle functions that were traditionally powered mechanically by engine power. Electrification can thus range from electrification of specific accessories (for example, electric power steering) to electrification of the entire powertrain (as in the case of a battery electric vehicle). Powering accessories electrically can reduce their energy use by allowing them to operate on demand rather than being continuously driven by the crankshaft belt. Some electrical components may also operate more efficiently when powered electrically than when driven at the variable speed of a crankshaft belt. Electrified vehicles that use electrical energy from the grid also provide a means for low-GHG renewable energy to act as a transportation energy source where it is present in the utility mix.

In the Technical Support Document (TSD)[136] accompanying the 2012 FRM, electric power steering and other improved accessories were discussed along with electrified vehicles under the topic of electrification. In this Draft TAR, electric power steering and improved accessories are now discussed separately in Section 5.2.8 in order to focus the current discussion on electrified vehicles and 12V stop-start systems, which share many common themes. As in the TSD, air conditioning is not explicitly examined as an electrified accessory technology but is discussed separately in Section 5.2.9 with respect to leakage, efficiency, and off-cycle credit provisions, oriented primarily toward conventional vehicles. Where applicable, electrified air conditioning is discussed in the context of electric vehicles, where it can have a strong impact on onboard energy consumption and driving range.

Electrified vehicles (or xEVs) are considered for this analysis to mean vehicles with a fully or partly electrified powertrain. This includes several electrified vehicle categories, including: battery electric vehicles (BEVs), which have an all-electric powertrain and use only batteries for propulsion energy; plug -in hybrid electric vehicles (PHEVs), which have a primarily electric powertrain and use a combination of batteries and an engine for propulsion energy; and hybrid electric vehicles (HEVs), which use electrical components and a battery to manage power flows and assist the engine for improved efficiency and/or performance. HEVs are further divided into strong hybrids (including P2 and power-split hybrids) that provide strong electrical assist and in many cases can support a limited amount of all-electric propulsion, and mild hybrids (such as belt integrated starter generator (BISG) hybrids, crankshaft integrated starter generator (CISG) hybrids, and 48V mild hybrids) that typically provide only engine on/off with minimum electrical assist.

BEVs and PHEVs are often referred to collectively as plug-in electric vehicles, or PEVs. Although the FRM referred to battery electric vehicles as EVs, this Draft TAR adopts the term BEV which is now more commonly used in the technical literature.

Fuel cell electric vehicles (FCEVs) are another form of electrified vehicle having a fully electric powertrain, and are distinguished by the use of a fuel cell system rather than grid power as the primary energy source. Although EPA has not included FCEVs in its Draft TAR fleet compliance modeling analysis, NHTSA did simulate the vehicles for its analysis. Technology developments relating to FCEVs are reviewed in Section 5.2.4.5.

As with the other technologies presented in this chapter, the agencies are reviewing, and revising where necessary, the assumptions for effectiveness and cost of electrification technologies for this Draft TAR. The agencies have carried out this effort along several paths. The agencies gathered information from many sources, including public sources such as journals, press reports, and technical conferences, as well as manufacturer certification data and information gathered through stakeholder meetings with OEMs and suppliers. EPA has also benchmarked selected vehicles by means of dynamometer testing at the EPA National Vehicle and Fuel Emissions Laboratory (NVFEL). The agencies have also been leveraging instrumented vehicle test data from the Argonne National Laboratory (ANL) Advanced Powertrain Research Facility (APRF). Among other purposes, EPA has used this data to inform development of the ALPHA model, and NHTSA has used this data to ensure that current powertrain technologies and controls used in Autonomie are representing state-of-the-art as well as include additional powertrains (i.e., the Voltec system). The agencies have also leveraged electric machine component performance data collected by Oak Ridge National Laboratory (ORNL) under U.S. DOE funding, and similar component and vehicle test data provided by other laboratories such as Idaho National Laboratory (INL). EPA also worked closely with ANL to improve and update the battery costing model, known as BatPaC,[137] which the agencies have used to update the projected costs of electrified vehicle battery packs. All of these sources have contributed to our assessment of the progress of electrification technology since the FRM.

Overview of Section

This Section 5.2.4 is intended to briefly review the assumptions for cost and effectiveness of the electrification technologies described in the FRM, and to review industry developments since the FRM that could inform the question of revising those assumptions for this Draft TAR analysis. The information described in this section thus forms the basis for revised cost and effectiveness assumptions described in Section 5.3.4.3, which become inputs to this Draft TAR analysis. Source data for most charts in Sections 5.2.4 and 5.3.4.3 are available in the Docket.[138]

Section 5.2.4 is organized in the following way:

- Subsection 5.2.4.1 provides a high-level overview of the major developments in electrification technologies since the FRM. This section is intended only as an executive summary to help place the topic of electrification into context.
- Subsection 5.2.4.2 provides a background in non-battery electrical components that are common to many of the electrification technologies, and briefly reviews the major directions of their development since the FRM. An understanding of these components is helpful to understanding developments in cost and effectiveness of each of the electrified vehicle categories. Developments in the cost or performance of specific classes of components are discussed in the context of the electrified vehicles in which they have been implemented.
- Subsection 5.2.4.3 includes subsections detailing each of the major electrified vehicle categories (stop-start, HEVs, PHEVs and BEVs). These sections serve to: (a) briefly review the significance of each electrified vehicle category as a means of reducing GHG emissions; (b) briefly review the major assumptions made about the electrified vehicle category in the FRM; and (c) review industry developments relating to how the category has evolved and been taken up in the fleet since the FRM.
- Subsection 5.2.4.4 focuses on developments in battery technology. Batteries are discussed separately and after discussion of the vehicle categories for several reasons. First, the battery performance requirements for each of the xEV categories is best understood after the categories have been fully defined and discussed. Second, a greater level of technical detail is required to adequately assess some battery developments that have a strong influence on effectiveness or cost of xEV technologies. Finally and perhaps most importantly, battery cost estimation is a particularly influential input to the cost assumptions for xEVs, and the battery cost estimates for different xEV categories rely on many detailed assumptions that are best understood and contrasted in the context of a battery discussion after trends in xEVs have been reviewed. The bulk of battery-related assumptions affecting xEVs are therefore covered in the battery section rather than the xEV sections.

Finally, Subsection 5.2.4.5 focuses on developments in FCEVs.

5.2.4.1 Overview of Electrification Technologies

The 2012 TSD and the FRM analysis identified electrified vehicles as offering a strong potential for reducing greenhouse-gas emissions. In the analysis conducted for the 2017-2025MY FRM, the cost-minimizing compliance pathway showed electrified vehicles playing an important supporting role in a fleet composed primarily of non-electrified powertrain configurations. The pathway presented by EPA showed OEM compliance with 2025MY standards with overall fleet penetrations of 2, 5, and 26 percent for BEVs, strong hybrids, and mild hybrids, respectively.[139]

Since the FRM, there has been significant growth in the number of HEV, PHEV, and BEV models available to consumers. HEVs are now part of the product line of almost every major OEM. In 2014, U.S. HEV sales were in excess of 450,000 units but declined to about 385,000 units in 2015.[140] Plug-in vehicles (BEVs and PHEVs) are also being offered in increasing numbers. In MY2015, 28 models of plug-in vehicles were available, an increase from 23 models in MY2014, and only a handful in 2012. In each of 2014 and 2015, U.S. plug-in vehicle sales were in excess of 115,000 units.[140]

Some aspects of BEV implementation and penetration have developed differently than predicted in the FRM. The FRM conceived that the BEVs most likely to play a significant part in OEM compliance would offer a real-world range of between 75 miles at the low end and up to 150 miles at the high end. Since then, the BEV market appears to have formed two segments, a consumer segment offering a driving range of around 100 miles at a relatively affordable price, and a luxury segment offering a much higher range (well in excess of 200 miles) at a higher price. Tesla Motors has had notable success at producing and marketing BEVs in the luxury segment, causing significant numbers of BEVs to enter the fleet that may not have been predicted by OMEGA on a pure cost-effectiveness basis.

Going forward, both BEV segments appear to be aggressively pursuing range increases in their second and third generation models. Both of the leading manufacturers in the consumer segment, Nissan and GM, have recently announced firm plans to offer a 200-mile range BEV in the 2017 time frame. Tesla is also making progress toward a long-stated intention to enter the consumer segment with the Model 3, which is widely described as a 200-mile BEV and targeted for introduction in 2017.

An increasing number of OEMs are beginning to add PHEVs to their product lines, utilizing both blended-operation architectures as well as extended-range architectures that offer varying amounts of all-electric range. The cost-minimizing pathway for compliance with the 2025MY standards did not project a necessity for significant fleet-level penetration of PHEVs (nominally, zero percent), although it did project that some primarily luxury- and performance-oriented OEMs might include PHEVs as part of their individual pathways.[141] The 2015 and 2016 MYs saw a discernible increase in PHEV20-style architectures from OEMs that tend to specialize in luxury or high-performance vehicles, suggesting that this projection was accurate. Second-generation PHEV models have begun to appear, typically offering an increased all-electric range or a more robust blended-mode operation that allows for increased all-electric capabilities in normal driving. Manufacturers have often cited customer demand for a more all-electric driving experience in making these changes.

Advancements in the cost and effectiveness of xEVs are closely related to advancements in battery, electric motor, and power electronics technologies. These technologies have advanced steadily since the FRM, with significant improvements in battery specific energy, battery cost, and non-battery component efficiency and cost contributing to improvements in production xEVs. The pace of industry activity in this area suggests that further advancements are likely to occur between now and the 2022-2025 time frame of the rule.

At the time of the FRM, empirical data regarding the cost and efficiency of xEV components was limited by the small number of production vehicles from which it could be gathered. Today, the relatively large number of production models provides much greater opportunity to empirically validate projections made in the FRM.

Battery cost is a major consideration in the cost of xEVs. At the time of the FRM there was great uncertainty in the manufacturing costs for these components and their potential to be reduced. There was also uncertainty regarding battery lifetime. Today, evidence of the need for battery replacement is rare, with most PHEV and BEV batteries showing good durability within the limits established by OEM warranties. Although the battery cost projections published in the FRM were significantly lower than estimates of prevailing costs at the time, recent evidence strongly suggests that these estimates were quite accurate, with at least one major manufacturer having announced battery costs from a major battery supplier that are very close to FRM projections even for the 2017-2018 time frame. Recent reports have suggested that lithium-ion battery cost has historically followed a pace of improvement of about 6 to 8 percent per year.[142] Advancements in cost and energy capacity of battery technology continue to be pursued actively by OEMs and suppliers alike, suggesting that there is room for further improvement within the 2022-2025 time frame of the rule.

Analysis of current and past production BEVs and PHEVs suggests that the FRM predicted a larger battery capacity per unit driving range than manufacturers have found necessary to provide. This could be due in part to differences in assumed powertrain efficiencies, usable battery capacity, or application of road load reducing technologies. Similar analysis also suggests that the industry has achieved comparable acceleration performance with significantly lower motor power ratings than the FRM anticipated. In other words, it is clear that in many ways the industry has found ways to do more with less, compared to many of the predictions of the 2012 FRM.

Because the vehicle architecture for electrified vehicles is fundamentally different from that of conventionally-powered vehicles, the consumer experience is likely to be different as well. In particular, the fueling requirements of BEVs and PHEVs call for changes in accustomed fueling habits, some of which may improve convenience (e.g. the ability to charge at home) while others may pose a challenge (e.g. a relatively long fueling time). A BEV with limited range might not provide an exact substitute for a conventional vehicle for many consumers today, while at the same time electrified vehicles can provide benefits of quiet operation, reduced maintenance, and the potential integration with future mobility systems that might include shared and autonomous vehicles. Chapter 6 contains a more complete discussion of the impact of efficiency technologies on other vehicle attributes.

The primary factors that influence the cost and effectiveness of electrification technologies are the cost and efficiency of their components. These include: energy storage components such as battery packs; propulsion components such as electric motors; and power electronics components, such as inverters and controllers, that process and route electric power between the energy storage and propulsion components. For the purpose of this analysis, these components are divided into battery components and non-battery components.

Battery components have a particularly strong influence on cost of xEVs. Because developments in battery technology may apply to more than one category of xEV, they are discussed collectively in Section 5.2.4.4. That section details developments in battery-related topics that directly affect the specification and costing of batteries for all xEVs, such as usable capacity, durability, thermal management, and pack topology, among others.

Non-battery components have a strong influence on both cost and effectiveness of xEVs. Because non-battery technologies are important to understanding the differences in architecture among xEVs, they are introduced prior to discussion of the individual electrified vehicle categories in Section 5.2.4.2.

5.2.4.2 Non-Battery Components of Electrified Vehicles

Non-battery components largely consist of propulsion components and power electronics. Propulsion components typically include one or more electric machines (an umbrella term that includes what are commonly known as motors, generators, and motor/generators). Depending on how they are employed in the design of a vehicle, electric machines commonly act as motors to provide propulsion, and/or act as generators to enable regenerative braking and conversion of mechanical energy to electrical energy for storage in the battery. Power electronics refers to the various components necessary to route current between the battery system and the propulsion components, including such devices as inverters and rectifiers, DC-to-DC converters, motor controllers, and on-board battery chargers.

The energy efficiency of non-battery components has been the focus of much industry research and development since the 2012 FRM. The impact of resulting improvements in efficiency and overall system optimization therefore need to be considered in developing estimates of xEV effectiveness. The agencies have studied and considered such improvements in developing new estimates of xEV effectiveness for this Draft TAR.

Costs of non-battery components have also begun to decline. Compared to engines and other conventional powertrain components, many of which have been reduced to commodity products for many years, the market in xEV non-battery components is far less developed. As OEMs seek xEV components for their products, they are less likely to encounter stock items that fully meet their requirements and therefore have often chosen to either produce them in limited numbers in-house, or to source them from suppliers that build to specification. While this dynamic may be expected to limit the potential for economies of scale to develop and be reflected in component costs in the near term, it is also likely that standardization and commoditization will occur as the industry matures. One example of industry movement in this direction is shown by the decision of LG to leverage its position as xEV battery supplier to several OEMs by expanding into xEV non-battery components. In a joint announcement with LGChem in October 2015,[143] GM described LG's role not only as supplier of battery cells for the Chevy Bolt BEV but also as supplier of many of its non-battery components. LG's established role as battery supplier to multiple OEMs suggests that it may be planning to supply non-battery components across the rest of the xEV industry as well. As another example, in 2016 Siemens and Valeo announced the formation of a joint venture for the production of high-voltage components across the full range of electrified vehicle types, citing among other advantages "substantial synergies in manufacturing and sourcing" and a focus on global markets.[144] Developments such as these can promote the potential for economies of scale to develop, and may be a significant driver of cost reductions if they continue in the future.

5.2.4.2.1 Propulsion Components

The components that provide propulsion for xEVs are known variously as electric motors, traction motors, motor/generators, e-motors, or electric machines. In this discussion, they will be referred to either as electric motors or generators (depending on the functional context), or collectively as electric machines.

The two main types of electric machines currently seen in production xEVs are permanent-magnet motors (also known as synchronous motors) and induction motors (also known as asynchronous motors). Although the permanent-magnet motors used in xEVs are sometimes called brushless direct-current (DC) motors, these as well as induction motors are powered by alternating current (AC), which must be converted from DC battery current by an inverter.

In the duty cycles typical of xEV applications, permanent-magnet motors have certain advantages in energy efficiency due in part to the presence of integral permanent magnets to generate part of the magnetic field necessary for operation. However, these magnets add to manufacturing cost, particularly when they contain rare earth elements. In contrast, induction motors use copper windings to generate all of the magnetic field and can be manufactured without rare earth elements. Although the windings are significantly less costly than magnets, generation of the field in the windings is subject to additional I^2R losses that are not present in permanent magnet motors. In some conditions, this causes induction motors to be slightly less energy efficient than permanent-magnet motors,[145,146] although the choice between the two types of motor ultimately depends on the specific application.

The majority of current xEV products use permanent-magnet motors. Induction motors are found in products of Tesla Motors, as well as the Fiat 500e and Mercedes-Benz B-Class Electric Drive. The BMW Mini-e and the Toyota RAV4 EV, both now discontinued, also used induction motors; in the case of the RAV4, the motor was supplied by Tesla.

Another type of motor, the switched reluctance or axial flux motor, has recently been suggested for use in xEVs.[147,148] Although current examples of this technology are challenged by difficulties with controllability, vibration, and noise, in the future these motors may potentially offer a lower cost solution than either permanent-magnet or induction motors.

Since the FRM, some manufacturers have demonstrated successful cost reductions in propulsion components. For example, the use of rare-earth metals in permanent-magnet motors is commonly cited as a concern due to their high cost and potential supply uncertainty. The 2016 second-generation Chevy Volt has reduced the use of rare-earths in its drive unit by more than 80 percent by using lower-cost ferrite magnets in place of rare-earths in one of its motors[149] and significantly reducing the rare-earth content of the other.[150] Another approach is seen in the BMW i3, which uses a hybridized motor design that combines aspects of the permanent-magnet motor and the reluctance motor, allowing rare earth content to be reduced by about half compared to a permanent-magnet motor of similar torque capability.[146]

Component integration has also contributed to lower costs. GM has cited integration of power electronics with the transmission and drive unit of the 2016 Volt as a significant enabler of cost reductions in that vehicle by eliminating long stretches of heavy cable and improving packaging efficiency.[151,152] Major changes to the configuration of the electric propulsion system reduced the total torque and power requirements, allowing the use of smaller bearings and rotors, and an increase in maximum motor speed to 11000 rpm from the 9500 rpm of the previous system. This led to a 20 percent reduction in motor volume and a 40 percent reduction in mass compared to the previous generation, as well as improved efficiencies. Similar improvements have propagated to the Cadillac CT6[153] and the Chevy Malibu Hybrid[154] through the sharing of related components. The 2016 Toyota Prius also utilizes improvements to the transaxle and motor that result in significant weight reduction and efficiency. A more compact motor design and an improved reduction gear allows for an improved power-to-weight ratio and provides for a 20 percent reduction in frictional losses.[155]

Industry activity is also focused toward improving the efficiency of propulsion motors. Although electric motors are already highly efficient (well in excess of 90 percent in many normal usage conditions), even small improvements in efficiency can pay significant dividends by reducing the battery capacity necessary for a given driving range. For example, GM has said that the increased range of the second generation Chevy Volt was achieved in part by improvements in motor efficiency.[151] Even the first generation of the Chevy Spark EV was described as having the highest drive unit efficiency in the industry, with an average battery-to-wheels efficiency of 85 percent in the city cycle and 92 percent in the highway cycle.[156] These efficiencies are higher than EPA assumed in the 2012 FRM xEV battery sizing analysis.

5.2.4.2.2 Power Electronics

Power electronics refers to the various components that control or route power between the battery system and the propulsion components, and includes components such as: motor controllers, that issue complex commands to precisely control torque and speed of the propulsion components; inverters and rectifiers, that manage DC and AC power flows between the battery and the propulsion components; onboard battery chargers, for charging the BEV or PHEV battery from AC line power; and DC-to-DC converters that are sometimes needed to allow DC components of different voltages to work together.

Inverters are power conditioning devices that manage electrical power flows between the battery and propulsion motors. While all batteries are direct current (DC) devices, modern traction motors operate on alternating current (AC) and therefore require an inverter capable of converting DC to AC of widely variable frequencies at variable power levels. As implemented in an electrified vehicle, the component commonly known as an inverter may also act as a rectifier, that is, convert AC to DC to send energy to the battery.

Modern inverters are semiconductor based, utilizing metal-oxide-semiconductor field-effect transistors (MOSFET) or insulated-gate bipolar transistors (IGBT). These designs are highly efficient, often operating well above 90 percent efficiency. Inverter designs vary in output waveform (square wave, sine wave, modified sine wave, or pulse-width modulated), which accounts in part for differences in their efficiency and the potential for heat generation. Inverter manufacturing cost is strongly associated with wafer size in manufacturing of substrate materials such as silicon carbide. While most wafer sizes are currently around 4 inches in diameter, larger wafers of 6 to 12 inches would reduce scrap rates and reduce cost substantially.[157]

Despite these low losses, the high power levels of electrified vehicles generate significant heat and require inverters to have aggressive liquid cooling, often residing on the coolant loop in a position prior to the propulsion motor to ensure sufficient cooling. Cooling elements such as fans, heat exchange surfaces and fins or heat sinks can add to volumetric requirements and are a common target of size and cost reduction. The similarity of materials and cooling needs offer an opportunity to further reduce cost by integrating the inverter with other power electronics components such as DC converters.[158]

The 2016 Chevy Volt provides one example of how improvements to the inverter and its packaging can lead to significant improvements in packaging and related costs. Major changes to the electric propulsion system served to reduce the current requirements of the inverter, reducing its volume by about 20 percent (from 13.1L to 10.4L) and its mass from 14.6 kg to 8.3 kg. This allowed the inverter module to be integrated into a small space at the top of the transmission. This integration into the transmission saved on assembly costs, served to protect the components and their sensitive interfaces in a sealed environment, and eliminated the need for heavy 3-phase cables. It also saved valuable underhood space for other components commonly associated with electrification. The reduction in inverter current was also said to reduce inverter switching loss by about half in conjunction with accompanying improvements to cooling. GM attributed a 6 percent improvement in electric drive system efficiency over the FTP cycle, a 30 percent increase in vehicle range and an 11 percent improvement in label fuel economy to these inverter improvements.[151,152] Similar improvements have carried over to other models that share related components, such as the Cadillac CT6 and the Chevy Malibu Hybrid.[153,154] Toyota also has introduced changes that improve inverter efficiency.[155] The 2016 Toyota Prius includes a new power control unit to which it attributes a 20 percent reduction in power losses. The power control unit also benefits from integration, residing in a position above the transaxle. Advances in the use of a silicon carbide substrate in the power control unit are also expected to significantly reduce power switching losses and allow a 40 percent reduction in the size of the coil and capacitor of the power control unit in production Toyota vehicles by around 2020.[159]

Many systems require DC-to-DC converters to allow DC components of different voltages to work together. They do not convert between AC and DC, but instead step up (or down) the DC voltage between two or more components or subsystems, either unidirectional or bi-directionally. One common application of a DC-to-DC converter is to allow low-voltage accessories to be powered by energy from the high-voltage battery by reducing the voltage from 300+ V to 14 V. These are also known as buck converters, and may operate at about 1.5 kW[160] to 3 kW.[167] Although many current production BEVs and PHEVs retain a low-voltage battery to power accessories, a buck converter is needed to keep the low-voltage battery charged in the absence of an engine-driven alternator, and can supplement power to the accessories. Another purpose of a DC-to-DC converter is to allow certain powertrain components to operate at their optimum voltage rather than being tied to the voltage of the high voltage battery. For example, a fuel cell stack or super capacitor may operate more efficiently at a higher or lower voltage than the high-voltage battery, or along a variable range of voltages.[161] A variety of topologies are under development to suit these varied applications.[160,161]

Controllers are electronic devices that implement control algorithms that control power flows through the electrified powertrain. Motor controllers are responsible for issuing the complex commands that precisely control torque and speed of the propulsion motor. A primary task of this controller is to determine the exact frequency of alternating current necessary for the motor to deliver the demanded speed and torque, and to control the inverter to provide it. A supervisory controller is another form of controller that implements higher-level vehicle control algorithms, including issuing high-level torque and speed commands to the motor controller. Supervisory controllers are not unique to electrified powertrains but may be functionally integrated with other components that are. Compared to other power electronics components, controllers are not typically large consumers of energy, but can benefit from cost reductions applicable to other components.

Onboard chargers are charging devices permanently installed in a PHEV or BEV to allow charging from grid electrical power. Level 1 charging refers to charging powered by a standard household 110-120V AC power outlet. Level 2 charging refers to charging at 220-240V AC power. The available power depends on the amperage of the household circuit, and can range from about 1 to 2 kW for Level 1 to about 5 to 7 kW for Level 2. Onboard chargers travel with the vehicle, and are distinct from stationary charging equipment (Electric Vehicle Supply Equipment, or EVSE) commonly installed at public or private charging stations. More information on PHEV and BEV charging infrastructure and EVSE can be found in Chapter 9, Infrastructure Assessment.

The widespread home availability of 110-120V AC power does not necessarily mean that Level 1 charging is preferable either for convenience or efficiency. Charging time at the Level 1 rate is much slower than at Level 2, and can become impractically slow for longer-range BEVs that may take longer than overnight to bring to full charge at Level 1 even after only partial depletion. However, Level 1 residential charging is widely relied upon by the current users of BEVs and PHEVs and provides a lower cost option for ownership that may continue to be sufficient for households with lower daily driving needs.

Charging efficiency can also vary significantly. In general, the efficiency with which a battery accepts DC charge current is highest at low charge rates.[162] However, the degree to which the manufacturer has optimized the charging circuitry for a specific preferred charge rate can also have a strong influence, because the efficiency of AC to DC conversion is also an important factor. According to tests performed by Idaho National Laboratory on a 2015 Nissan Leaf, the efficiency of Level 1 charging ranged from only 61.8 percent to a maximum of 78.4 percent, while that of Level 2 charging ranged from 81.5 percent to 90.5 percent.[163] This suggests that the design of the charging circuitry can have a greater effect on charging efficiency than charge rate alone, and that manufacturers may optimize the charging system to accommodate the mode of charging it expects customers to most commonly utilize.

DC fast charging is increasing in availability and popularity, and can support charging at much higher rates than Level 2 (up to 150 kW in some cases, subject to the capability of the vehicle being charged). Charging at these higher rates may result in a lower net efficiency relative to Level 2, and may require more robust battery cooling to dissipate the heat generated during a charge.

Although charging efficiency is primarily relevant to upstream emissions and is not a factor in onboard energy consumption, there is significant potential for efficiency improvement in these components that may be indicative of similar potential in other power electronics components. For example, between Gen1 and Gen2 of the Chevy Volt, the energy efficiency, size and weight of its onboard charger was improved significantly.[164,152] Level 1 charging efficiency improved from 86.8 percent in Gen1 to 94.5 percent in Gen2, an improvement of 8.9 percent. Efficiency at Level 2 increased similarly from 89.6 percent to 95.5 percent, an improvement of 6.5 percent. These improvements allowed the overall system efficiency (from the wall plug to the battery) of Level 2 charging to improve to 88.4 percent, and that of Level 1 to 86.7 percent (improvements of 8.6 percent and 9.3 percent, respectively). Power density of the unit improved from 326 W/kg to 605 W/kg (85 percent), while volumetric power density improved from 492 W/liter to 889 W/liter (81 percent), which led to significant packaging advantages. The fact that these improvements to charger efficiency were achieved despite their lack of a strong impact on highly visible attributes such as driving range or power suggests that similar improvements to other components that do affect range or power are even more likely to be pursued successfully.

Battery management systems (BMS)[165,283] are an important factor in maintaining and utilizing the available capacity of the traction battery. The primary role of a BMS is to maintain safety and reliability by preventing usage conditions that would damage or excessively degrade the battery. The BMS may therefore limit voltages and currents on the pack, module, or individual cell level, and monitor pack or cell temperature as well as other parameters.

Another important role of the BMS is to balance the charge levels of the individual battery cells so that each cell is maintained at a similar voltage and state of charge. This can play an important part in determining the usable portion of total battery capacity and in maintaining battery life. In a battery containing hundreds of cells, small variations in resistance will exist among individual cells, and differences in cell temperature will result not only from these differences but also from differences in cell location within the pack and proximity to cooling media. During a normal charge or discharge of the pack, these differences will affect cell efficiency and cause some cells to approach their voltage or charge limits sooner than others. Without balancing, the entire pack will effectively reach its charge or discharge limit when the weakest cell reaches its limit. In this case, the charge contained in the remaining cells goes unutilized. Effective cell balancing can increase utilization significantly.

BMS systems may employ passive or active balancing. Passive balancing acts to identify the cells that are approaching their limits and selectively modifies their charge or discharge rates, usually by dissipating their energy resistively, to allow the remaining cells to continue operating. Active balancing shuttles energy among cells rather than dissipating the energy. Active balancing is potentially more energy efficient than passive balancing but is typically more costly to implement. The cost and effectiveness of active balancing is an active area of industry research toward reducing the necessary battery capacity and power for a given application.

5.2.4.2.3 Industry Targets for Non-Battery Components

Establishing targets can be an effective way of focusing industry effort toward a common goal. For example, the battery cost and performance targets established by the United States Advanced Battery Consortium (USABC) are familiar to most in the battery industry and have become important reference points by which developments in battery technology are often measured. While industry targets such as these can vary in their purpose and achievability, they can provide valuable guidance on what some in the industry consider to be potential directions for future technology.

Targets for cost and performance of non-battery components have been established by U.S. DRIVE,[166] a government-industry partnership managed by the U.S. Council for Automotive

Research (USCAR), which also manages USABC. Members include the U.S. Department of Energy, industry members of USCAR, and several other organizations including major energy companies and public energy utilities. The U.S. DRIVE targets apply to electric motors, inverters, chargers, and other power electronics components for the 2015 and 2020 lab year[U] time frames.[167] These targets, some of which are shown in Table 5.1, include performance targets such as specific power, specific energy, and energy and power density (volumetric), as well as cost targets.

The U.S. DRIVE targets were established specifically with respect to HEVs, which were seen as presenting the greatest challenge in meeting the targets due to their being on the low end of the power range compared to PEVs. The targets therefore apply best to an HEV-sized 55 kW system. U.S. DRIVE expects the targets to be less difficult to meet for higher-power PEV systems, in part because their more powerful powertrains may incur less overhead cost (for connectors and the like) that are not necessarily directly proportional to power.[168] This suggests that the U.S. DRIVE targets would be relatively conservative when applied to PEVs.

Although the U.S. DRIVE figures are only targets, the industry has shown remarkable progress in approaching these goals. It is notable that U.S. DRIVE targets for specific power are quite close to what was already available in some production HEVs at the time they were set. Since some of the goals were being met in higher-priced products, bringing these levels of performance to the average PEV may largely be a matter of cost reduction rather than technological breakthrough.

Table 5.1 U.S. DRIVE Targets for Electric Content Cost and Specific Power

Component	U.S Drive Target (Lab Year)	
	2015	2020
Electric motor	1.3 kW/kg	1.6 kW/kg
	$7/kW	$4.7/kW
Power electronics	12 kW/kg	14.1 kW/kg
	$5/kW	$3.30/kW
Motor and electronics combined	1.2 kW/kg	1.4 kW/kg
	$12/kW	$8/kW
3 kW DC/DC converter	1.0 kW/kg	1.2 kW/kg
	$60/kW	$50/kW

The 2020 lab year target for specific power of combined motor and power electronics has some support in current literature. Assuming a five year lag between lab demonstration and production, the 2020 lab year corresponds to 2025. A presentation by Bosch[169] at The Battery Show 2015 states that the electric motor and power electronics for a 100 kW, 20 kWh BEV system in the 2025 time frame is expected to comprise about 37 percent of electric content weight, with battery weight comprising the remaining 63 percent. Assuming the 20 kWh battery pack has a specific energy of about 140 Wh/kg (as indicated by ANL BatPaC for an NMC622

[U] It should be noted that a minimum of five years typically passes between successful demonstration of a technology in a lab and its introduction into the market.

pack at 115 kW net battery power), and a corresponding weight of 143 kg, the non-battery content would be estimated at about 53 kg. The 100 kW system would then represent a non-battery specific power of 100 kW/53 kg, or 1.88 kW/kg. While the U.S. DRIVE target of 1.4 kW/kg is not directly comparable because it is based on a 55 kW traction motor, the result for the 100 kW example is directionally correct in the sense that U.S. DRIVE considers the targets easier to achieve for more powerful systems.[168] Most BEV and PHEV motors modeled in this analysis are larger than 55 kW, suggesting that the U.S. DRIVE figure for a 55 kW system may represent a fairly conservative figure for these applications.

Although the U.S. DRIVE figures are targets and therefore not necessarily indicative of industry status, EPA has confidence that the targets for specific power represent attainable production goals during the time frame of the rule. This is based in part on the observation that the 2020 specific power target for electric motor and power electronics combined is very close to levels that were already being attained by some production vehicles at the time they were set.[170] Further, the motor of the recently announced Chevy Bolt BEV already appears to exceed the U.S. DRIVE target at 1.97 kW/kg (based on a mass of 76 kg and peak power of 150 kW).[171] This example is consistent with confidential business information conveyed to EPA through private stakeholder meetings with OEMs that suggests that cost and performance targets for some types of components are already being met or exceeded in production components today, or are expected to be met within the time frame of the rule.

5.2.4.3 Developments in Electrified Vehicles

In this Draft TAR, each of the electrified vehicle categories represents a distinct GHG-reducing electrification technology that manufacturers may choose to include as part of a compliance pathway. These technologies range from 12-volt stop-start systems without accompanying hybridization, to mild and strong hybrids (HEVs), to plug-in vehicles (PHEVs and BEVs) and fuel-cell electric vehicles (FCEVs). The propulsion and power electronics technologies discussed in the previous section are integral to understanding the architecture and capabilities of each of these electrification technologies. Developments in each of these electrification technologies are described in this section.

5.2.4.3.1 Non-hybrid Stop-Start

In this analysis, non-hybrid stop-start refers to a technology that reduces idling by temporarily stopping the engine when the vehicle stops and restarting it when needed. This eliminates much of the fuel consumption associated with idling. In urban driving conditions that include a large amount of idling at intersections and in congested traffic, stop-start can provide significant GHG benefit.

Non-hybrid stop-start is also commonly known as idle-stop or micro hybrid. In the 2012 FRM, it was referred to as conventional stop-start. In this Draft TAR analysis, as in the FRM, non-hybrid stop-start is limited to engine stopping and restarting in a 12V context, with no accompanying hybridization. For this reason, the term micro-hybrid will not be used to refer to non-hybrid stop-start systems. The non-hybrid stop-start classification should not be confused with mild and strong hybrids that include a stop-start function. Systems that include brake energy regeneration or other hybrid features would be classified as hybrids. However, as in the Ricardo analysis of the 2012 FRM, non-hybrid stop-start may include a strategy known as "alternator regen" that charges the 12V battery more aggressively by increasing the alternator field upon vehicle deceleration.

Non-hybrid stop-start is therefore the simplest form of electrification discussed in this section. It is typically implemented by: (a) upgrading to a higher-performance starter capable of higher power and increased cycle life, (b) upgrading to a higher-performance 12V battery to improve cycle life and reduce voltage drop on restart; (c) adding an appropriate control system to manage stopping and starting as transparently as possible; and in many cases, (d) modifying certain accessories to allow for adequate service while the engine is off.

In the 2012 FRM, the effectiveness estimates for stop-start were derived from the Ricardo modeling study. The agencies estimated the 2-cycle effectiveness of stop-start technology to be in the range of 1.8 to 2.4 percent, depending on vehicle class. The 2012 FRM considered stop-start to be a new technology and assigned it a steep learning curve for the years 2012-2015 and a flat learning curve for the years 2016-2025. On the basis of projected costs and effectiveness, the agencies projected that stop-start would achieve a fleet-level penetration of 15 percent[172] in the cost-minimizing pathway for compliance with the 2025MY standards.

Since the 2012 FRM, rapid growth in the application of 12V stop-start systems is evidence of the technology's potential to provide cost-effective emissions reductions. The 2015 EPA Trends Report projects that non-hybrid stop-start will be present on almost 7 percent of new non-hybrid car and truck production in MY2015, with total penetration of stop-start at nearly 9 percent when mild and strong hybrids are included.[173] Penetration has grown steadily each year, reaching 0.6 percent in 2012, 2.3 percent in 2013, and 5.1 percent in 2014, with 6.6 percent projected for 2015.[174] BMW and Mercedes-Benz are the most notable adopters, each including stop-start in about 70 percent of their projected 2015 production.[175]

As a GHG-reducing technology, the effectiveness of stop-start depends on the amount of idle time included in the assumed test cycle. The standard EPA test cycles contain short periods of idle, but less than some believe is present in real world driving. In order to provide a more accurate credit basis for the real-world benefit of stop-start, the 2012 FRM provided for stop-start technology to be eligible for off-cycle credits under the Off-Cycle Program. The Off-Cycle Program is discussed further in Section 5.2.9.

In contrast to the FRM projections of 1.8 to 2.4 percent effectiveness under EPA test cycles, other sources have suggested an average of 3.5 percent.[176,177,178] As one example, the 2015 Ford Fusion 1.5L TGDI is available with and without a 12V stop-start option, providing an opportunity to assess the effectiveness of stop-start as implemented in this vehicle. The difference in estimated fuel economy between the two versions suggests an effectiveness of about 3.5 percent on a fuel economy basis. The automotive supplier Schaeffler Group has presented an engine stop-start technology[179] it describes as capable of providing a 2-cycle combined fuel economy improvement of about 6 percent over the city cycle and 2 percent over the highway cycle, or about 3.42 percent combined. The 2015 Mazda 3 is available with and without the Mazda i-ELOOP regenerative braking and stop-start system. A comparison of certification test data for this vehicle with and without the system suggests that its two-cycle GHG effectiveness is about 3.35 percent.[180]

Some test cycles used in other parts of the world include a greater proportion of idle time and therefore assign a greater benefit to stop-start. This would naturally make stop-start more attractive to manufacturers in regions that certify under these cycles, and may be a factor in the greater penetration of stop-start that has been observed worldwide. Stop-start[176] has been popular in Europe due to high fuel prices and the stringent EU CO_2 emission target established in 2009. In 2014, about 60 to 70 percent of vehicles sold in the European market offered stop-start.

Because stop-start technology alters the customary operation of the engine, it has potential to alter the traditional feel of driving. Frequent restarts of the engine, although rapid and seamless in most implementations, can increase the sense of noise, vibration, and harshness (NVH). Drivers unaccustomed to stop-start may feel uncomfortable having the engine switch off in stop and go traffic, particularly if accessories such as heat or air conditioning are also affected. Some of the seamlessness and potential benefit of stop-start can be eroded by individual driving habits. For example, if a driver repeatedly pulls up toward the leading car as traffic compacts while waiting at an intersection, the engine may restart each time, reducing fuel savings and adding to NVH.

Manufacturers often cite consumer acceptance factors in the adoption of stop-start in the U.S market. Early introductions of the technology involved lower volume vehicles and adaptations of systems originally designed for the European market. Manufacturers have considered customer feedback from these early applications in the implementation of recent stop-start systems, which are now smoother and more unobtrusive to the driver. For example, some suppliers have proposed continuously engagement of the starter motor to improve the restart process. Others have implemented systems that maintain a specific piston position while stopped in order to achieve a fast and smooth restart by firing a single cylinder. As a result, improved systems promise greater effectiveness through more frequent and longer periods of idle stop time while operating in a more transparent manner.

Vehicles with sufficiently smooth and seamless stop-start technology have been well-received by consumers,[181] especially when paired with some explanation of the system's benefits and operating characteristics at the time of delivery. With these more recent implementations, it is more common now for stop-start systems to be applied as standard equipment on high-volume vehicles like the Chevrolet Malibu, Chrysler 200, Jeep Cherokee, and Ram 1500 truck. Ford expects to offer it on 70 percent of its North America vehicle lineup by 2017,[182] including the 2015 F-150 truck.

The introduction of stop-start has stimulated development of 12V battery systems capable of providing the enhanced performance and cycle life that it requires. Much of this activity has involved variations of lead-acid chemistries, such as absorbed-glass-mat (AGM) designs and lead-carbon formulations. For example, at the 2015 Advanced Automotive Battery Conference (AABC), a Planar Layered Matrix (PLM) 12V enhanced lead-acid battery was exhibited by Energy Power Systems (EPS). EPS claimed this technology increases battery power and regenerative charging capability by a factor of four while increasing the battery life by a factor of five, at a similar cost to a conventional AGM lead-acid battery.

Other developments have shifted toward lithium-ion chemistries specially adapted for stop-start applications. As one example, Maxwell Technologies has developed a 12V lithium-ion battery combined with a 395V ultra-capacitor pack designed for 12V stop-start systems.[183] The dual pack was said to provide quicker engine start, lower voltage drop, capacity and life improvement while providing capability to operate at -30 degrees Celsius. Since the battery and ultra-capacitor operate at different voltages, these systems require additional electronics for DC to DC conversion. These systems are also likely to cost more than lead-acid based systems. The cost of the Maxwell dual pack stop-start system is estimated at about $230/pack, which is higher than that of an advanced lead-acid battery. In general, use of the lithium-ion chemistry for 12V stop-start applications continues to face challenges with regard to cost as well as cold-start operation.

The Mazda i-ELOOP system[184] represents an incremental step beyond basic stop-start, using ultracapacitors to store regenerative brake energy during deceleration and coasting. While the system cannot use the reclaimed energy for propulsion, it supplements the energy used by accessories and climate control, potentially saving energy by allowing the engine to stay off for slightly longer periods.

Based on a review of these and similar industry developments, as well as data collected from other sources, the agencies have updated effectiveness estimates for stop-start technology. Updated cost and effectiveness estimates are discussed further in Sections 5.3 (GHG Assessment) and 5.4 (CAFE Assessment).

5.2.4.3.2 Mild Hybrids

In this analysis, mild hybrid refers to a technology that supplements the internal combustion engine by providing limited hybridization, typically including a limited amount of electrical launch assistance, some regeneration, and stop-start capability. Together, these features reduce energy consumption by optimizing loading of the engine, enabling some engine downsizing, allowing the engine to turn off at times, and recovering a portion of the energy that would otherwise be wasted by friction braking. Mild hybrids commonly are implemented in part by replacing the standard alternator with an enhanced power, higher voltage, higher efficiency belt-driven starter-alternator which can provide some propulsion assist and also recover braking energy while the vehicle slows down (regenerative braking). Although the belt-driven basis of these systems can limit their power capability to approximately 10 kW to 15 kW,[185] mild hybrids can provide greater benefit than stop-start systems while keeping cost significantly lower than that of a strong hybrid.

Mild hybrids operate at a higher voltage than 12V stop-start systems. Even the relatively mild demands of stop-start[186] technology pushes a 12V electrical system to its limits. Achieving the 10 to 15 kW demanded of a mild hybrid application at 12V could lead to discharge currents of 1000 Amps or more, and would require very thick, heavy, and expensive electrical conductors. In order to achieve effective launch assist and regeneration, mild hybrids therefore operate at higher voltages of 48V to 120V or higher, with an increased battery capacity as well. The higher system voltage allows the use of a smaller, more powerful electric motor and reduces the weight of the motor, inverter, and battery wiring harnesses.

In the 2012 FRM analysis, mild hybrid technology was referred to as "higher-voltage stop-start/belt integrated starter generator (BISG)" and was limited to BISG architecture, as exemplified by the Chevrolet Malibu eAssist system. The primary source of effectiveness data used by EPA was derived from the Lumped Parameter Model based on modeling of the Malibu Eco BAS (BISG) system with a 15 kW motor and 0.5 kWh battery. EPA cost estimates were based on an analysis of this system with a 0.25 kWh battery. NHTSA used estimates of BISG mild hybrid effectiveness developed by ANL using Autonomie. EPA assumed an absolute CO_2 effectiveness ranging from 6.8 to 8.0 percent depending on vehicle class (2012 RIA, p. 1-18).

The absolute effectiveness for the CAFE analysis ranged from 8.5 to 11.6 percent depending on vehicle class. These effectiveness values include only the effectiveness related to the hybridized drivetrain (battery and electric motor) and supported accessories.

On this basis, the agencies projected that mild hybrids would achieve a fleet-level penetration of 26 percent[187] in the cost-minimizing pathway for compliance with the 2025MY standards.

The EPA Trends Report does not distinguish between mild and strong hybrids in its accounting of hybrid vehicle penetration. Therefore it is difficult to separate the relative penetration of mild hybrids from that of strong hybrids since the 2012 FRM. Although most analysts had forecast the market share of hybrid vehicles to slowly but steadily rise, hybrid market share (including mild and strong hybrids) has leveled off at about 3 to 3.5 percent[188] of the total light vehicle market since 2009. According to a report by the International Council on Clean Transportation (ICCT),[189] GM mild hybrid systems accounted for about 2 percent of the 2014 U.S. market, a decline from about 5 percent in 2013. Other sources have remained optimistic that penetration levels will eventually grow substantially. For example, the automotive supplier Continental has projected market penetration rates of three million BEVs, 12 million strong hybrids and 13 million 48V mild hybrids by 2025.[190]

Like stop-start technology, mild hybrid technology alters the customary operation of the engine and so can alter the traditional feel of driving. In many situations the engine may turn off less frequently and be off for longer periods, although the cycling may appear more random because it is not necessarily connected to stop and go operation. Some of the effectiveness of mild hybrids may be diminished by individual driving habits, leading to possible dissatisfaction with fuel economy. For example, the fuel economy benefit of mild hybrids may fall off more quickly with aggressive driving due to the lower potential for engine-off operation under these conditions.

The 2015 National Academy of Sciences (NAS) report estimated a 10 percent effectiveness for mild hybrid technology[191] based upon the 11 percent fuel consumption reduction observed in the 2013 GM Malibu Eco. The NAS estimate appears reasonable when considering improvements in the GM Ecotec engine and six-speed automatic transmission, and when considering differences between the vehicle's 0-60 mph acceleration times (which are reported to be about 7.8 seconds for the base 2013 Malibu LT[192] and 8.2 seconds for the 2013 Malibu Eco[193]).

The GM Malibu 15 kW 115V eAssist BISG mild hybrid improved fuel economy about 11 percent over the conventional Malibu Eco 2.5L PFI engine with a six speed transmission. This effectiveness figure includes the benefits of other non-hybrid technologies (such as low rolling resistance tires, underbody aerodynamic panels and radiator grille active shutters) that are present on the e-Assist mild hybrid package.

The 2013 GM Malibu Eco's eAssist system uses a 15 kW BISG induction motor with 11 kW launch assist during heavy acceleration and 15 kW of recuperative braking power.[194] The effectiveness of a 12 to 15 kW electric machine with a liquid-cooled integrated inverter in a 48V mild hybrid is comparable to that of a 15 kW motor in 100V+ mild hybrid when taking into consideration the 30 pound weight reduction from the battery pack and the three, long and heavy 3-phase AC cables used in the 100+V BISG system. For an equivalent mass, 48V mild hybrid technology effectiveness[195] will be slightly less than that of 100V+ mild hybrids.

Since the 2012 FRM, the GM eAssist platform has migrated to other vehicles in the GM lineup. In February 2016, General Motors announced a limited pilot program offering a version of its eAssist mild hybrid system on approximately 200 GMC Sierra 1500[196] and 500 Chevrolet Silverado[197] 2WD pickups in California. This option is offered at a retail price of $500, significantly lower than the approximately $1000 cost attributed to the 2013 Malibu Eco hybrid system by an FEV teardown analysis.[198] GM credits this system with up to a 13 percent improvement in city fuel economy. This development is significant in part because it is the first example of a BISG system applied to production pickup trucks by a major manufacturer. GM stated that it would "monitor the market closely […] and adjust as appropriate moving forward." GM is also offering the eAssist BISG mild hybrid as an option to Chevrolet Equinox and GMC Terrain midsize SUVs, and Buick Verano, Buick Regal, and Buick Lacrosse. At least one analyst expects annual sales of these vehicles to grow to about 100,000 by 2020,[188] suggesting that BISG may become a significant contributor to the compliance path of manufacturers that rely on this technology.

The Honda Civic IMA (Integrated Motor Assist) or P1 mild hybrid integrates a 1.5L inline four cylinder Atkinson cycle engine[199] with a CVT transmission and a 17 kW CISG motor to achieve a 29.7 percent total GHG effectiveness (calculated from two-cycle certification data comparing the 2015 1.5L Honda Civic IMA to the 2015 1.8L Honda Civic sedan). The effectiveness attributable to the mild hybrid technology alone can be estimated by subtracting the effectiveness of the other technologies present on the vehicle. This includes about 1.9 percent for low rolling resistance tires (LRRT1), 0.7 percent for low drag brakes (LDB), 1.3 percent for electrical power steering (EPS), 0.7 percent for LUB, 3 percent for use of Atkinson cycle ICP and DCP, 3.5 percent for use of a CVT, 3 percent for HEG, 0.8 percent aerodynamics and 1.5 percent for weight difference, resulting in about 13.3 percent GHG effectiveness for this system. This comparison does not consider the small 0-60 acceleration performance loss (from 9 seconds to 9.8 seconds) between the standard 1.8L sedan and the IMA hybrid.

Combined two-cycle certification test data comparing the 2015 Mercedes-Benz E400 20kW120V P2 mild hybrid and the comparable E350 conventional vehicle indicated about 13 percent GHG effectiveness.

In addition to its own benefits, mild hybridization may help enable the use of other technologies that can further improve efficiency. For example, fuel consumption reduction may approach 20 percent when an electric supercharger is used in 48V mild hybrids combined with regenerative braking energy recovery, engine downsizing and downspeeding.[200] Audi is expected to market a system utilizing this technology in 2017. As another example, a 48V, 7 kW electric supercharger[201] has been shown to deliver an extra 40 to 70 kW at the crankshaft by boosting the engine combustion process. Hence, the electric supercharger may be an effective accompaniment to engine downsizing and downspeeding.

The only high-voltage BISG mild hybrid systems currently present in the U.S. market are the 115V Buick Lacrosse eAssist and the 90V 2017 Chevrolet Silverado truck[197] mild hybrid system. Hyundai is, however, using BISG technology for torque smoothing in its high voltage BISG Hybrid Starter Generator (HSG) drivetrain. About 15 percent of the weight reduction in the 2017 Chevrolet Silverado large truck mild hybrid system was achieved by reducing the battery cell count from 32 cells to 24 cells, and eliminating three 3-phase AC cables that had previously connected the battery pack to the motor. EPA estimates the cost of the 90V, 15 kW Silverado system would be approximately 85 percent of the 115V, 15 kW 2013 Malibu Eco cost projected by the FEV teardown study ($1045), or about $890.

A 48V mild hybrid truck was announced in the recent FCA business plan[202] for the 2018 Dodge Ram 1500 large truck using next-generation powertrains.[203] Schaeffler[204] and Hyundai[205] also recently demonstrated advanced engineering prototypes of small and mid-size SUV 48V mild hybrids.

Compared to 12V systems, high voltage BISG imposes higher costs for the battery pack, shock protection safety, and active cooling, but with a higher return in effectiveness. For example, A123 Systems has projected a fuel economy effectiveness of 12 percent for a 48V mild hybrid system utilizing its 48V battery technology.[206] At this level of effectiveness, this system was described as being more cost effective (at $55 per percent fuel economy gain) than a full hybrid solution (at $83).

To date, most mild hybrids such as the aforementioned Malibu eAssist have been designed to operate at a voltage of 100V or higher. However, since the 2012 FRM, evidence has accumulated to suggest that many functions of a BISG mild hybrid can be provided at a lower voltage, such as 48V, at significantly reduced costs. Although the effectiveness of 48V mild hybrids[195] will be slightly less than that of higher-voltage mild hybrids (for example, a 48V system may have a regenerative energy capturing efficiency of about 50 percent[207] compared to perhaps 85 percent for a typical strong hybrid), it can still provide up to 10 to 15 kW of launch assist and battery charging power. 48V mild hybrid prototype demonstration vehicles from Audi, Hyundai, Mitsubishi, and Johnson Controls have been described as delivering about 10 to 15 percent CO_2 reduction and fuel economy improvement.[208] Continental, a major Tier 1 supplier of electrified automotive systems, has presented a prototype small car with a 10 kW BISG 48V mild hybrid system, said to provide a 7 percent CO_2 reduction.[209] In the FRM, the agencies calculated a 7.4 percent GHG effectiveness for small cars equipped with a 10 kW BISG mild hybrid system, which is comparable to the Continental results.

Industry appears to be coalescing on a 48V standard for such mid-voltage hybrid applications, with manufacturers such as Audi, BMW, Daimler, Porsche and VW having initiated a 48V standard known as LV148.[210]

48V mild hybrid technology can also be understood as an alternative to stop-start that is not as costly as adopting a higher voltage mild hybrid technology. Compared to 12V stop-start, 48V mild hybrids provide several benefits for a relatively small cost increase,[211] such as faster engine starting, more engine-off time, significant regenerative braking capacity, and better electrical support for accessories while the engine is off.

For these reasons, the agencies now expect 48V mild hybrid technology to become more common than anticipated at the time of the 2012 FRM. The agencies are therefore adding the 48V mild hybrid architecture to this Draft TAR analysis.

48V mild hybrid technology has received an increasing amount of attention since the 2012 FRM, with a number of OEMs and suppliers introducing several developmental 48V mild hybrid systems capable of significant CO_2 and fuel consumption reductions. At the 2015 SAE Hybrid and Electric Vehicle Technology Symposium, Controlled Power Technology (CPT) exhibited a switched-reluctance motor-generator technology and an electric supercharger for 48V vehicle electrification. Bosch has presented a 48V mild hybrid system scheduled to be ready for production by 2017[212] that it describes as capable of a 15 percent reduction in fuel consumption. At the 2015 Consumer Electronics Show (CES), Continental exhibited a 48V mild hybrid system which consists of a 48V Belt Integrated Starter Generator (BISG) replacing 12V alternator, DC/DC converter and a 48V lithium-ion battery pack. The BISG motor is an induction motor, and liquid cooled by engine coolant. The motor can be decoupled for downhill coasting by disconnecting the transmission from the engine. Continental expects this 48V mild hybrid system to begin production in 2016.[213] In concert with these introductions, suppliers are also predicting significant market penetration for 48V systems within the time frame of the rule. Bosch projected some 4 million 48V mild hybrid vehicles worldwide in 2020, while Eaton expected up to 3 million 48V mild hybrids globally by 2020.[189]

48V mild hybrid technology is estimated to be significantly less expensive than strong hybrid technology at about 25 percent of the cost. Several advantages of 48V systems contribute to this lower cost. The voltage is lower than the 60V safety threshold that would otherwise require more robust electrical shock protection. The small power levels associated with these components promotes integration of the inverter with the motor and the elimination of long stretches of cable, further isolating the AC portion of the circuit. The relatively small 48V battery pack is significantly less costly than for a strong hybrid due to its smaller capacity, and may be composed of fewer cells due to its lower voltage. The battery may not require liquid cooling, instead being passively cooled with appropriate placement and packaging. The relatively low power requirements of a 48V system also promotes use of relatively inexpensive motor technology (such as induction or switched reluctance) without as strong a concern over NVH or efficiency.

Recent developments in the 48V platform have suggested that it is also capable of pushing the limits of what would be considered a mild hybrid. New P2, P2/P4 and P0/P4 48V system architectures have been presented by various suppliers such as Bosch, Shaeffler, Continental, and Control Power Technologies, ranging from 20 kW to 45 kW of assist capability.[190] The effectiveness for these new, more powerful systems, particularly those on the higher end of the power range (30-45kW) may approach that of P2 strong hybrids but at a much lower cost. For example, Bosch has presented a 2nd generation, 48V P2-architecture mild hybrid currently in development.[212] In this 48V P2 system, a more powerful motor-generator is integrated into the transmission (to create a transmission-integrated starter-generator or TISG architecture). As with a P2 strong hybrid, the motor can be decoupled from the engine to propel the vehicle in an electric-drive mode in stop-and-go traffic and for short distances.

Transcending the BISG format provides a way around common mild hybrid limitations, such as the 15 kW peak motor power limit, belt efficiency losses, and tandem operation of the engine with the motor. Stronger formats such as Crank-Integrated Starter Generator (CISG) P1 architecture, as well as Transmission Integrated Starter Generator (TISG) P2 architecture, overcome the peak motor power limitation in BISG P0 mild hybrids and further increase the potential effectiveness of mild hybrid technology. The Honda IMA CISG P1 mild hybrid system cannot run the electric motor alone without simultaneously operating the internal combustion engine,[214] while the TISG P2 mild hybrid format allows the engine shut down while the electric motor works independently for braking energy recuperation and vehicle propulsion. The effectiveness of TISG P2 mild hybrids therefore may have higher effectiveness potential than that of CISG P1 mild hybrids.

The effectiveness of TISG P2 mild hybrids appears to be higher than that of CISG P1 mild hybrids. GETRAG projected about 15 percent effectiveness for a 48V 21 kW TISG P2 mild hybrid at the 14th VDI Congress.[185] This system employs a 7 speed dual clutch hybrid transmission, which integrates one common oil circuit for cooling and lubrication, and a combined e-machine and inverter applicable not only to the 48V 21 kW mild hybrid but also to other variants such as a 220V+, 50 kW strong hybrid and a 360V+, 110 kW plug-in hybrid application. This hybrid transmission also supports other efficiency-enhancing features such as pure electric driving, extended sailing, more efficient launch assist and brake energy recuperation, battery charging when the vehicle is standing, and generator-mode/load shift; features very similar to those provided by strong hybrids.

Based on a review of these and similar industry developments, as well as data collected from other sources, the agencies have updated effectiveness estimates for mild hybrid technology. Updated cost and effectiveness estimates are discussed further in Sections 5.3 (GHG Assessment) and 5.4 (CAFE Assessment).

5.2.4.3.3 *Strong Hybrids*

In this analysis, strong hybrid refers to hybrid technologies that have higher power capability and larger battery capacity than mild hybrids, thus providing for more effective management of power from the internal combustion engine, greater levels of regenerative braking, and more powerful electric propulsion capable of accelerating the vehicle with less (if any) assistance from the engine. Strong hybrids provide greater effectiveness than mild hybrids by better optimizing loading of the engine, allowing additional engine downsizing, allowing the engine to turn off for longer periods, and recovering a greater portion of braking energy. These enhanced functions tend to require higher voltages (as high as 300V to 400V) and more powerful batteries with greater energy capacity, typically on the order of 1 to 2 kWh. These attributes add to complexity due in part to safety requirements associated with higher voltages and greater battery capacity. Although strong hybrids are costlier than mild hybrids, they can access a greater degree of fuel economy and CO_2 reduction than mild hybrids, and include some of the highest fuel economy vehicles currently in production.

Strong hybrids include several distinct architectures. On a sales-weighted basis, the power-split hybrid electric vehicle (PSHEV) represents the most common architecture, largely by virtue of its use for many years in the Toyota Prius hybrid. This system replaces the traditional transmission with a single planetary gearset and two motor/generators. The smaller motor/generator uses the engine to either charge the battery or supply additional power to the drive motor. The second, more powerful motor/generator is permanently connected to the vehicle's final drive and always turns with the wheels, as well as providing regenerative braking capability. The planetary gearset splits engine power between the first motor/generator and the output shaft to either charge the battery or supply power to the wheels.

The two-mode hybrid electric vehicle (2MHEV) is a hybrid electric drive system that uses an adaptation of a conventional stepped-ratio automatic transmission by replacing some of the transmission clutches with two electric motors that control the ratio of engine speed to vehicle speed, while clutches allow the motors to be bypassed. This improves both the transmission torque capacity for heavy-duty applications and reduces fuel consumption and CO_2 emissions at highway speeds relative to other types of hybrid electric drive systems.

The P2 hybrid is a hybrid technology that uses a transmission integrated electric motor placed between the engine and a gearbox or transmission, with a wet or dry separation clutch which is used to decouple the motor/transmission from the engine. A P2 hybrid would typically be equipped with a larger electric machine than a mild hybrid system but smaller than a power-split or 2-mode hybrid architecture. Disengaging the clutch allows all-electric operation and more efficient brake-energy recovery. Engaging the clutch allows efficient coupling of the engine and electric motor. Based on simulation, when combined with a DCT transmission, the P2 hybrid architecture provides similar or improved fuel efficiency to other strong hybrid systems with reduced cost.

In the 2012 FRM, P2 hybrid was the only hybrid architecture that was applied in the agencies' analysis. Although PSHEV and 2MHEV technology were discussed because they were present in the market at the time of the FRM, they were not included in the analysis because the industry was expected to trend toward more cost-effective hybrid configurations such as P2.

The primary reference EPA used for strong hybrid effectiveness in the 2012 FRM was the Ricardo modeling study which modeled a P2 with a future DCT. On this basis EPA estimated an absolute CO_2 effectiveness for P2 strong hybrids ranging from 13.4 to 15.7 percent depending on vehicle class (see 2012 RIA, p. 1-18). These figures included only the effectiveness related to the hybridized drivetrain (battery and electric motor) and supported accessories, and did not include the effect of any accompanying advanced engine technologies. The quoted figures were based on electric motor sizes assumed in the Ricardo vehicle simulation results and would vary with other motor sizes.

On this basis, the agencies projected that strong hybrids would achieve a fleet-level penetration of 5 percent[215] in the cost-minimizing pathway for compliance with the 2025MY standards.

The EPA Trends Report does not distinguish between mild and strong hybrids, nor specific architectures of strong hybrids, in its accounting of hybrid vehicle penetration. Therefore it is difficult to use this source to assess the relative penetration of P2 and other strong hybrid architectures since the 2012 FRM. However, it is expected that strong hybrids are making up the majority of the market.

A recent report by the International Council on Clean Transportation (ICCT)[189] reviews market penetrations for various hybrid architectures. According to this report, the market share of the P2 hybrid architecture among all hybrids has been relatively small, having grown from about 9 percent in 2013 to about 12 percent in 2014. Toyota has continued to lead the U.S. hybrid market with 66 percent of U.S. hybrid sales in 2014. These sales largely account for the dominance of power-split hybrids in the market. In the same year, Ford claimed a 14 percent share of the U.S. hybrid market, also with power-split hybrids. P2 hybrids are primarily represented in the U.S. market by Hyundai/Kia and Honda, with 8 percent of total 2014 hybrid sales. The Honda integrated-motor-assist (IMA) architecture represented only 3 percent of the 2014 hybrid market, and is expected to be replaced by a P2 system in the near future.

Compared to the more mature, 4th generation power split hybrid architectures of Toyota and Ford, EPA believes the P2 hybrid architecture is still in a relatively early stage of development and has yet to be fully optimized. Manufacturers are continuing to make strides toward improving this architecture in recently introduced models by refining power electronics and component efficiency and integrating parts. For example, Hyundai has improved the 2nd generation Sonata hybrid by fully integrating a 38 kW traction motor and all of the other hybrid powertrain components within the transmission. The reduced weight has led to improved fuel economy with reduced costs, as evidenced by the observation that there is no major difference in effectiveness between this P2 vehicle and the 2015 Toyota Camry power-split hybrid. Going forward, similar opportunities for major cost reduction and fuel economy improvement are likely to arise in competing P2 hybrid systems.

Differences in configuration account for some of the cost and effectiveness differences between P2 and power-split architectures. The input power-split architecture requires two motors, which consist of a small generator and a bigger traction motor which drives through a simple power-split planetary gear set. The P2 architecture uses a single, smaller traction motor, but drives through a more complex conventional transmission gearing. The Honda two-motor architecture does not use a power-split planetary gear set, and therefore requires a bigger motor to directly transmit power to the drive axle compared to the typical input power-split hybrid system. For example, the Honda Accord 2-motor hybrid uses a 124 kW traction motor[216] while the Toyota Camry power-split hybrid uses a 105 kW traction motor.[217] Highly efficient motor-integrated DCT transmissions have recently entered production or are under development and are being adopted in the latest P2 parallel hybrid designs. P2 parallel hybrid architecture also provides higher towing capacity while the power-split hybrid architecture is limited to less than 3500 pounds trailer towing capacity.

Even the relatively well-developed power-split architecture continues to show room for efficiency improvements. Toyota redesigned the 2016 Prius[218] transaxle and motor in its 4th generation Hybrid Synergy Drive (HSD) to reduce combined weight by 6 percent and volume by 12 percent. The planetary gear arrangement in the reduction gear has been replaced with parallel gears, reducing mechanical losses by approximately 20 percent. The 53 kW main traction motor is mounted on a parallel shaft, enabling the transmission case volume to be reduced substantially while also reducing frictional losses by about 20 percent. The power control unit, which combines the controller, inverter and DC/DC converter, was attached to the top of the transaxle and its size reduced by about 33 percent by eliminating several high-voltage cables. The lithium-ion battery pack, which is available on the Eco trim level, is 6 percent smaller and 31 percent lighter than the nickel-metal hydride (Ni-MH) version, while providing the same power output and degree of hybridization.

Further evidence that the effectiveness of input power-split hybrids and P2 parallel hybrids are getting closer is shown by the 2017 Hyundai IONIQ P2 hybrid, announced in 2016. The combined fuel economy of this vehicle, with the GEN2 Hyundai P2 parallel hybrid drive, is expected to be about 53 mpg, which is comparable to the 52 mpg fuel economy of the 2016 GEN4 Toyota Prius hybrid. This vehicle also employs advanced technologies such as a gasoline direct injection (GDI) inline 4 cylinder Atkinson cycle engine, cooled EGR, CVVT, dual circuit cooling system, 6 speed dual clutch transmission (DCT), exhaust heat recovery system, and an intake oil control valve, which act together to increase engine thermal efficiency to as high as 40 percent.

As reported by ICCT[189] (and reproduced here in Figure 5.28), the estimated costs for hybrid systems have tended to decline steadily in the years after their introduction. If these trends continue, significant reductions in hybrid system cost may be expected during the time frame of the rule.

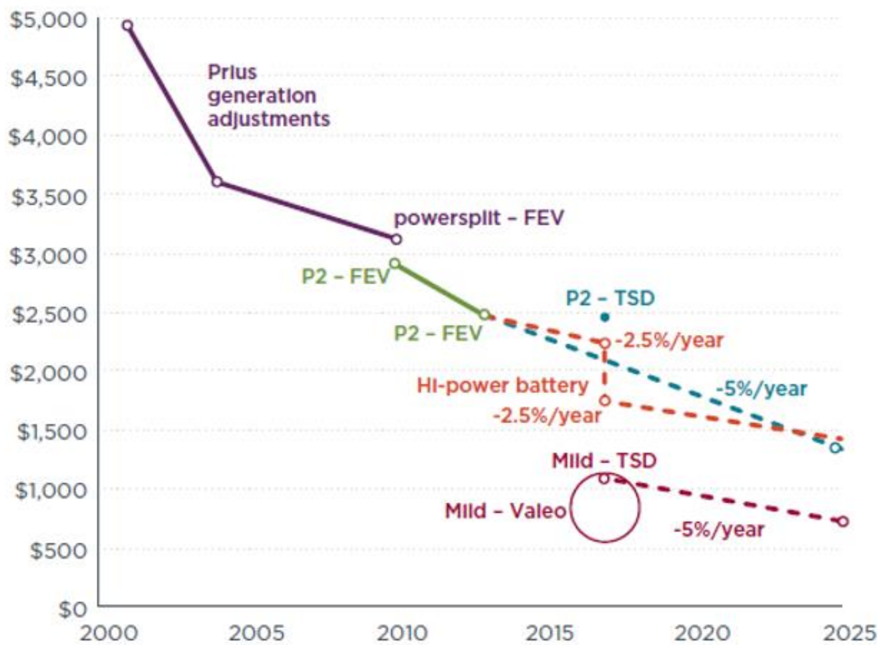


Figure 5.28 Hybrid System Direct Manufacturing Cost Projection (ICCT, 2015)

The overall cost of power-split, P2 and two-motor hybrid systems appear to be comparable. For example, as estimated by an FEV teardown in 2010,[219] the power-split hybrid cost of $2,565[220] is only slightly higher than the $2,392 cost estimate for a P2 hybrid system. EPA is therefore combining all strong hybrid architectures under the strong hybrid category for the purposes of this Draft TAR analysis. NHTSA has included both power split and pre-transmission HEVs in its analysis. While Atkinson engines were exclusively used for the power split HEV, multiple engine and transmission technologies were included for the pre-transmission analysis.

Based on a review of these and similar industry developments, as well as data collected from other sources, the agencies have updated cost and effectiveness estimates for strong hybrid technology. Updated cost and effectiveness estimates are discussed further in Sections 5.3 (GHG Assessment) and 5.4 (CAFE Assessment).

5.2.4.3.4 *Plug-in Hybrids*

A plug-in hybrid electric vehicle (PHEV) is much like a hybrid electric vehicle, but with at least three significant functional differences. The first is the addition of a means to charge the battery pack from an outside source of electricity (usually the electric grid). Second, a PHEV has a much larger battery capacity, and often a greater usable fraction as well. Finally, it has a control system that allows the battery to be significantly depleted during normal operation.

Deriving some of their propulsion energy from the electric grid provides several advantages for PHEVs. PHEVs offer a significant opportunity to replace petroleum used for transportation energy with domestically-produced electricity. The reduction in petroleum usage does, of course, depend on the amount of electric drive the vehicle is capable of providing under its duty cycle. PHEVs also provide electric utilities the possibility to increase electric generation during off-peak periods overnight when there is excess generation capacity and electricity prices are lower. Utilities like to increase this base load because it increases overall system efficiency and lowers average costs. PHEVs can lower localized emissions of criteria pollutants and air toxics especially in urban areas by operating on electric power. The emissions from the power generation occur outside the urban area at the power generation plant which provides health benefits for residents of the more densely populated urban areas by moving emissions of ozone precursors out of the urban air shed. Unlike most other alternative fuel technologies, PHEVs can initially use an existing infrastructure for refueling (charging and liquid refueling) so investments in infrastructure may be reduced.

Depending on the operating strategy chosen by the manufacturer, a PHEV either provides for a significant all-electric range (AER) during which the engine does not operate, or provides for blended operation in which the engine provides some of the propulsion energy while the battery contributes the remainder. In this discussion, the former is referred to as a PHEV with AER, and the latter is referred to as a blended PHEV.

In the 2012 FRM analysis, PHEVs were modeled in two configurations, designated PHEV20 and PHEV40 (having 20 miles and 40 miles, respectively, of all-electric range). Range was modeled as an approximate real-world range comparable to an EPA label range (specifically, it was modeled as 70 percent of a projected two-cycle range). Both PHEV configurations were assigned component sizing consistent with their operation as PHEVs with AER. This tended to assign a more powerful electric powertrain than would have been required by a blended PHEV, which is assisted by the engine.

In the 2012 FRM analysis, EPA assigned PHEVs an effectiveness derived from the SAE J1711 recommended procedure for accounting for utility factor (the balance between miles traveled on electricity in all-electric mode and other miles powered by fuel). On this basis PHEV20 was assigned an absolute CO_2 effectiveness of 40 percent, and PHEV40 was assigned 63 percent (see 2012 RIA, p. 1-18). NHTSA modeled a PHEV30 and PHEV 50 with utility factors of 0.5226 and 0.6887 respectively.

In the FRM analysis, the cost-minimizing pathway for compliance with the 2025MY standards did not project a necessity for significant fleet-level penetration of PHEVs (nominally, zero percent). The analysis did project that some primarily luxury- and performance-oriented OEMs might include PHEVs as part of their individual pathway to achieve compliance with 2025MY standards.[221]

At the time of the FRM, only a few PHEVs were commercially available in the U.S. market. The most prominent examples were the Chevy Volt and the Fisker Karma, both of which debuted as MY2011 vehicles, and the 2012 Toyota Prius Plug-In Hybrid. Production of the Karma was discontinued in late 2012 as Fisker encountered financial difficulties. Fisker now belongs to the Chinese company Wanxiang Group and has not resumed significant production to date.

Even these early PHEVs demonstrated important differences in their operating strategy that remain visible in today's market. The Volt and Fisker both offered a significant AER by including a distinct charge-depleting mode in its operating strategy. In contrast, the Prius utilized a more blended mode of operation in which the engine could regularly operate during the charge depletion stage depending on driving conditions, for example, if the vehicle exceeded a certain speed or power demand. Both strategies continue to appear in the market today, with some vehicles emphasizing AER and others emphasizing overall fuel economy in blended operation. Some PHEVs that employ blended operation are able to achieve an all-electric range during EPA city and highway test cycles, but may operate in blended mode (using a combination of gasoline and electricity) when driven more aggressively. Operation in blended mode may be converted to an equivalent AER by applying a utility factor that considers the contribution of stored electricity to the total distance traveled in this mode. Therefore both types of PHEVs are capable of displacing conventionally-fueled mileage with electrically fueled mileage.

The 2011 Chevy Volt had an EPA-rated AER of 38 miles, while that of the Fisker was 32 miles. The Prius was rated at 6 miles AER (11 miles including blended mode).

Since the FRM, several new models of PHEV have entered production, with several additional models announced for future production or otherwise known in the form of concept cars. Table 5.2 shows a summary of PHEV models that have been in production during the period since the FRM and their EPA-estimated range (which may include operation in blended mode).

Table 5.2 Trends in EPA-Estimated Range of PHEVs

	EPA range (mi)				
PHEV model	2012	2013	2014	2015	2016
Chevy Volt	35	38	38	38	53
Fisker Karma	33	-	-	-	-
Toyota Prius Plug-In Hybrid	11	11	11	11	NL
Ford Fusion Energi	-	20	20	20	20
Ford C-Max Energi	-	20	20	20	20
Honda Accord PHV	-	-	13	-	-
McLaren P1	-	-	19	19	-
BMW i3 Rex	-	-	72	72	72
BMW i8	-	-	15	15	15
Cadillac ELR	-	-	37	37	40
Cadillac ELR Sport	-	-	-	-	36
Porsche Panamera S E-Hybrid	-	-	16	16	16
Porsche 918 Spyder	-	-	-	12	-
Mercedes-Benz S550e	-	-	-	14	14
BMW X5 xDrive40e	-	-	-	NA	14
Porsche Cayenne S e-Hybrid	-	-	-	14	14
Hyundai Sonata PHEV	-	-	-	-	27
Mercedes-Benz C350e	-	-	-	-	18.6*
Audi A3 e-tron	-	-	-	-	16
Audi A3 e-tron ultra					17
BMW 330e	-	-	-	-	14
Mercedes-Benz GLE 550e 4MATIC	-	-	-	-	18*
Volvo XC90 T8 Hybrid	-	-	-	-	14
Mean AER (not sales weighted)	26.3	22.3	26.1	24.0	24.4

Notes:
NL = vehicle not listed in Fuel Economy Guide
NA = rating not available in Fuel Economy Guide
* = approximated from press or manufacturer estimates

Since the FRM, the continued development and production of PHEVs as evidenced in Table 5.2 has likely been driven in part by manufacturers having chosen to consider PHEVs as part of their pathway for compliance with the 2017-2025 standards, but even more so by California's zero emission vehicle (ZEV) regulation. In 2012, CARB adopted increased requirements for ZEVs and PHEVs through MY2025. A 2015 National Academy of Science report on PEV deployment[222] cites the California ZEV regulation as being particularly influential in increasing PEV production and adoption.

In addition, PHEVs from all manufacturers continue to be eligible for a federal tax credit of up to $7,500, effectively reducing their net cost to consumers.[223,224] This credit applies to the first 200,000 PEVs (PHEVs and BEVs combined) that are produced by a given manufacturer and rapidly phases out thereafter. While most manufacturers are unlikely to approach this limit for at least several years, some of the leading PEV manufacturers such as General Motors, Nissan, and Tesla are beginning to approach the limit. For example, if the Gen2 Chevy Volt sells well, and the recently introduced Chevy Bolt EV does also, it is possible that General Motors could reach the limit by the end of 2017. Strong future sales of the Tesla Model X and Model 3, or the anticipated 200-mile version of the Nissan Leaf, could cause Tesla and Nissan to approach the limit by the end of 2018.[225] However, in addition to Federal incentives, many states including California and most of the states that have adopted California's ZEV regulation offer incentives at the state and local levels.

It is important to note that most PHEVs are built on global platforms, meaning that economies of scale for the U.S. market may be driven in part by incentives in other countries. Incentives for PHEVs in the European Union and China are particularly notable because many manufacturers that serve the U.S. also serve these markets.

Trends in PHEV Electric Range

The electric range of a PHEV (either AER or equivalent AER) is largely a function of the provided battery capacity. Figure 5.29 shows the relationship between the battery capacity of the PHEVs in Table 5.2 and their EPA-estimated electric driving range (or the best estimate available at writing).

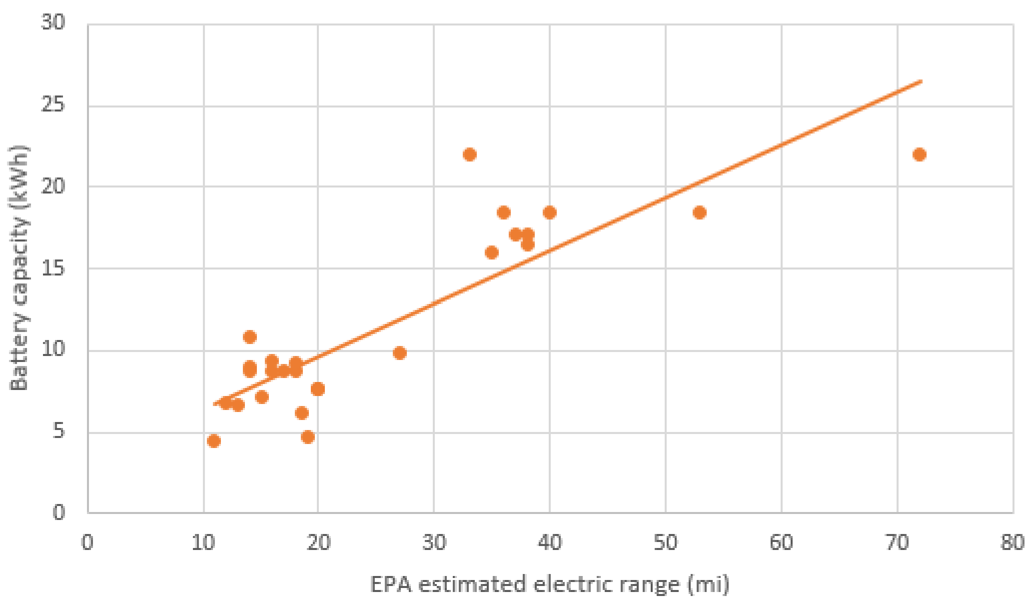


Figure 5.29 Battery Gross Capacity and Estimated AER or Equivalent for PHEVs[V]

As the Table and Figure shows, PHEV electric range varies considerably among models. Among the 2012-2016 PHEVs depicted, two distinct clusters appear, one consisting of longer-range PHEVs with AER in the vicinity of 35 to 40 miles, and another consisting of shorter-range vehicles offering between 10 and 20 miles of range (either AER or its equivalent in blended operation).

The longer-range cluster consists of various versions of the Chevy Volt and Cadillac ELR (which shares the Voltec powertrain), the Fisker Karma (at 33 miles), and the BMW i3 (at 72 miles). These are PHEVs with AER that can provide a true all-electric drive mode under a wide

[V] Range figures gathered from 2012-2016 EPA Fuel Economy Guides.

range of operation. Longer-range PHEVs require a larger battery capacity which tends to increase their purchase price relative to shorter range PHEVs.

The shorter-range cluster includes several blended-operation PHEVs. With the exception of the Toyota Prius PHV (11 miles) and the Ford Energi models (20 miles), these emerged primarily in the 2015 and 2016 MYs from OEMs that tend to specialize in luxury or high-performance vehicles. This suggests that these OEMs are considering PHEVs as a compliance strategy, as projected in the FRM. For example, when BMW announced the U.S. versions of the 330e and the X5 xDrive40e PHEVs in November 2015, BMW Product Manager Jose Guerrero was quoted as saying that the timing of introductions such as these "wasn't a competitive impulse by any manufacturer … it was an internal impulse that we know that in the future our cars need to be more efficient, and this is a way … into that efficiency."[226] The Mitsubishi Outlander PHEV, expected to enter the U.S. market in 2016 as a 2017MY vehicle,[227] is also expected to have an EPA AER in the neighborhood of 20 miles. These and similar announcements suggest that a distinct segment of PHEV20-type vehicles is likely to continue in the future as manufacturers continue to select this lower cost pathway.

Where new generations of the same model have been announced, the range has in some cases been increased. For example, the AER of the 2016 Chevy Volt increased from 38 miles to 53 miles. Going forward, several OEMs have indicated that second generation PHEV products will have more AER and more electric power capability, by targeting US06 capability, with minimal if any reliance on the engine and 30 miles or more of AER. For example, the FCA Pacifica plug-in minivan was announced in January 2016 as targeting a 30 mile all-electric range, with capability to operate all-electric over most operating conditions.[228] Honda is reported to be considering a 40 mile AER for an upcoming PHEV that would replace the now-discontinued Honda Accord PHV, which had an AER of only 13 miles.[229] Similarly, other manufacturers including Toyota, GM, and Ford have suggested that their 2017 to 2018 PHEV products will be targeting at least 30 miles of electric range.

In such announcements, manufacturers have frequently cited customer desire for an all-electric driving experience. As one example, GM appears to credit consumer demand for more range as part of the impetus for increasing the range of the 2016 Volt. According to Chief Engineer Andrew Farah, "We listened to our customers … they were very clear when they told us that they wanted more range."[230] General Motors may have even coined the term "range anxiety" in order to promote the extended range of the Volt PHEV versus battery-only BEVs. These manufacturers appear to be responding by increasing the potential for all-electric operation by increasing electric powertrain power ratings and battery capacity.

The California Zero-Emission Vehicle (ZEV) program also may be influencing PHEV range. To qualify as transitional-zero emission vehicles (TZEVs) under the program, PHEVs must provide at least 10 miles of AER operation on the UDDS drive schedule (as well as meet certain criteria pollutant standards).[231] Since many PHEV manufacturers market in ZEV states as well as other states, the ZEV program provides a strong incentive for producing PHEVs with AERs above this threshold.

Other incentive programs may be encouraging longer PHEV electric range. One example is the China New Energy Vehicles Program.[232] Renewal of this program in 2013 increased the eligibility requirements for PHEVs to a minimum 50 km (30 mile) AER (under the NEDC cycle) in order to qualify for purchase subsidies.[233] There is some evidence that this may be encouraging manufacturers of global-market PHEVs to increase AER to at least this level.[234] For example, the Cadillac CT6 PHEV was announced in April 2015 at the Shanghai Auto Show, where it was described as qualifying for the New Energy Vehicles incentives with a range in excess of 60 km (37 miles).[235] The U.S. version will have the same 18.4 kWh battery pack as the China version, suggesting that its AER will be similar. As of July 2016, at least one local U.S. incentive in the state of Washington will also adopt a 30 mile PHEV range requirement to qualify for a sales tax exemption up to $3,100.[236]

Manufacturers have continued to pursue and implement improvements in the efficiency and cost of battery and non-battery components for PHEVs. One example is the 2016 Chevy Volt, in which the weight of the battery pack was reduced by 14 kg despite an increase in its capacity from 17.1 kWh to 18.4 kWh. The weight of the traction motor was also reduced by 45 kg, and additional weight and cost were saved by integrating the inverter with the motor and eliminating long runs of high voltage electrical cable.[151,152]

Improvements in component efficiency and road load have both improved performance of production PHEVs. For example, GM has indicated that the 2016 Chevy Volt improved its average electric powertrain efficiency over the EPA city and highway cycles by 3 percentage points (or 4 percent absolute) compared to the first generation Volt, improving from 86 percent to 89 percent for the city, and from 84 percent to 87 percent for the highway. Drive unit losses (including losses of the electric motor, inverter, and transmission) were reduced by 39 percent in the city cycle and by 35 percent in the highway cycle.[237] The Gen2 Volt also provides a good example of the use of standard road load improvements to increase range in a PHEV.[164] Here, significant changes to the electric propulsion system were accompanied by improvements in brake drag, reductions in accessory load, and significant improvement of vehicle mass efficiency.

In the 2012 FRM, the agencies envisioned PHEV20 and PHEV40 as representative of PHEVs that were likely to play a significant role in achieving fleet compliance during the time frame of the rule. As Table 5.2 and Figure 5.29 show, PHEV20 continues to be represented by several 20-mile and shorter range PHEVs that either continue to be available or have been introduced since the FRM. PHEV40 has now been surpassed in real-world range by the 2016 Chevy Volt at 53 miles, and by the BMW i3, which with its range extender option becomes classified as a PHEV with 72 miles AER.

EPA and CARB therefore considered replacing PHEV40 with a longer range, such as PHEV50, in this Draft TAR analysis. Several uncertainties made it unclear as to whether it would be preferable or useful to do so. First, although at least two PHEVs have exceeded PHEV40, it is also true that other production PHEVs such as the Cadillac ELR and CT6 continue to fall on the lower side of this line. Second, if PHEV ranges do in fact increase toward PHEV50 in the future, it is likely to be enabled at least in part by developments other than increased battery size alone, such as a larger usable capacity, improved powertrain efficiency, improved battery specific energy, and reduced road loads. Revising the PHEV40 range would therefore require that the agencies not simply increase the battery size alone, but also must acquire a full understanding of the factors that are enabling this increased range in practice, and represent them accordingly in the battery sizing model. Because not all manufacturers are likely to be following the same path, modeling these factors faithfully required careful consideration. For this Draft

TAR analysis, EPA has chosen to retain PHEV40 with a 40-mile label range. NHTSA models PHEV50 with a 50 mile 2-cycle range.

In later sections, the agencies will reexamine the 2012 FRM assumptions for other parameters that affect PHEV battery sizing for this Draft TAR analysis. These include assumptions for usable battery capacity, electric powertrain efficiencies, battery specific energy, and specific power of electric machines and power electronics.

Trends in PHEV Motor Sizing

In addition to driving range, the motor power of PHEVs is another important input to the agencies' projection of battery and system costs for PHEVs. In the 2012 FRM, PHEVs of a given vehicle class (small car, large car, etc.) were assigned an electric motor power rating (in kW) that would preserve the same engine-power-to-weight ratio that was observed in conventional vehicles of that class. This method assumed that the all-electric acceleration of PHEVs relates to the power rating of the electric motor in the same way that the engine-powered acceleration of conventional vehicles relates to the power rating of the engine. However, electric motors differ markedly from combustion engines, particularly in their delivery of low-speed torque. Electric motors deliver maximum torque at the lowest end of their speed range, while combustion engines must develop significant speed to deliver a comparable torque. This strong low-end torque allows electric-drive vehicles to deliver high acceleration at low speeds. This might allow a PHEV or BEV to deliver acceleration performance similar to that of a conventional vehicle but with a significantly lower nominal motor power rating than a comparably performing combustion engine. At the time of the 2012 FRM, it was unclear to what extent this phenomenon would influence electric motor sizing in production vehicles, leading to the decision to assign PHEV motor power based on the nominal power-to-weight ratios of conventional vehicles.

The issue of proper motor sizing for PEVs is being revisited for this Draft TAR analysis. Accurately assigning PEV motor power is important on several fronts. First, the motor power rating has a direct effect on the battery power rating, which determines its power-to-energy (P/E) ratio and its cost. Second, EPA is revising the battery sizing methodology that was used in the 2012 FRM by accounting for the weight of the propulsion motor and power electronics separately from the weight of the battery. This makes an accurate determination of motor power ratings more critical than before.

An accurate accounting of motor cost also requires an accurate accounting of motor power. As in the 2012 FRM, EPA estimates PHEV motor cost as a function of peak power output. For more discussion of the decision to scale motor cost to power output, see Section 5.3.4.3.6, Cost of Non-Battery Components for xEVs.

Since the 2012 FRM, the number of production PHEVs has increased and provides a much larger sample size from which some observations may be drawn. Figure 5.30 plots the drive motor power output ratings and curb weights of moderate- and high-performance PHEVs produced from MYs 2012 to 2016.

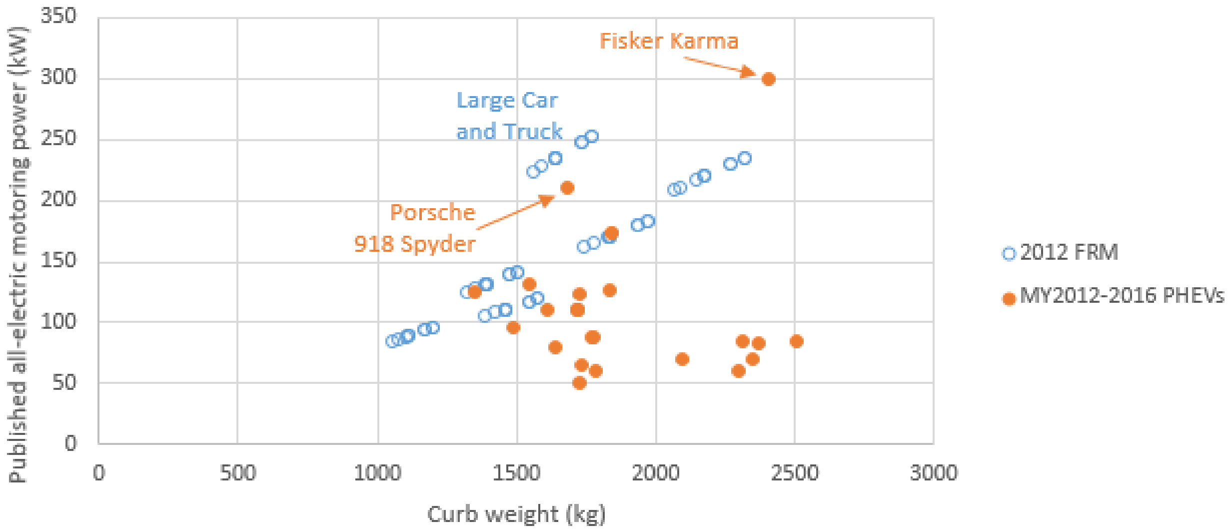


Figure 5.30 Comparison of Motor Power of 2012-2016MY Production PHEVs and FRM Estimates

In the Figure, the solid orange dots represent actual PHEVs certified for MYs 2012-2016. The blue circles represent the motor power ratings and weights assigned to PHEVs of various ranges and weight reductions in the 2012 FRM. The chart suggests that the 2012 FRM assigned significantly higher PHEV motor power ratings than the majority of PHEV manufacturers have actually specified in their products. Part of this effect could be due to the significant presence of blended-operation PHEVs in the market, which do not require as large a motor power output as non-blended PHEVs with AER. However, this alone does not account for the difference because many of the 2012 FRM estimates also over predict the motor power of non-blended PHEVs with AER.

Based on this analysis and a new power-to-weight study described in Section 5.3, EPA has revised the PHEV motor power ratings assumed for its GHG assessment. The assessment will therefore adopt power ratings closer to those suggested by the power-to-weight ratios that PHEV manufacturers appear to be following, while maintaining an estimated acceleration performance equivalent to conventional vehicles. Assigning a more accurate power rating to the PHEV motor will allow greater fidelity in the projected cost of both the battery and non-battery components of PHEVs. Specific adjustments to PHEV motor power sizing are discussed in Section 5.3.

NHTSA is basing its analysis on full vehicle simulation results, and will be using component power and energy values from Autonomie (where each vehicle powertrain model is sized to meet similar vehicle technical specifications) to calculate costs.

Trends in PHEV Battery Sizing

Accurately assigning battery capacity to PHEVs is also important. In the 2012 FRM, EPA used a battery sizing methodology to assign battery capacities to PHEVs modeled for the analysis. Now that a number of PHEVs are on the market and have been rated for all-electric range by EPA, it is informative to compare the 2012 FRM projections of PHEV battery capacity and range to the PHEVs that have entered the market for MYs 2012-2016.

Figure 5.31 compares the battery capacities of 2012-2016MY PHEVs (from Figure 5.29) to the battery capacities that were estimated for the 2012 FRM analysis.

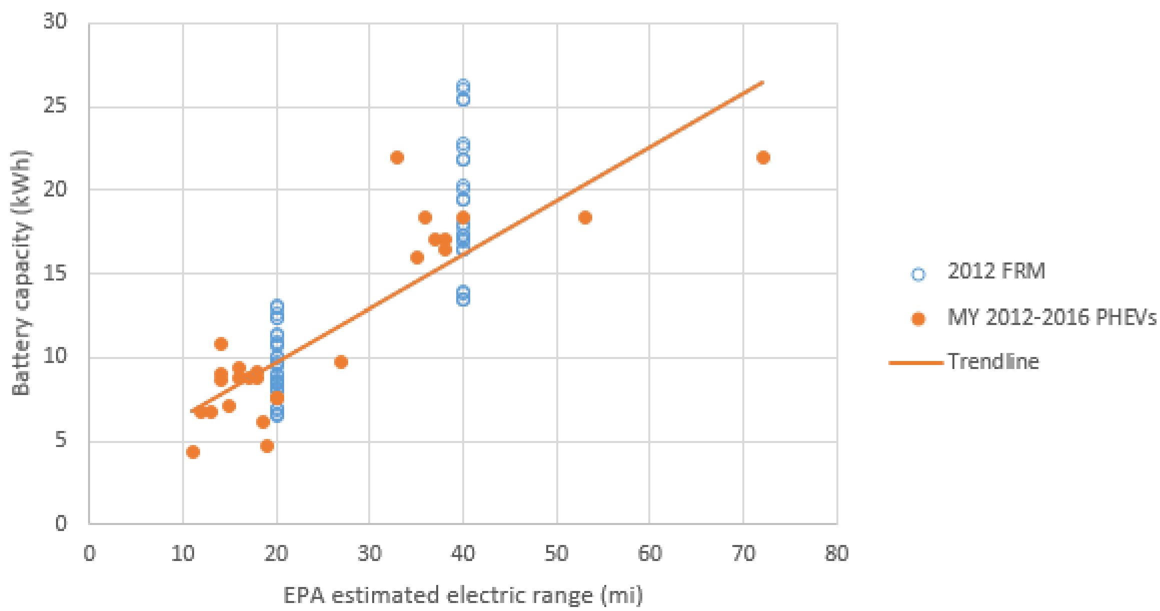


Figure 5.31 Comparison of 2012-2016MY PHEV Battery Capacities to 2012 FRM Estimates

For each PHEV range (20 and 40 miles), several values (depicted by the blue circles) are seen in Figure 5.31 above, corresponding to the FRM estimates for each of the vehicle classes (Small Car, Standard Car, Large Car, etc.) and several glider weight reductions ranging from 0 percent to 20 percent.

It can be seen from the plot that the FRM estimates for PHEV20 battery capacity line up quite well with the population of production vehicles of a similar range. The FRM estimates for PHEV40 also appear to line up fairly well, but show a wider spread and tend to predict a larger battery capacity per unit range than the trend line would suggest.

There are several possible reasons the 2012 FRM sizing methodology may have estimated larger battery capacities for a given range than seen in production. First, differences in vehicle weight are not represented in the plot comparison and could be responsible for some of the difference in predicted battery capacity for a given range. Second, it is possible that the relatively high cost of battery capacity being experienced in the 2012-2016 time frame (compared to the agencies' predicted costs for the 2020 time frame) may have caused manufacturers of some PEVs to apply higher levels of aerodynamic drag reduction, rolling resistance reduction, and mass reduction than assumed in the agencies' analysis, in order to save on battery cost. The 2012 FRM analysis assumed only a 10 percent reduction in each of aerodynamic drag and rolling resistance for battery sizing purposes, with varying levels of mass reduction. Finally, it is possible that the 2012 FRM assumptions for electric drivetrain efficiency, usable battery capacity, or other parameters under predicted what the industry has actually achieved.

For these reasons EPA is examining the assumptions used in its battery sizing methodology and making adjustments where appropriate. Specific adjustments to the PHEV battery sizing methodology used by EPA will be developed and discussed in Section 5.3. NHTSA will be directly using Autonomie results for battery power and energy, based on multiple sizing algorithms that were developed and validated in Autonomie to size a wide range of vehicle powertrains to meet performance requirements.

5.2.4.3.5 *Battery Electric Vehicles*

Battery electric vehicles (BEVs) are vehicles with all-electric drive powered by batteries charged from an outside source of electricity (usually the electric grid). The analysis conducted for the 2012 FRM modeled three BEV configurations, designated EV75, EV100 and EV150 (having 75, 100, and 150 miles range, respectively)[W]. The cost-minimizing compliance pathway projected a 2 percent fleet-level penetration of BEVs.[238]

At the time of the FRM, only a few BEV models had become commercially available in the U.S. market. The most prominent examples were the 2011-12 Nissan Leaf and the Tesla Roadster, which were available nationwide. A few other BEVs were available in 2012 to very limited markets or through demonstration programs, such as the BMW Mini E and Toyota RAV4 EV. Production of the Tesla Roadster was discontinued in early 2012 but was soon replaced by the Tesla Model S. Other BEVs available near the time of the FRM were the Mitsubishi i-MiEV, BYD e6, Coda Sedan, and Ford Focus Electric.

These early BEVs were designed for different market segments, and showed significantly different philosophies on the matters of performance and driving range. Most, such as the Leaf and Mini E, were designed as moderate-performance vehicles with a driving range of 100 miles or less, seen as best suited to driving in urban areas. In contrast, the Tesla Roadster was designed for a high-performance market segment at a much higher price, allowing it to offer a much longer range (245 miles by EPA estimate). Subsequent Tesla vehicles have continued to pursue similarly aggressive range and performance targets at relatively high purchase prices, while several other manufacturers continue to define a distinct segment targeting shorter ranges and moderate performance at lower purchase prices. These two segments will likely continue to exist within the time frame of the rule.[239,240]

Since the 2012 FRM, several new models of BEV have entered production, with several additional models announced for future production or otherwise known in the form of concept cars. Table 5.3 shows a summary of BEV models that have reached production since the FRM, and their EPA estimated range.

[W] As with PHEVs, the indicated range was meant to represent an approximate real-world range comparable to an EPA label range (specifically, 70 percent of a projected two-cycle range).

Table 5.3 Driving Range of 2012-2016MY BEVs

	EPA range (mi)				
BEV model	**2012**	**2013**	**2014**	**2015**	**2016**
Azure Dynamics Transit Connect	56	-	-	-	-
Coda	88	88	-	-	-
BYD e6	122	127	127	127	-
Toyota RAV4 EV	103	103	103	-	-
Mitsubishi i-MiEV	62	62	62	NL	62
Ford Focus Electric	76	76	76	76	76
Tesla Model S (85 kWh)	265	265	265	265	265
Nissan Leaf (24 kWh)	73	75	84	84	84
Tesla Model S (40 kWh)	-	139	-	-	-
Tesla Model S (60 kWh)	-	208	208	208	-
Scion iQ EV	-	38	-	-	-
Honda Fit EV	-	82	82	-	-
Smart fortwo	-	68	68	68	68
Fiat 500e	-	87	87	87	84
Kia Soul EV	-	-	-	93	93
BMW i3 BEV	-	-	81	81	81
Chevy Spark EV	-	-	82	82	82
Volkswagen e-golf	-	-	NA	83	83
Mercedes-Benz B-Class ED	-	-	87	87	87
Tesla Model S (70 kWh)					234
Tesla Model S 70D	-	-	-	240	240
Tesla Model S 85D	-	-	-	270	270
Tesla Model S P85D				253	253
Tesla Model S (90 kWh)	-	-	-	265*	265*
Tesla Model S 90D	-	-	-	270*	294
Tesla Model S P90D	-	-	-	253*	270
Tesla Model X 90D	-	-	-	NA	257
Tesla Model X P90D	-	-	-	-	250
Nissan Leaf (30 kWh)	-	-	-	-	107

Notes:
NL = vehicle not listed in Fuel Economy Guide
NA = rating not available in Fuel Economy Guide
* Manufacturer applied 85 kWh EPA range figure for EPA labeling purposes

Since the FRM, the continued development and production of BEVs as evidenced in the above table has likely been encouraged in part by several regulatory factors. The 2017-2025 GHG/CAFE regulation assigns a high GHG effectiveness to BEVs, further enhanced by assigning 0 g/mi for upstream emissions and a multiplier for the earlier years of the rule. Some manufacturers have therefore chosen to consider BEVs as part of their pathway for compliance with the 2017-2025 standards. Production of BEVs also generates GHG credits that may be used for regulatory compliance or sold to other manufacturers. Production of BEVs can also assist manufacturers in meeting fleet average criteria pollutant regulations such as EPA's Tier 2 and Tier 3 standards or CARB's LEV II and LEV III standards. And, just as with PHEVs, California's ZEV regulation continues to drive BEV production to generate ZEV credits as manufacturers prepare for ever increasing requirements through 2025 model year.

In addition, BEVs from all manufacturers continue to be eligible for a federal tax credit of up to $7,500, effectively reducing their net cost to consumers.[223,224] Because this credit applies to the first 200,000 eligible vehicles (BEVs and PHEVs combined) produced by a given manufacturer, it is likely to continue to influence the BEV market for some time. At current rates of production, it is possible that some manufacturers may begin approaching the 200,000 limit by 2018, with others following soon after.[225] In addition to the Federal tax credit, many states, including California and many of the states that have adopted California's ZEV regulation offer incentives for ZEVs at the state and local levels.

BEVs continue to be offered at a significant price premium to conventional vehicles, largely due to the cost of the battery, as well as non-battery components that have yet to reach high production volumes. Some BEVs, particularly those targeted primarily for sale in the ZEV states, are available for purchase only in those states. Despite the higher purchase price and limited availability, BEV production levels have grown significantly since the FRM.

Through November 2015, Nissan had sold about 88,000 Leaf EVs, and GM had sold about 90,500 Volt PHEVs and Spark EVs combined. Analysts have widely speculated that a slight decline in PEV sales in MY2015 (relative MY2014) is due at least in part to anticipation of new models with longer range and enhanced features. For example, expectations of a refreshed version of both the 2016 Volt and 2016 Leaf existed long before either became available. The 2016 Leaf offers a larger 30kWh pack, increasing range significantly, while the 2016 Volt also offers a longer range, better fuel economy and other enhancements such as improved seating.

The demand for high-end BEVs, such as those produced by Tesla Motors, has accounted for a significant portion of this production despite their high purchase price. These vehicles compete in a market segment with other high-priced vehicles and are seeing success in that segment. This suggests that a demand for BEVs exists relatively independently of the regulatory factors that are largely oriented toward the broader automotive market. If the performance attributes that are attracting this segment of buyers can be sufficiently retained at a lower price point, this could further drive demand for BEVs in the future.

Trends in BEV Driving Range

Growth in the BEV market since the 2012 FRM has greatly expanded not only the available choice of vehicle models and trims, but also the available driving ranges. BEV driving range is largely a function of battery capacity. Figure 5.32 shows the relationship between the battery capacity of the BEVs in Table 5.3 and their EPA estimated driving range.

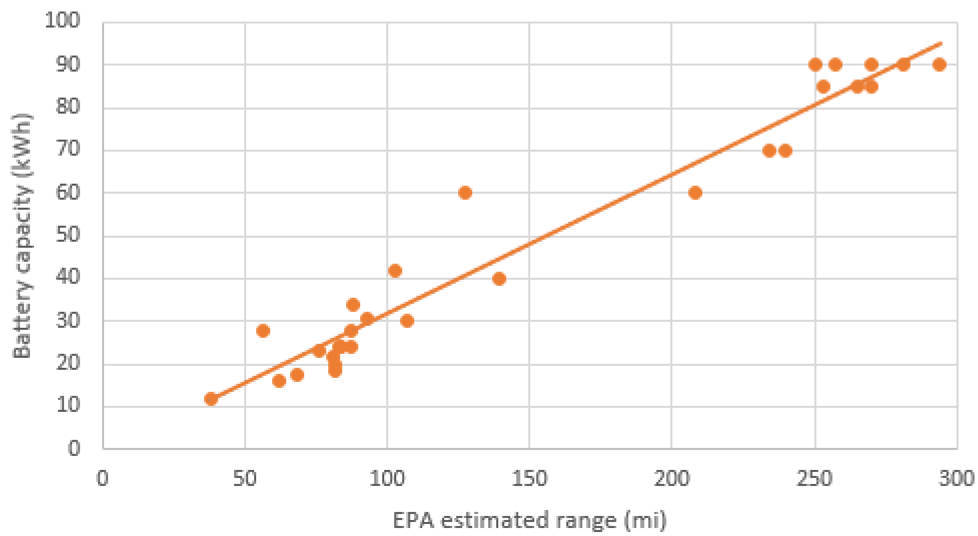


Figure 5.32 Battery Gross Capacity and EPA Estimated Range for BEVs[X]

It has become apparent since the FRM that manufacturers have been pursuing increased driving range. Several examples serve to illustrate this trend. The Nissan Leaf was introduced in 2011 with an EPA-rated range of 73 miles. The 2013 model increased this to 75 miles, while 2014 and later models earned a higher rating of 84 miles by eliminating a partial charge option, allowing the range to be evaluated at 100 percent charge. This trend indicates that Nissan perceives increased range as a desirable goal. As another example, in January 2016, it was reported that the range of the BMW i3 might increase by about 50 percent due to improved battery chemistry and electronics, to approach perhaps 120 miles.[241] In May 2016, BMW announced that the range would be approximately 114 miles, due in part to a 50 percent increase in cell capacity.[242] In January 2016, Volkswagen also indicated that a new version of the e-Golf could expect a possible 30 percent increase in range over the current model (or about 108 miles) due to an increase in cell capacity from 28 A-hr to 37 A-hr.[243] The 2017 Ford Focus BEV is also expected to increase its range to 100 miles compared to its original range of 76 miles.[244] The 2017 Hyundai Ioniq BEV also targets a range of more than 100 miles.[245]

A trend toward increased range also seems to be playing out across manufacturers, as new products are introduced to compete in the market. For example, the Kia Soul EV was introduced in 2014 with a range of 93 miles, surpassing the Leaf. Not long after in 2015, Nissan announced the 2016 Nissan Leaf, offering an EPA range of 107 miles with a new 30 kWh battery pack.

Future vehicles expected to enter the market in the relatively near term (2016-2017) have increasingly targeted even longer ranges. Both the Chevy Bolt (expected to debut as a MY2017 vehicle) and a future version of the Nissan Leaf have been described by their manufacturers as targeting a 200 mile range. As of April 2016, the Tesla Model 3 is being described as offering a 215 mile range and entering production in late 2017.[246]

Even Tesla Motors, which already offers a range in excess of 200 miles in its current vehicles, has shown an interest in increased range as evidenced by regular increases in battery capacity.

[X] Range figures gathered from 2012-2016 EPA Fuel Economy Guides.

After announcing in 2012 that the Tesla Model S would be available in three battery sizes (40 kWh, 60 kWh, and 85 kWh), the 40 kWh version was canceled in 2013, prior to its production. In April 2015, the battery capacity of the 60 kWh version was increased to 70 kWh, which along with powertrain improvements increased its range from 208 miles to 240 miles. In September of the same year the 85 kWh version was increased in capacity to 90 kWh by use of an improved chemistry[Y]. Tesla also announced in 2015 an available battery upgrade for the discontinued Roadster that would increase its range by about 40 percent.

Manufacturers have frequently cited customer demand in the quest for increased range. When the 40 kWh Model S was canceled, Tesla attributed the decision to low demand, further saying, "Customers are voting with their wallet that they want a car that gives them the freedom to travel long distances when needed."[247] Although this statement clearly promotes Tesla's market strategy of offering a longer driving range than other BEV-manufacturing OEMs, similar sentiment has been expressed by other OEMs in marketing their electrified vehicles or announcing future plans. Customer demand for an affordable BEV with a longer driving range than currently available is implicit in the 200-mile range target of both the future Nissan Leaf and the 2017 Chevy Bolt.

Obviously, one way for an OEM to increase range is to increase the battery capacity. Simply increasing the battery capacity in the absence of other improvements may be prohibitive because it increases the cost of the vehicle accordingly. On the other hand, improved battery manufacturing or battery chemistry (in terms of cost or energy density) might enable a larger capacity while offsetting some of the cost penalty. For example, both Tesla and Nissan have utilized improved chemistry to increase capacity within the existing footprint of their respective packs; while GM and Nissan have hinted strongly at improved chemistry being the enabler of the affordable 200-mile range target for the Bolt and future Leaf. These and other examples are discussed in more detail in Section 5.2.4.4.1.

Increasing the usable capacity (i.e. widening the usable state-of-charge window) of the battery may also be possible; for example, by use of an improved chemistry, or by acting on experience that indicates that the existing buffer capacity may be reduced. Improvements in battery management systems (BMS) may also lead to greater utilization of the available battery capacity. Examples of OEM activity in this area are reviewed in more detail in Section 5.2.4.4.3

Range can also be increased by reducing vehicle energy consumption. This can be done by improving the energy efficiency or weight of non-battery powertrain components (electric machines and power electronics) or even the battery itself. For example, the dual motor versions of the Tesla Model S achieve a slightly higher range than the single motor versions due to an improved powertrain efficiency resulting from the ability to selectively operate one or both motors as conditions warrant. Range may also benefit from standard road load improvements such as light-weighting, improved aerodynamics, and lower rolling resistance.

In addition to increased range, a larger battery may carry other ancillary benefits for manufacturers and consumers. Because a large battery stores more energy per charge cycle than a small battery, it is likely to experience fewer charge-discharge cycles in the course of providing

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[Y] The manufacturer chose to apply the 85 kWh EPA range figure to the 90 kWh version for EPA labeling purposes. Marketing materials attribute an additional 6% range to the 90 kWh version.

a given number of vehicle miles. For example, a battery that provides for a range of 200 miles can provide a lifetime mileage of 150,000 miles with about 750 charge-discharge cycles, while a 100-mile battery may require 1,500 cycles. The smaller number of expected cycles may promote a longer battery lifetime or relax manufacturer provisions for battery durability, such as increasing the permissible charge rate or the usable capacity. A larger battery might also experience a much shallower average state-of-charge (SOC) swing in the course of meeting its mileage target, with similar implications for durability. Another advantage of a large battery is a reduction in average discharge rate (C-rate), which can allow consideration of chemistries and configurations that would not be suited to smaller batteries. For example, Tesla may have selected a chemistry that supports notably low C-rates in recognition that the large size of the battery acts to minimize per-cell power requirements.[248] Of course, a drawback of a larger battery over a smaller battery is its greater weight, which tends to reduce the overall energy efficiency of the vehicle.

In the same way that cabin air conditioning can have a significant impact on fuel economy of conventional vehicles,[249] both heating and air conditioning can have a strong impact on BEV energy efficiency and range. While the impact of passenger comfort on range can be great for both BEVs and PHEVs, BEVs are at a particular disadvantage because all energy for heating and cooling must come from the battery. In contrast, PHEVs may choose to operate the engine if needed (for example, the Chevy Volt operates the engine to help with cabin heating in cold weather). Cabin heating and cooling for BEVs is therefore an active area of research toward increasing BEV range.[250,251]

Some BEVs, such as the Nissan Leaf, have employed heat pump-based HVAC in place of resistive heating. When the temperature differential between the outside air and the desired cabin temperature is not too large, this method can be much more efficient than resistive heating at controlling cabin temperature. Another approach to passenger comfort that has been used for BEVs and PHEVs involves heated and cooled surfaces, for example, the steering wheel and seats, instead of or in addition to heating the cabin air, which one study has shown can reduce cooling and heating energy in a PHEV by about 35 percent.[252] Pre-conditioning the passenger cabin while plugged in to a charging station is yet another approach, which can reduce the use of onboard energy for heating and cooling (although it does consume energy at the station).

Modeled BEV Ranges in the 2012 FRM and this Draft TAR

As previously noted, the FRM analysis modeled three BEV range configurations (EV75, EV100 and EV150). At the time of the 2012 FRM, the agencies envisioned EV150 as the maximum BEV range that was likely to play a significant role in achieving fleet compliance during the time frame of the rule. Since that time, EV150 has been surpassed by several longer-range vehicles that are under production or recently announced. Tesla vehicles with a range well in excess of 200 miles were already in production at the time of the FRM, and have since continued to grow in range and market share. Although these vehicles currently constitute a luxury segment that may not be fully representative of a mass-market vehicle, their success at achieving significant market penetration shows that at least one OEM has found it preferable to comply with the 2017-2025MY standards and generate additional GHG credits by producing an EV200 instead of an EV150. Announcements from Nissan and GM that target a 200-mile range in BEVs to be produced as early as 2016 also suggest that EV200 may be a more accurate representation of the higher-range BEV segment than EV150. Therefore, based on the current direction of the industry, the agencies have replaced EV150 with EV200 in this Draft TAR analysis.

It is uncertain whether adoption of EV200 in place of EV150 is likely to have a significant impact on the projected cost-minimizing pathway for fleet compliance with the 2017-2025 standards. There is limited potential for either EV150 or EV200 to be selected by OMEGA and the Volpe model as part of a cost-effective compliance path, because the relatively high cost of the larger battery is likely to overshadow any gain in effectiveness. That is, since EV75, EV100, and EV150/200 all are assigned a GHG effectiveness of 100 percent (with upstream emissions assessed at 0 grams per mile), the incremental cost of EV150/200 vs. EV75 or EV100 strongly discourages its selection on a pure cost-effectiveness basis. On the other hand, adopting EV200 has the advantage of more accurately reflecting the evolving electrified vehicle fleet.

In adopting EV200, the agencies gave careful consideration to the resulting implications for the battery sizing and costing methodology. The increase in range from 150 to 200 miles had to be modeled in a way that accounts for how manufacturers would be expected to achieve the incremental range. In addition to increasing gross battery capacity, manufacturers would likely also rely on other changes to better utilize the available capacity, perhaps by increasing the usable capacity, improving powertrain efficiency, improving battery specific energy, and reducing road loads. Many of the refinements to the battery sizing methodology that are discussed in Section 5.3 resulted from this effort to faithfully represent the paths available to manufacturers to achieve EV200.

In Section 5.3 EPA is reexamining the 2012 FRM assumptions for all xEV parameters that affect battery sizing for this Draft TAR analysis. These include assumptions for usable capacity, electric powertrain efficiencies, specific energy of the battery, and specific power of electric machines and power electronics. Also, because the cost effectiveness of standard road load improvements is greater for BEVs than for conventional vehicles and even other xEVs (due to the potential to save on battery cost), EPA is also reexamining the assumptions for road loads as they affect battery sizing for BEVs. In addition, NHTSA will be reassessing the battery and electric machine performance parameters based on available literature and vehicle test data from the ANL APRF.

Trends in BEV Motor Sizing

In addition to driving range, the motor power of BEVs is another important input to the agencies' projection of battery and system costs for BEVs. As discussed previously with respect to PHEVs, the 2012 FRM analysis assigned BEVs of a given vehicle class a motor power rating that would preserve the same engine-power-to-weight ratio observed in conventional vehicles of that class. This method assumed that the electrically-powered acceleration of BEVs relates to the power rating of the electric motor in the same way that the engine-powered acceleration of conventional vehicles relates to the power rating of the combustion engine. However (as discussed in the PHEV section previously), electric motors differ markedly from combustion engines in their delivery of low-speed torque, delivering maximum torque at the lowest speeds, while combustion engines must develop significant speed to deliver a comparable torque. This might allow a BEV to deliver acceleration performance similar to that of a conventional vehicle while using a significantly lower nominal motor power rating than a comparably performing combustion engine. At the time of the 2012 FRM, it was unclear to what extent this phenomenon would influence BEV propulsion motor sizing, leading to the decision to assign BEV motor power based on the nominal power-to-weight ratios of conventional vehicles.

As previously discussed in relation to PHEVs, the issue of proper electric motor sizing for BEVs is being revisited for this Draft TAR analysis. Accurately assigning the motor power of a BEV is important for several reasons. First, the motor power rating has a direct effect on the battery power rating, which determines its power-to-energy (P/E) ratio and its cost. Second, the agencies have revised the battery sizing methodology to account for the weight of the electric motor and power electronics separately from the energy content of the battery. This makes an accurate determination of motor power ratings more critical than before. Finally, an accounting of motor cost requires an accounting of motor power. As in the 2012 FRM analysis, EPA estimates electric motor and power electronics costs as a function of peak output power, in accordance with several examples of similar industry practice. For more discussion of the decision to scale motor cost to power output, see Section 5.3.4.3.6, Cost of Non-Battery Components for xEVs.

Since the FRM, the number of production BEVs has increased and provides a much larger sample size from which to draw observations. Figure 5.33 plots the motor power ratings and curb weights of BEVs produced from MYs 2012 to 2016.

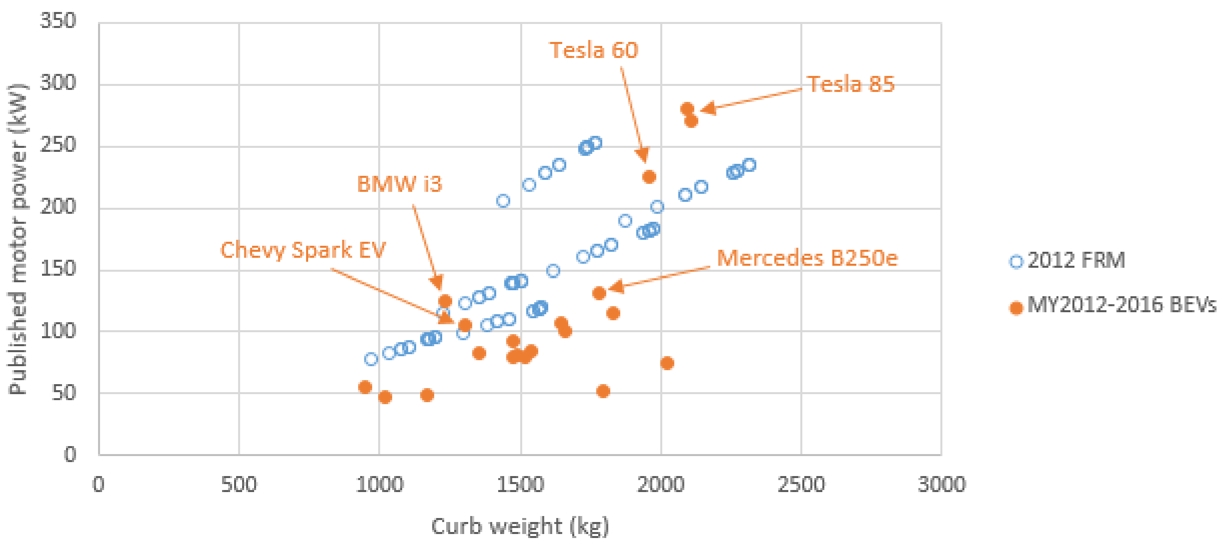


Figure 5.33 Comparison of Motor Power of 2012-2016MY Production BEVs and FRM Estimates

In the Figure, the solid orange dots represent the motor power ratings and curb weights of production BEVs (excluding the highest-performing Tesla vehicles in excess of 350 kW) produced for MYs 2012-2016. The blue circles represent the motor power ratings and weights assigned to BEVs of various ranges and classes in the 2012 FRM. The chart suggests that the FRM assigned significantly higher BEV motor power ratings than the majority of BEV manufacturers have actually provided. Among moderate-performance vehicles, the BMW i3 and the Chevy Spark EV have motor power ratings that are closest to the levels assumed in the FRM. Even the higher-market Mercedes B250e is at a lower power-to-weight ratio than the FRM would have assumed.

Based on this analysis and a new power-to-weight study described in Section 5.3, EPA has revised the BEV motor power ratings assumed for this Draft TAR analysis. The analysis will therefore adopt power ratings closer to those suggested by the power-to-weight ratios that BEV manufacturers appear to be following, while maintaining an estimated acceleration performance equivalent to conventional vehicles. As with PHEVs (discussed in the previous section), assigning a more accurate power rating will allow greater fidelity in the projected cost of both the battery and non-battery components of BEVs. Specific proposed adjustments to BEV motor power sizing are developed and discussed in Section 5.3. NHTSA will be directly using Autonomie results to assign the power of electric motors for BEVs. Multiple sizing algorithms have been developed and validated in Autonomie to size a wide range of vehicle powertrains to meet specific vehicle performance.

Trends in BEV Battery Sizing

The 2012 FRM analysis employed a battery sizing methodology to assign battery power ratings and energy capacities for modeled BEVs. Now that a number of BEVs are on the market and have been rated for range by EPA, it is informative to compare the FRM projections of BEV battery capacity and range to the BEVs that have entered the market for MYs 2012-2016. Figure 5.34 shows the range and battery capacity plot of Figure 5.32, annotated with the assumed battery capacities and ranges used in the FRM.

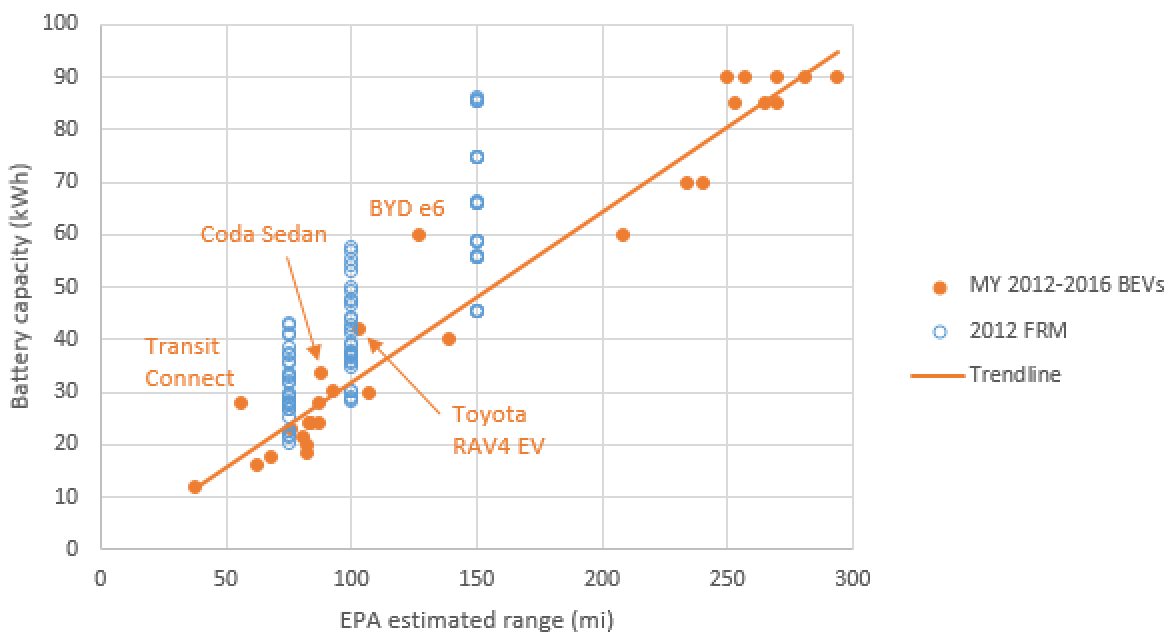


Figure 5.34 Comparison of 2012-2016MY BEV Battery Gross Capacities to FRM Estimates

The FRM modeled batteries for EV75, EV100, and EV150 at several assumed glider weight reductions ranging from 0 percent to 20 percent. For each BEV range (75, 100, and 150 miles), several values are seen in Figure 5.34 above, corresponding to each of the vehicle classes (Small Car, Standard Car, Large Car, etc.) and glider weight reductions of 0 percent and 20 percent.

Following trends seen in the MY2008 fuel economy data, the 2012 FRM modeled large BEVs such as Large Car and Small/Large MPV with substantially larger power-to-weight ratios and significantly higher fuel consumption compared to smaller vehicles such as Small Car and Standard Car. This led to significantly different battery capacity projections for a given range, obscuring the comparison to observed MY2012-2016 BEVs. In order to assess how well the 2012 FRM technique predicted battery sizes for each class, it is therefore necessary to consider the larger and smaller vehicle classes separately. Because the vehicle classes in the Fuel Economy guide, from which the range data is taken, are different from the six vehicle classes used in the FRM, only an approximate comparison can be made by dividing the fleet into a group of smaller-to-moderately sized vehicles and a group of larger vehicles.

Figure 5.35 shows data for small and moderately sized passenger cars, which in the FRM would be classed as Small Car and Compact Car, and in the Fuel Economy guide are classed variously as Minicompact, Subcompact, Compact, and Midsize (importantly, the Nissan Leaf is classed as Midsize and so is included in this group).

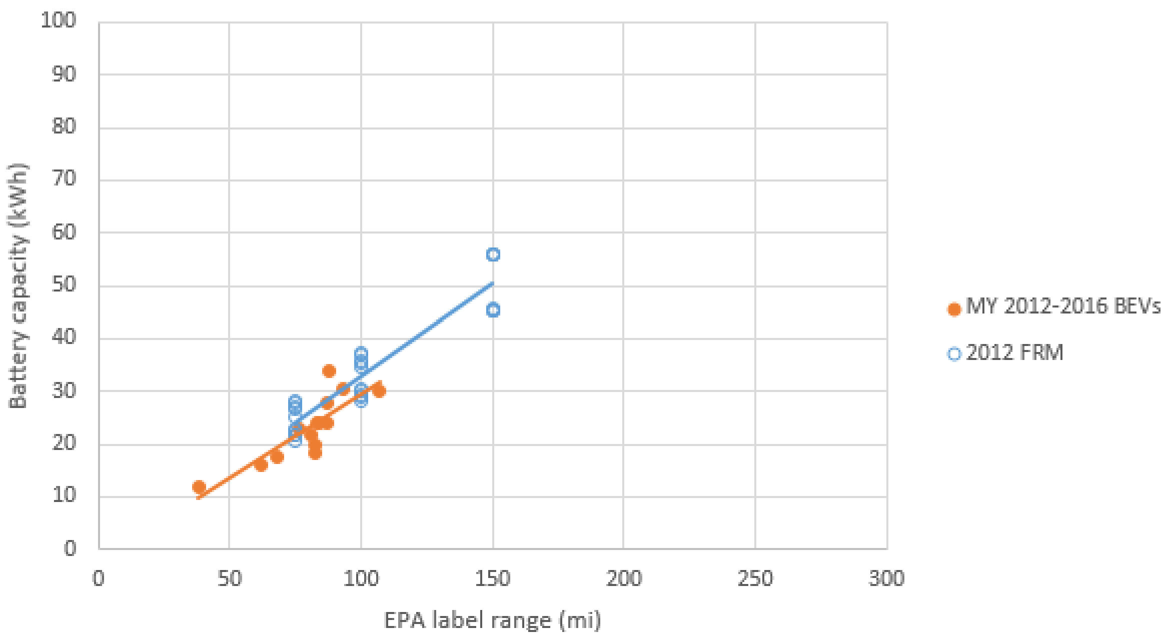


Figure 5.35 Comparison of 2012 FRM-Projected Battery Capacity to MY2012-2016 BEVs (Smaller Vehicles)

This plot shows that for smaller BEVs, the FRM projections of battery capacity appear to fit reasonably well with MY2012-2016 BEVs. Even so, there is a tendency for the 2012 FRM projections to have somewhat overestimated the battery capacity that manufacturers have provided for these vehicles.

Figure 5.36 shows data for larger cars and SUVs, which in the FRM were classed as Large Car, Small MPV and Large MPV, and in the Fuel Economy guide are classed variously as Large Car, Small SUV 2WD, and Standard SUV. Variations of the Tesla Model S are classified as Large Car and so represent the bulk of production examples shown in the plot.

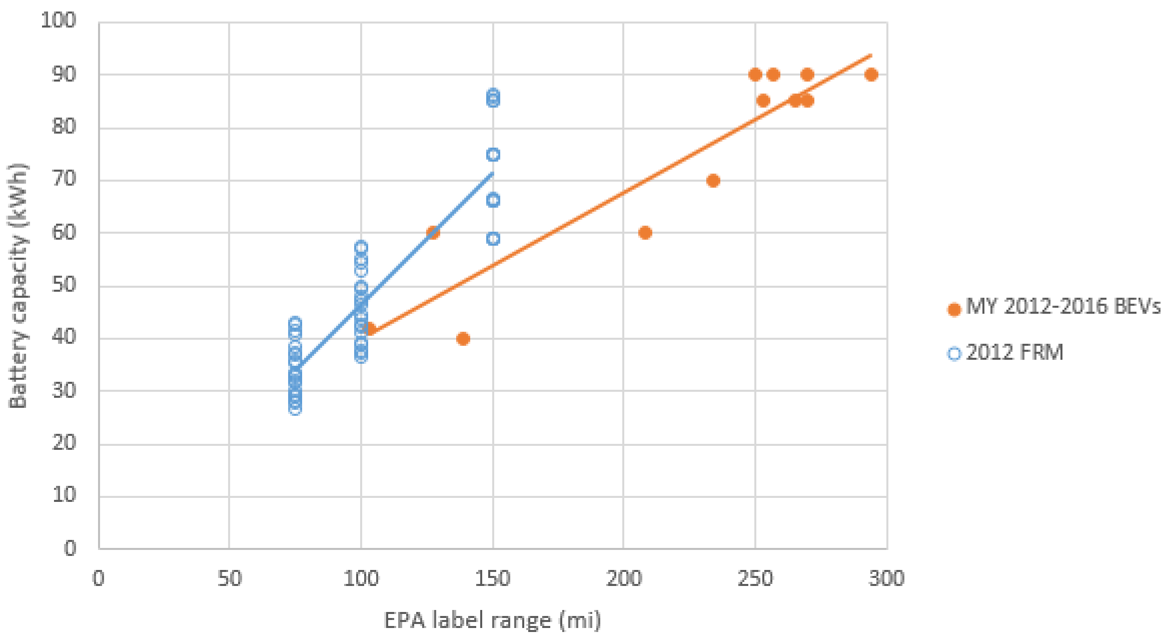


Figure 5.36 Comparison of 2012 FRM-Projected Battery Capacity to MY2012-2016 BEVs (Larger Vehicles)

This plot shows that for larger BEVs, the tendency for the 2012 FRM methodology to overestimate battery capacity is much stronger for all except the shortest ranges (which are largely not present in the market). A trend line of the FRM projections is not only at a higher level but also appears to diverge substantially as the range increases. Although the FRM did not project ranges beyond 150 miles, it appears that the 2012 FRM battery sizing methodology would fail dramatically at estimating battery capacity for 200-plus mile BEVs, such as for example the Tesla models depicted at the far right of the plot, and even the EV200 configuration the agencies have adopted to replace EV150.

As discussed with reference to PHEVs in the previous section, there are several possible reasons the 2012 FRM battery sizing methodology may have estimated larger battery capacities for a given range than seen in production. First, differences in vehicle weight are not represented in the plot comparison, and could be responsible for some of the difference. Second, it is possible that the relatively high cost of battery capacity being experienced in the 2012-2016 time frame (compared to the agencies' predicted costs for the 2020-2025 time frame) may have caused manufacturers of some BEVs to apply higher levels of aerodynamic drag reduction, rolling resistance reduction, and mass reduction than assumed in the agencies' analysis, in order to save on battery cost. The 2012 FRM analysis assumed only a 10 percent reduction in each of aerodynamic drag and rolling resistance for battery sizing purposes, with varying levels of mass reduction. Finally, it is possible that the 2012 FRM assumptions for electric drivetrain efficiency, usable battery capacity, or other parameters under predicted what the industry has managed to achieve.

For these reasons, EPA has examined the assumptions used in the BEV battery sizing methodology and made adjustments where appropriate. Specific proposed adjustments to the BEV battery sizing methodology are discussed in Section 5.3. As noted earlier, NHTSA will use Autonomie results for BEV batteries, based on multiple sizing algorithms that have been developed and validated in Autonomie to size vehicle powertrains to meet specific vehicle performance targets.

5.2.4.4 Developments in Electrified Vehicle Battery Technology

For many types of electrified vehicles, particularly PHEVs and BEVs, battery cost is the largest single component of vehicle cost. Battery pack cost is determined in part by the configuration of the pack, which should be tailored to the specific performance goals of the vehicle.

Pack configuration may be decomposed into a large number of primary design parameters which the vehicle designer can specify to determine the performance of the pack and ultimately its cost. In configuring a pack, the primary performance targets are energy capacity in kilowatt-hours (kWh) and power capability in kilowatts (kW). These performance targets are determined by design choices such as: battery chemistry (Li-ion is composed of a number of closely related but differently performing chemistries); pack voltage, usable portion of total capacity, cell capacity (Ampere-hours per individual cell), cell topology (the electrical and physical arrangement of cells and modules in the pack), and cooling method (passive or active, and air or liquid), among others. Further, for a pack defined by a given set of these design parameters, the assumed annual manufacturing volume will also influence the projected cost.

It is customary to refer to battery cost in terms of cost per kWh. However, in order to make valid comparisons on this basis it is important to understand that cost per kWh is strongly influenced by the power-to-energy (P/E) ratio of the battery. Intuitively, a BEV battery optimized for energy storage capacity (low P/E) will have a low cost per kWh because the materials and construction are oriented toward providing maximum energy capacity. Conversely, an HEV battery optimized for power (high P/E) will have a higher cost per kWh, because the materials and construction are oriented toward providing power, while the metric of cost per kWh continues to focus on energy. For these reasons, cost per kWh figures derived from energy-optimized BEV or PHEV battery packs should not be used to estimate the cost of a power-optimized HEV pack, or vice versa. Comparisons of cost per kWh are only valid when the applications have a similar P/E ratio.

It is also important to be aware of whether a quoted cost per kWh is on a cell basis or a pack basis. Figures found in press literature may be of either type. Costs quoted on a cell basis will be much lower than for a full pack that includes battery management, disconnects, and thermal management. In the 2012 FRM and this Draft TAR, all cost per kWh figures are presented on a pack basis.

Finally, the energy capacity of a battery pack (kWh) may be characterized either by gross capacity or usable (net) capacity. Gross capacity, also known as nominal or nameplate capacity, is the total amount of energy that can be reversibly stored in a complete charge and discharge cycle of the battery, without regard to long term durability. It is a relatively fixed quantity that is a function of the amount of electrode active materials contained in the battery. Usable capacity is the portion of gross capacity that the manufacturer believes can be regularly used in an application while maintaining a desired level of durability. Although usable capacity is the metric that relates best to performance attributes such as driving range, usable capacity varies widely among different vehicle types and individual models of each type. For consistency it has become customary to refer to the size of xEV battery packs by their gross capacity, and to refer to battery cost per gross kWh. The 2012 FRM and this Draft TAR follow this standard.

5.2.4.4.1 *Battery Chemistry*

In the 2012 FRM, the agencies based their battery cost analyses on outputs of the then-current version of the ANL modeling tool BatPaC[137], which models several well established lithium-ion chemistries. As shown in Table 5.4, the choice of chemistries available in BatPaC included:

Table 5.4 Lithium-ion Battery Chemistries Available in ANL BatPaC

Chemistry	Cathode	Anode
LMO-G	Lithium-Manganese Oxide	Graphite
LMO-LTO	Lithium-Manganese Oxide	Lithium Titanate Oxide
NMC333-G	Nickel-Manganese-Cobalt (3-3-3)	Graphite
NMC441-G	Nickel-Manganese Cobalt (4-4-1)	Graphite
NCA-G	Nickel Cobalt Aluminate	Graphite
LFP-G	Lithium-Iron Phosphate (Olivine)	Graphite

Certain chemistries are better suited for certain types of packs than for others. For example, the specific versions of NMC chemistry that are modeled by BatPaC are well suited for packs having a large energy capacity such as BEV packs, but due to limits on area specific impedance (ASI), they are not as well suited for small, power-dense packs for HEVs. Considerations such as these ultimately led to the chemistry choices employed by the agencies in the FRM. BEV and PHEV40 batteries were configured with NMC441-G, while PHEV20 and HEV packs were configured with LMO-G.

Since the 2012 FRM, the lithium-ion family of chemistries has continued to dominate xEV battery technologies seen in current and announced production vehicles. As expected, NMC/NCM cathode formulations are increasingly being seen in BEVs announced since the FRM, including in mixed formulations with LMO. For example, the Kia Soul BEV uses an NCM cathode.[253] In the 2015 NAS report (p. 4-26), the committee mentions the use of NMC cathodes for the 2020-2025 time frame, lending further support to the agencies' choice. PHEVs and HEVs are being seen not only with LMO-dominant cathode formulations, such as in the original Chevy Volt, but also with NMC and blended NMC cathode formulations, as in the 2016 Chevy Volt,[254] the Ford C-Max Hybrid HEV and C-Max Energi PHEV.[255] These are presumably optimized for the relatively high P/E ratio of these applications. Lithium-iron phosphate cathodes are also being promoted for HEV use.[256] While it is not possible for BatPaC to model every (often proprietary) variation in cathode formulation, the available choices are likely sufficient to represent the cost spectrum applicable to this family of chemistries.

Since the FRM, xEV batteries have trended away from pure LMO cathodes toward blends of NMC with LMO. [257] In particular, most HEV batteries currently in production appear to utilize either NMC or LMO blended with NMC. For example, the 2016 Chevy Malibu Hybrid battery is said to use an NMC cathode[258] while the Volt uses NMC blended with LMO.[254] This contrasts with the agencies' assumption of LMO chemistry for HEV and PHEV20, which was the result of the limited number of high-power chemistries modeled by earlier versions of BatPaC.

Version 3 of BatPaC, released for beta in November 2015, includes additional cathode chemistry options, including the more common NMC622 in place of NMC441, and a userselectable blend of NMC and LMO. The blended cathode option will allow the agencies to consider a blended NMC-LMO cathode for HEV and PHEV20 batteries, to better represent their usage in existing platforms.

At the time of the 2012 FRM, practically every production xEV was using a Li-ion chemistry, with the nickel-metal-hydride (NiMH) battery of Toyota HEV products being the primary exception. After using NiMH in the Prius since its introduction in 1997, there are signs that even the Prius may be moving toward Li-ion. By 2012 Toyota had already adopted a lithium-ion chemistry for the Prius PHEV, a platform which requires a larger battery capacity than the standard hybrid. In October 2015, Toyota announced that the 2016 Prius hybrid would also begin offering a Li-ion battery as an option.[155,259]

Since the 2012 FRM, industry research has continued into more energy- and power-dense variations of the lithium-ion platform, including improved cathode material blends, lithium-rich, manganese-rich, nickel-rich, and higher voltage (e.g. 5V) spinel cathodes, and the use of silicon in the anode. Other research is concerned with even more advanced platforms, including lithium-sulfur, and several metal-air chemistries (lithium-air, aluminum-air and zinc-air) among others. These advanced chemistries are not yet available in cells suitable for xEV use, but potential examples are beginning to emerge.

Lithium-sulfur (Li-S) cells are beginning to be seen in some highly specialized applications. A Li-S cell manufactured by Sion Power is used in the Airbus-sponsored Zephyr high-altitude unmanned aerial vehicle (UAV) to store solar energy for nighttime flight. The low-temperature performance of Li-S cells may have in part led to the choice of this chemistry for this application.[260] Oxis Energy is expected to release a commercial Li-S battery cell in 2016, with an eye toward xEV applications.[261,262]

Silicon is also beginning to appear in the anode of commercial Li-ion cells. While it takes 6 carbon atoms in a carbon anode to accept 1 lithium ion, a silicon atom can accept several. However, uptake of lithium ions by silicon is accompanied by extreme volumetric expansion, leading to complications such as disintegration of the anode matrix and loss of electrical conductivity. For this reason many are currently focusing on very small additions of silicon to an otherwise carbon-based anode to achieve incremental improvements in specific energy. In 2015 Tesla Motors Inc. announced a 90-kWh Model S pack that was said to achieve a greater specific energy by including a small amount of silicon in the anode.[263]

Solid-state lithium-ion cell technology is another active area of research. Most solid-state construction concepts retain the traditional anode and cathode couples but replace the liquid electrolyte with a solid (usually polymer) electrolyte. Others seek to enable use of lithium metal as the anode by leveraging the solid nature of the electrolyte to prevent dendrite formation. Solid state construction leads to the possibility of more efficient production techniques, such as building complete battery cells by printing or deposition, potentially in complex shapes that conform to available packaging space, or in flat shapes that could be integrated structurally with the vehicle. Minimizing the resistance of the solid electrolyte is a primary research target for enabling this technology. As an indicator of interest in this technology, the British appliance manufacturer Dyson purchased the solid-state lithium-ion battery firm Sakti3 for $90 million in October 2015.[264] In March 2016, it was widely reported that Dyson may be planning to produce an electric vehicle, as suggested by evidence that the company is receiving U.K. government funding for this purpose.[265] Similarly, Bosch, a major automotive supplier, acquired solid-state lithium-ion developer Seeo in 2015, citing potential applicability of the technology for increasing the range of electric vehicles.[266]

While promising, these and similar early examples of Li-S electrode couples, silicon anodes, and solid-state construction will need time to show that engineering targets for cycle life, dimensional stability, and durability in demanding xEV applications have been reliably met. Until then, reliable estimates of their cost or commercial availability will not be available. Metal-air chemistries will require even more development before they will be mature enough to characterize their potential use in automotive applications or their production costs. The 2015 NAS report (Finding 4.5, p. 4-44) further supports the conclusion that "beyond Li-ion" chemistries such as these are unlikely to be commercially available during the time frame of the rule. At this time the agencies consider it unlikely that fully proven forms of such chemistries will become commercially employed in xEV applications on a broad scale during the time frame of the rule. The developmental state of these chemistries and the unavailability of well-developed cost models prevent their inclusion in the agencies' analysis.

5.2.4.4.2 Pack Topology, Cell Capacity and Cells per Module

Pack topology refers in general to the way cells and modules are electrically connected to form a pack. Modules are collections of cells that act as building blocks for a pack. Cell capacity is the charge capacity of an individual cell, and is closely related to pack topology.

To fully understand developments in these areas and the agencies' choices for these parameters in the modeling of battery packs for costing purposes, an example of how these parameters interact will now be presented as background.

One approach to configuring a battery pack would start with a target pack voltage for the application. Target voltage typically refers to the nominal voltage expected at about 50 percent SOC. For PEVs, the targeted voltage is typically between 300 V and 400 V. The most commonly used Li-ion chemistries provide a nominal voltage between 3 V and 4 V per cell. Assuming a 3.8 V cell and a target of 365 V, a BEV pack might be constructed of 96 cells connected as series elements (3.8 V * 96 = 365 V). The target energy capacity of the pack (kWh) would then be achieved by specifying the capacity of each cell. The larger the target pack capacity, the larger the required capacity of the cell. In this example, to target a 24 kWh pack capacity, each series element would need to have a capacity of about 66 A-hr:

24,000 W-hr / 3.8 V / 96 cells = 66 A-hr

Manufacturers have several options for providing this cell capacity. The simplest would be to manufacture cells of 66 A-hr capacity. This results in one cell at each series position, minimizing the number of cells and interconnections, potentially minimizing the cost of the pack. In practice, manufacturers may instead be compelled to use smaller cells, perhaps to better address thermal management considerations, or to match an existing cell size offered by a cell supplier. The 66 A-hr required at each series position might then be provided by two 33 A-hr cells, or three 22 A-hr cells, connected in parallel. The exact cell capacity could vary slightly to match available products if some variation in pack capacity or voltage are permissible. Increasing the pack capacity, for instance doubling it to 48 kWh, could in theory be achieved either by doubling the number of series elements (from 96 to 192) or by doubling the A-hr capacity of each series element (to 132 A-hr). The first option is problematic because it would double the voltage to 730 V, which presents a safety issue and may be outside the typical operating voltage range of available power electronics. The larger cell capacity of the second option may be difficult to achieve in a single cell while maintaining effective thermal and current distribution characteristics within the cell. For these reasons, larger packs are often found to include parallel strings of two or more smaller cells at each series position. Tesla products are an extreme example, composed of thousands of very small cells, which results in as many as 36 cells in each series position.

Another important aspect of pack topology is the format of the individual cell. As at the time of the FRM, most industry cell development and current automotive cell applications continue to be centered on prismatic (rectangular) cell formats composed of stacked or flat-wound electrode strips housed in metal cans or polymer pouches. ANL BatPaC models a prismatic format housed in a stiff polymer pouch. Tesla remains almost unique in its use of small, cylindrical 18650-format cells. Because Tesla has built significant market share, this difference has potential significance to the projection of future pack costs. Also, there is some evidence that other manufacturers are beginning to consider cylindrical cells. In 2015 Volkswagen announced the R8 e-tron which has a pack composed of cylindrical cells; potentially, other products such as the Q6 e-tron and the Porsche Mission E might also share this format if this is an indication of VW's future battery construction approach. Additionally, in November 2015 Samsung SDI announced that it would supply cylindrical cells to a China customer for use in electric SUV battery packs.[267] According to one analysis, about 38 percent of currently available BEV models have packs composed of cylindrical cells, with the rest roughly evenly divided between prismatic pouch and prismatic metal can[268] (although it is unclear whether the relatively large number of Tesla sub-models are counted as separate models). About 40 percent of HEV models use packs composed of cylindrical cells, according to the same source.

Despite the differences between prismatic and cylindrical cell formats, there may be limited potential for large differences in pack costs to result. First, material costs per unit energy storage are likely to be similar on a cell basis. Cylindrical cells and prismatic cells differ primarily in the manner in which layers of active materials are packaged together, one being a spiral winding of a single electrode strip and the other a stack of multiple smaller strips. Although the assembly process is different, both methods utilize active material with similar efficiency. This is significant because material costs are the most dominant component of total cell cost.[137,269,270,142] Second, while cylindrical cells may benefit from a somewhat simpler cell manufacturing process and the highly commoditized status of the 18650 format, the large number of 18650-format cells that must be connected to build a pack may work against these advantages. While larger cylindrical cells might be used, their heat dissipation properties may limit their practical size. While 18650-format cells have good thermal qualities, larger cells begin to face challenges in rejecting heat from the core of the cylinder where the maximum temperature tends to develop.[271] Despite Tesla's success with the cylindrical format, it remains unclear whether either format possesses a greater potential to eventually minimize pack cost. Therefore the agencies believe that the cost estimates of the BatPaC model should be reasonably accurate for both cell formats.[272]

In the 2012 FRM analysis, xEV packs were preferably configured with a single series string of cells. The largest BEV packs were the exception, being configured with a parallel string of two cells in each series position, in order to limit voltage to the desired range and limit the required A-hr capacity of the cells. Since the 2012 FRM, xEV battery packs (with the exception of Tesla, as previously mentioned) have largely continued to follow the practice of having one, two or three cells in parallel at each series position.

In the 2012 FRM analysis, maximum cell capacity was limited to 80 Ampere-hours (A-hr) or less. While the cells of most packs configured for the analysis were well under this limit, some larger BEV packs approached the limit. Therefore the cell capacity limit is primarily relevant to the configuration of large BEV packs.

An 80 A-hr cell capacity was generally larger than the cell capacities observed in large BEV packs at the time of the 2012 FRM. The agencies expected that as the industry matured, manufacturers would achieve economies by gradually optimizing cell capacities to the requirements of the application, including an increase in cell capacity for large packs in order to minimize the number of cells while limiting the total voltage. Since that time, there is some evidence that manufacturers have begun moving toward larger cell capacities as expected.

In October 2014 GM announced that the Chevy Volt generation 2 battery pack would have fewer cells (192 vs 288) that are each about 50 percent greater in capacity. In the original pack, each series element was composed of three cells in parallel, while the new configuration has only two.[273] The 30 kWh trim of the 2016 Nissan Leaf, announced in September 2015, is said to achieve its increased capacity within the same size and footprint of the lower-trim 24 kWh pack by utilizing a more energy dense chemistry variation. The number of cells remained unchanged at 192, implying an increase in the A-hr capacity of each cell.[274] Similarly, the 2017 BMW i3 achieves a 50 percent increase in capacity over the earlier model, within the same pack volume, by using a 94 A-hr cell in place of a 60 A-hr cell.[242]

The latter example further suggests that cell suppliers are pushing the envelope of cell capacity for vehicular applications beyond the 80 A-hr limit used in the agencies' 2012 analysis. The 60 A-hr cell format that Samsung SDI had been supplying to BMW for the pre-MY2017 BMW i3 pack was already one of the larger light-duty BEV cell formats in use when it was replaced by the 94 A-hr format. At AABC 2015, Samsung SDI presented further plans for manufacturing prismatic cells of 90 to 120 A-hr by 2020.[275] The presenter also mentioned a goal of eventually producing 180 A-hr cells for BEV use, using a new chemistry with high NCM content plus silicon. This suggests that at least some suppliers are already anticipating a market in vehicular applications for these very large format cells.

Module configuration is another topology issue. In general, the more cells that are included in each module, the fewer modules and the lower the cost of their connections. Since the number of modules must be a whole number, the number of cells per module can depend on the total number of cells necessary to reach a voltage or capacity target, and so need not be the same for every size of pack.

In the FRM, battery modules for all xEVs were configured with 32 cells per module. The Chevy Volt provided one example of a manufacturer that was already using at least 32 cells per module, in a liquid-cooled application similar to that assumed in the agencies' analysis of BEVs and PHEVs. Although most BEVs at the time had fewer than 32 cells per module, this figure was selected to represent expected improvements in cell reliability and packaging methods as manufacturers gained experience over time.

Since the FRM, some further evidence has emerged to support the agencies' expectation that the industry will tend toward increasing the number of cells per module.

It is now understood that the original Chevy Volt battery was configured with 7 modules of 36 cells each and 2 modules of 18 cells each. A similar configuration is retained in the recently announced 2016 Volt. Similarly the Kia Soul EV battery consists of 192 cells in 8 modules,[276,277] varying from 20 to 28 cells per module.

As another example, in September 2015, Nissan announced a new battery pack option to be available for the 2016 Leaf. The two higher-trim versions of the Leaf, the SV and SL, will include a 30 kWh pack in which the number of cells per module is increased from 4 to 8.[278] While the number of cells per module is still relatively small, Nissan's continued use of passive air cooling as a thermal management strategy may place a smaller limit on the number of cells per module than for the more common liquid-cooled packs that are modeled in the agencies' analysis.

Subsequently, in November 2015 at the Tokyo Auto Show, Nissan revealed its IDS concept vehicle, powered by a newly developed 60 kWh pack.[279] In interviews with the press, a number of details were shared regarding the design of this pack. The pack was described as having 288 cells utilizing an NMC cathode chemistry. Assuming a nominal cell voltage of 3.75V typical of these chemistries, each cell would be sized at about 55.5 Ampere-hours, significantly larger than in the Leaf pack. The IDS pack also appears to install in a footprint similar to that of the 30 kWh version of the Leaf battery. Nissan has not yet specified the number of cells per module in the 60 kWh pack, but evidence suggests it is significantly larger than in the Leaf packs. One interesting aspect of the design approach for this pack is its support for a variable module stack height, suggesting a variable number of cells per module may be specified depending on the target capacity of the pack. In one press report,[280] an official was described as saying that Nissan had taken a conservative approach to the number of cells per module in earlier packs, and due to the lack of failures or other issues with those packs, were now able to consider an approach that supports a much larger number of cells per module in the new pack.

In January 2016, GM announced details of the Chevy Bolt battery pack.[281] As with the 60 kWh Nissan IDS pack, this 60 kWh pack is composed of 288 cells in 96 cell groups of 3 cells each. The cells are distributed among 10 modules, or about 28 to 30 cells per module. Three individual cells are connected in parallel at each series position. Assuming a nominal cell voltage of 3.75V, this suggests an individual cell capacity of 55.5 Ampere-hours (identical to that of the Nissan IDS pack).

As noted above, the ideal number of cells per module may vary depending on the capacity of the pack and the size of the cells. In the 2012 FRM, the agencies assumed all modules would have 32 cells. In this Draft TAR analysis, it may be more appropriate to optimize the pack topology by varying the number of cells per module in order to better match performance targets and minimize cost.

5.2.4.4.3 Usable Energy Capacity

As previously noted in the introduction to this section, batteries may be described with respect to their gross energy capacity or their usable energy capacity. Usable capacity refers to the portion of gross capacity that the manufacturer believes can be regularly used in an application while maintaining a desired level of durability. It is thus an important parameter for battery sizing because it determines the gross capacity necessary to provide a target usable capacity for an application.

The concept of usable capacity is often accompanied by several closely related terms. In this discussion, the following terms are used and defined as follows. State-of-charge, or *SOC*, refers to the percentage of total energy (kWh) or charge (Ampere-hour) capacity that remains in a battery at a given time, ranging from 0 to 100 percent on a gross capacity basis. *SOC design window*,[282] or simply SOC window, refers to the usable portion of total capacity intended by design, expressed in terms of SOC; for example, an SOC design window might be described as the range between 25 percent and 75 percent SOC, or alternatively as an SOC window of 50 percent. *SOC swing* may be used interchangeably with SOC window but is used here to refer more specifically to observed in-use behavior rather than a design context. *Usable capacity* is thus determined by SOC design window (in a design context) or implied by an observed SOC swing (in-use). Usable capacity may refer either to a usable energy (in kWh) or the usable portion of gross capacity (in percent).

For lithium-ion chemistries, SOC is not always measurable with precision and is commonly estimated by means of algorithms that include measurements of current, voltage and battery pack temperature, both instantaneous and over time. The construct of SOC window therefore inherits some of these traits. While it is most convenient to think of the boundaries of an SOC window in terms of SOC percentages, it may also be defined by an allowable range of battery voltages, or a combination of the two.

The SOC design window that a manufacturer assigns to a battery is typically selected to balance battery durability with energy availability. Owing to the complexity of battery behavior and vehicle control algorithms, it is possible that some controllers may not refer to a single rigidly defined SOC window, but instead, may define multiple or variable SOC windows that apply to different usage conditions or are determined by the controller's observation of patterns of usage or battery health monitoring over a short or long term. For example (and particularly for HEVs), because extreme but intermittent usage conditions may have a different degree of impact on battery life than normal usage, it is possible that some manufacturers may program their controllers to define multiple target windows, to allow a wider swing to accommodate temporary, extreme conditions while following a narrower swing for normal conditions. As another example, some manufacturers may widen the allowable SOC swing as the battery ages (perhaps by allowing a wider range of allowable voltages, or modifying the allowable SOC window) in order to maintain driving range or usable capacity. Although the concept of a single SOC design window may therefore be overly simplistic for some vehicles, it remains useful for battery sizing purposes.

Setting an appropriate SOC window can be influenced by the effectiveness of the battery management system (BMS). Improved BMS systems are one potential path toward enabling a wider SOC window or a reduced battery capacity for a given range.[283]

The SOC design window is a primary factor in the sizing of a battery for a particular use. That is, the desired electric driving range for a PEV, or the amount of energy buffering capability desired for an HEV, combined with the SOC window, directly suggests the necessary gross capacity of the battery. In the 2012 FRM, for battery sizing purposes, the agencies assumed a 40 percent usable SOC window would apply to HEVs, 70 percent for PHEVs, and 80 percent for BEVs.

Increases in PHEV and BEV driving range that have been observed since 2012 may have been enabled in part by increases in SOC design window and hence usable capacity. The 2015 NAS report also stated (p. 4-5), "as extended in-use experience is obtained, the battery SOC swing may be increased for all electrified powertrains." For these reasons, it is appropriate to review the usable capacity assumptions used in the 2012 FRM and to make any applicable revisions for this Draft TAR analysis.

Usable capacity for HEVs

For the 2012 FRM, a 40 percent usable capacity was chosen by the agencies for strong HEVs predicted to be available in the 2020-2025 time frame. At that time, 40 percent was greater than the 20-30 percent observed in production HEVs of this type. The agencies chose 40 percent on the expectation that improvements in battery technology and manufacturer learning would enable a wider SOC design window by 2020.

The 2015 NAS report (p. 4-5) was skeptical of the agencies' choice of a 40 percent usable capacity for HEVs and suggested using a value closer to the 20 to 30 percent observed in production HEVs. The report supported this position in part by contending that, by virtually doubling the SOC window, the HEV batteries projected in the analysis would be "half the cost and size" of what would be required. However, the agencies believe that the wider SOC window would not have this effect. At the high power-to-energy (P/E) ratio of an HEV battery, cost is not as strong a function of capacity (kWh) as a function of power (kW). Therefore reducing battery capacity from e.g. 0.50 kWh to 0.25 kWh, while holding the required power constant, would not correspondingly reduce the cost by half, because the reduction in capacity would push the P/E ratio to a higher level, counteracting much of the cost reduction. Cost projections generated by BatPaC confirm this trend and show that, for a given power capability, the cost of a 0.25 kWh pack would be very similar to that of a 0.50 kWh pack. For example, BatPaC Version 3 projects that an HEV pack sized for a power output of 15 kW would cost $634 as a 0.25 kWh pack, and $660 as a 0.50 kWh pack, a difference of only about 4 percent.[Z] Therefore at these relative pack capacities, EPA's use of a 40 percent SOC design window for sizing purposes does not have a large impact on projected cost.

The agencies also believe that developments in battery technology and manufacturer learning observed since 2012 have been consistent with the agencies' expectation that a 40 percent usable capacity will be applicable to HEVs in the 2020-2025 time frame. Since the 2012 FRM, numerous HEV models and battery systems intended for such vehicles have been announced. It is clear that although some HEV manufacturers have continued to use a rather conservative SOC window (for example, at AABC 2015, it was reported that the 2016 Malibu Hybrid uses a 1.5

[Z] BatPaC inputs: LMO-G chemistry, 1 module of 28 cells, EG-W (liquid) cooling, HEV-HP vehicle type, 450K annual production volume.

kWh pack of which 30 percent is usable (450 Wh of 1500 Wh)[258]), there is also evidence that some manufacturers have begun increasing the SOC design window in subsequent generations of HEVs.

Specifically, recent developments in batteries for 48V mild hybrids, which have smaller batteries than strong HEVs but similarly demanding requirements, have supported a relatively wide swing. At AABC 2015, Bosch presented a 0.25 to 0.50 kWh battery system designed for use in a 48V hybrid. This battery was described as having been designed for an SOC window from 30 percent to 80 percent SOC (a 50 percent usable capacity) despite its small total capacity.[284] Also at AABC 2015, A123 Systems presented a battery system for a 48V hybrid that uses a proprietary chemistry variation on Lithium-iron phosphate which the company calls Ultraphosphate. Like the Bosch system, this 0.37 kWh pack supports a window from 30 percent to 80 percent SOC (50 percent usable capacity). A123 indicated that production of this pack is planned to begin in 2017.[256]

In 2014, EPA tested a 2013 Volkswagen Jetta Hybrid supplied by Transport Canada as part of an exploratory benchmarking exercise. Several braking and acceleration episodes were performed with the intention of eliciting maximum swing of the 1.1 kWh battery. Multiple energy swings were observed in both charge and discharge ranging from 0.56 to 0.65 kWh, equivalent to a gross SOC swing of about 51 to 59 percent.[285] Although this testing documented that the vehicle controller will permit this SOC swing to occur under these usage conditions, it remains unclear whether this degree of swing would be observed regularly over normal usage. A limited amount of testing over steady-state and standard test cycles elicited smaller swings of up to approximately 30 percent. The short duration of standard test cycles and variation in the observed swing prevented firm conclusions from being drawn about the exact SOC design window the controller regularly permits.

Going forward, it is possible that improvements in cell balancing may also act to support downsizing of HEV battery sizes or widening of SOC windows from their current levels. For example, at AABC 2015, NREL presented work showing that use of active cell balancing instead of passive balancing can result in a 50 percent reduction in the necessary capacity of an HEV battery while also eliminating the need for liquid cooling.[286]

These findings suggest that EPA's choice of 40 percent usable capacity for HEVs remains a conservative estimate for the 2020-2025 time frame.

In the NHTSA analysis conducted by Argonne National Laboratory using the Autonomie model, a 15 percent to 20 percent usable SOC window was assumed for HEVs during standard test procedures at ambient temperature. Higher usable SOC swings were measured at Argonne's APRF under different test conditions (i.e. A/C on).

Usable capacity for PHEVs

For the 2012 FRM, a 70 percent usable capacity was chosen by the agencies to represent both PHEV20 and PHEV40 vehicles. The usable portion of total capacity for a PHEV tends to be narrower than for a BEV. One reason for this difference is that when a BEV reaches its minimum SOC, it is taken out of operation and recharged, while a PHEV instead begins to operate in charge-sustaining mode (charging and discharging within a narrow SOC band) for an indefinite time. The need to provide a proper lower-end buffer for the SOC band, and to avoid extensive operation at a very low SOC, encourages setting a higher minimum SOC point for a PHEV than for a BEV. PHEV batteries also tend to have a larger P/E ratio due to their need to provide similar power levels as a BEV battery while having a smaller capacity. A smaller SOC window would be appropriate under such conditions to promote battery life. The 2015 NAS report (p. 4-12) affirmed that a 70 percent usable capacity is appropriate for a PHEV architecture.

At the time of the 2012 FRM, relatively few PHEVs were in production to serve as examples of this platform. The primary production example was the Chevy Volt, which was about to be released in its first generation (referred to here as Gen1). Prior to its release, the usable capacity of the pre-production Gen1 Volt battery was commonly reported as approximately 8 kWh of a total 16 kWh, or about 50 percent. The first production Gen1 Volt is now understood to have utilized about 10.2 of 16 kWh, or about 64 percent.[287] Testing of a 2012 Chevy Volt by Argonne National Laboratory showed the vehicle to be utilizing an SOC window between 87 percent SOC and 18 percent SOC (69 percent usable capacity).[288]

The initial generations of the Chevy Volt are often described as having adopted a conservative battery management approach by utilizing a narrow SOC design window and liquid cooling. Since the 2012 FRM, GM widened the SOC window for the Volt on at least two occasions while increasing the battery capacity on at least three. The Gen1 model was upgraded in the 2013MY from 16 kWh gross capacity to 16.5 kWh, and further increased for the 2015MY to 17.1 kWh. During this process the usable energy increased from 10.2 kWh in the 16 kWh version to 11.2 kWh in the 17.1 kWh version. This represented a small increase in usable energy capacity, from 63.75 percent of gross capacity to 65.5 percent. The Gen2 Volt, released for the 2016MY, now uses 14 kWh of 18.4 kWh gross, or about 76.1 percent usable capacity. This represents a 25 percent increase in usable capacity from the last Gen1 model.[287]

The PHEV batteries modeled in the 2012 FRM are similar to the Volt battery in that they are liquid cooled, enabling the same level of temperature control that is often cited as being responsible for the dependability of the Volt battery. The production 2016 Volt battery now exceeds the 70 percent usable capacity assumed by the agencies, potentially suggesting that the 70 percent figure is conservative.

It should be noted that the 2016 Volt battery is sized for a 53 mile AER, and accordingly may have a significantly lower P/E ratio than that for a PHEV20. This may allow it to enjoy a wider SOC design window than the smaller battery of a PHEV20 or possibly even that of a PHEV40. Therefore the Volt example is not by itself conclusive that a wider SOC window would be appropriate for PHEV20 or PHEV40.

According to results of testing at Argonne National Laboratory, the Ford Fusion Energi utilizes about 5.9 kWh of its 7.6 kWh gross capacity, or about 78 percent. This provides an additional data point suggesting that a wider SOC window than 70 percent may be appropriate even for some shorter-range PHEVs. The Fusion Energi is rated at 20 miles of AER, and utilizes a blended depletion style that may utilize the engine if driven more aggressively than in the standard EPA test cycles. This engine supplementation at elevated power demands is likely to result in lower peak power demands on the battery, potentially making wider swings less demanding on the battery.

These findings suggest that EPA's assumption of 70 percent usable capacity for PHEVs remains a conservative estimate for the 2020-2025 time frame.

Usable capacity for BEVs

For the 2012 FRM, an 80 percent usable capacity was assigned to BEV batteries. This was based on knowledge of manufacturer plans as well as examples seen in the press for early production BEVs such as the Nissan Leaf and other developmental vehicles. The 2015 NAS report (p. 4-12) affirmed that an 80 percent usable capacity is appropriate for BEVs.

Since the 2012 FRM, a large number of BEV models have reached production, and thousands of BEVs have accumulated a great degree of road usage. This has provided abundant opportunity for manufacturers to begin drawing conclusions regarding the appropriateness of the SOC design windows they chose to implement in their first generation models, and even to begin applying the findings to subsequent model generations. It has also provided many opportunities for research organizations to test these vehicles to ascertain aspects of their design and behavior, including SOC swings observed in use. Table 5.5 summarizes some estimated SOC swings observed in 2012-2016MY BEVs, which are further described below.

Table 5.5 Estimated SOC swings for selected MY2012-2016 BEVs

Example	Estimated SOC swing	Source
ANL EV benchmarking (various)	80 to 90 percent	Argonne National Laboratory
Tesla Model S 85	85 percent	AVL
2015 Kia Soul EV	90 percent	Idaho National Laboratory
BMW i3	87 percent	Idaho National Laboratory

Argonne National Laboratory (ANL) operates an ongoing research program to benchmark xEVs.[288] Vehicle testing from multiple instrumented battery electric vehicles has shown that the vehicles operate usable SOC windows ranging from 80 percent to 90 percent whether air cooled or water cooled[AA]. The agencies will continue to analyze data from these tests to establish the SOC swings being seen in current and newly released xEVs.

At AABC 2015, AVL presented the results of a teardown of a Tesla Model S battery pack.[248] AVL reported that cycling tests of the pack suggested that 73 kWh of the 85 kWh gross capacity is accessible, suggesting that this pack may be utilizing an 85 percent usable capacity. This result is in line with reports from Model S owners that have suggested a usable capacity of about 75 to 76 kWh.[289]

The Advanced Vehicle Testing Activity group at Idaho National Laboratory has tested the batteries of several BEVs currently in production.[290] In testing of the 2015 Kia Soul EV, the measured battery capacity ranged from 30.4 to 30.5 kWh in each of four test vehicles. The service manual for the 2015 Kia Soul EV is reported to list a nominal SOC range of 5 percent to 95 percent, or 90 percent usable, for the high voltage battery system.[291] A 90 percent SOC window would amount to about 27 kWh of usable energy, the same as Kia advertises. In a

[AA] Instrumented battery electric vehicles include: 2015 Chevrolet Spark EV, Kia Soul EV, 2014 Smart EV, 2013 Nissan Leaf, 2012 Ford Focus Electric.

departure from the practice of most other OEMs, Kia may be advertising the usable capacity rather than the gross capacity.

Technical specifications for the BMW i3 indicate a battery capacity of 18.8 kWh.[292] Numerous press sources widely repeat this figure as a usable SOC while consistently citing a gross SOC of 21.6 kWh or 22 kWh. The 21.6 kWh figure is highly consistent with the results of battery testing by Idaho National Laboratory[293,294,295,296] for four 2014 BMW i3 vehicles under test, which indicated gross capacity ranging from 21.4 kWh (one vehicle) to 21.7 kWh (three vehicles). Like Kia, BMW appears to be advertising the usable capacity of the i3 battery rather than the gross capacity. A gross capacity of 21.6 kWh suggests a usable capacity of 87 percent.

In May 2014, the Chevy Spark EV underwent changes to its battery that may indicate a widening of SOC design window. In announcing a change in cell supplier from A123 Systems to LG Chem, General Motors also indicated that the new Spark battery would be reduced in capacity from 21 kWh to 19 kWh, while keeping the same range of 82 miles and the same mpge.[297] Given that rated mpge did not change, this suggests that retention of the original range was more likely made possible by widening the SOC design window than by increasing powertrain efficiency. A widened window could be enabled by either the use of a different battery chemistry (going from A123's Lithium-Iron Phosphate to LG Chem's NMC+LMO chemistry), and/or an increased comfort level due to ongoing experience with the platform. Since the original A123 cathode chemistry (Lithium-Iron-Phosphate or LFP) is comparable to LG Chem's LMO-dominant chemistry in terms of allowable SOC swing, it suggests that experience may have played at least some role in this change.

At AABC 2015, Honda reported that their decision to extend the lease option on the Fit EV by 2 years was based on learning that the batteries in these vehicles were experiencing lower degradation than projected.[298] This suggests that it might be possible to widen the SOC design window in future releases while maintaining durability targets.

The agencies' 2012 choice of 80 percent usable capacity for BEVs appears consistent or slightly conservative in light of the trends discussed here.

5.2.4.4.4 Thermal Management

Battery thermal management includes battery cooling to reject heat generated during use, and in many cases battery heating to warm the battery in cold weather. In systems where active thermal management is present, the battery management system (BMS) will work to keep the battery within a preferred temperature range during use.

Battery thermal management systems are commonly divided into passive systems (where the outside of the pack is exposed to ambient air) and active systems (where a cooling medium is circulated through the pack, or thermoelectric components are integrated with the pack). Active cooling media may be ambient air, cabin air, air conditioned by the vehicle A/C system, a liquid coolant, or the A/C system refrigerant.[299,300,301,302]

For the FRM, the agencies assumed PEV packs would employ active liquid cooling, which was seen in production vehicles such as the Chevy Volt and in several limited-production PEVs at the time of the FRM. In contrast, HEV packs were assumed to employ passive air cooling acting on the outside of the pack, which was the prevalent method seen in HEVs at the time.

One recent approach to cooling battery packs involves placement of a bottom cooling plate beneath the packaged battery cells rather than between each cell. Coolant or refrigerant circulates through the plate and cools the battery cells conductively. This approach is used in the BMW i3 battery, was once used in the Chevy Spark A123-supplied battery, and is possibly being used in the Chevy Bolt pack.[303]

Direct circulation of refrigerant rather than an intermediary fluid such as a glycol-water mix can also improve heat rejection and vehicle packaging by eliminating the secondary cooling loop that would otherwise be needed to reject heat to the atmosphere. The BMW i3 utilizes refrigerant cooling.[299]

Active liquid cooling continues to be the predominant thermal management method for the battery packs of BEVs and PHEVs announced since the FRM. The notable exception is the Nissan Leaf, which continues to use passive air cooling as it has since its first generation. At the time of the FRM, some in the industry and press were expressing skepticism about Nissan's choice of passive air cooling.[304,305,306] Some customers had also begun reporting unexpected battery degradation in hot climates such as Arizona, which some attributed to inadequate thermal management. During the 2014 MY, Nissan adjusted the chemistry of the battery pack to better withstand high temperatures.[307] Although Nissan has continued to use passive air cooling in the 2016 Leaf (and also in the new 60 kWh pack under development), all other production BEV and PHEV packs introduced since the FRM use some form of liquid or refrigerant-based cooling. The 2015 NAS report (under "Cooling," p. 4-17) tended to affirm the agencies' assumption of liquid cooling for BEV packs by independently noting the potential inadequacy of passive air cooling in the Leaf pack.

Although HEV packs were the only packs modeled with passive air cooling in the 2012 FRM analysis, there is some evidence that even these packs may be moving toward liquid cooling. Although air cooling continues to predominate,[302] a presentation by Mahle at TMSS 2015 suggests that air cooling is increasingly being displaced by liquid cooling even in HEV packs.[300] Johnson Controls has also described a 260 V, 1.7 kWh HEV battery product with provision for liquid cooling.[308] Effective cooling and heating capability is often cited as a potential path toward reducing the size of xEV batteries by allowing more of their capacity to be utilized while minimizing degradation.[302,294] This suggests that liquid cooling may become one of the enablers for future HEV batteries to provide the 40 percent usable capacity assumed in the agencies' analysis.

As previously described, EPA uses ANL BatPaC to model the cost of xEV batteries, including mild and strong HEV batteries. BatPaC provides cost estimates for several cooling options, including active air cooling (cabin air or cooled air) and liquid cooling (glycol/water mix). It does not model passive air cooling without air channels between the cells, as might be found in passively cooled HEV batteries. EPA performed several trials to investigate the impact of the available cooling choices for HEV batteries, and found that BatPaC assigns similar or slightly lower costs for its implementation of liquid cooling than for its implementation of active air cooling. For these reasons EPA now uses the liquid cooling option under BatPaC to model the cost of HEV packs, as already done for PHEV and BEV packs.

5.2.4.4.5 *<u>Pack Voltage</u>*

In the 2012 FRM analysis, EPA limited pack voltages to certain ranges depending on whether the pack was intended for an HEV, PHEV, or BEV. HEVs were targeted to about 120V while PHEVs and BEVs ranged from 360V to 600V. For this Draft TAR analysis (as described in detail in Section 5.3), EPA lowered the voltage range for PHEVs and BEVs to between approximately 300 and 400V to reflect trends observed since the FRM. NHTSA designed pack voltages to meet the voltages currently in the market and to reflect the trend of lowering the pack voltage by using high capacity batteries to reduce cost.

To some degree, the customary voltage range for a given xEV category is an outgrowth of the relative size of the battery. Small battery packs for HEVs can be composed of a correspondingly small number of cells, which limits the attainable voltage even if all cells are placed in series. These lower voltages are also consistent with the desire to maintain safety as well as with any need to interface with the 12V electrical system that typically remains in these vehicles. Larger packs for PHEVs and BEVs are typically composed of a much larger number of cells and so can easily reach a much higher voltage if desired. While safety considerations continue to place a practical upper limit on system voltage, a moderately high voltage is consistent with the greater power flows required by these vehicles and offers the added benefit of conducting energy at a lower amperage, which reduces the necessary weight and cost of electrical conductors and reduces I^2R losses. Compatibility of available supplier parts may also encourage different manufacturers to target a similar voltage envelope. Many manufacturers of PHEVs and BEVs appear to have targeted the range between 300V and 400V.

The system voltages chosen by the agencies for modeling xEVs were based on those seen in production xEVs at the time of the FRM. Since the FRM, the agencies have not observed a strong trend away from these general voltage ranges in newly released xEV products, with the possible exception of the upper voltage limit for PHEVs and BEVs.

EPA's original 600V upper limit on BEV battery voltage had been set to accommodate the largest BEV packs that were modeled in the 2012 FRM analysis. Most PHEV and BEV packs modeled in the 2012 FRM were in the 300V-400V range. The only pack modeled in the 2012 FRM that approached the 600V limit was a Large Truck EV150 pack at 586V. At the time, VIA Motors was producing a plug-in electric truck with a 650V battery pack that served as a corroborating example. However, later versions of this and other VIA products have since adopted a lower battery voltage of around 350V to 380V, suggesting that some advantage was seen to adopting a lower voltage.

Examples of PHEVs and BEVs in the 600V range continue to exist. The McLaren P1 PHEV, first introduced to the U.S. in 2014 as a very limited production high-performance vehicle, operates at 535V. In September 2015, Porsche announced the Mission E concept BEV that would operate at 800V. The higher voltage was described as enabling much faster charging as well as lower conductor weight.[309] These examples suggest that voltage ranges higher than the typical 300V-400V may continue to be applicable at least to high performance BEVs and PHEVs.

5.2.4.4.6 *Electrode Dimensions*

The electrodes of a lithium-ion cell are in the form of flat foil strips coated with active materials and stacked or rolled together. Several important parameters of cell performance are controlled by the dimensions of the electrode; in particular, the thickness of the active material coatings on the electrodes and the aspect ratio (length-to-width ratio) of the electrodes.

In general, thinner electrode coatings promote power density, while thicker coatings promote energy density. By default, BatPaC limits coating thickness to no less than 15 microns and no more than 100 microns due to various practical considerations.[137] The lower limit represents interfacial impedance effects associated with very thin electrode coatings.[310] The typical precision of coating equipment, at around plus or minus 2 microns,[311] would also become challenged below this thickness. The upper limit represents material handling and ion transport considerations. Thicker coatings may be prone to flaking when uncut electrode sheets are rolled or unrolled for shipment and processing. Thicker electrodes also require ions to travel a greater distance through the active material during charge and discharge, leading to effects such as increased resistance, reduced power capability, and the potential for lithium plating on charging. In the 2012 FRM, electrode coating thickness was therefore limited to 100 microns. In practice, this limit was only encountered by the most energy intensive packs for large BEVs. In the latest release of BatPaC, ANL has improved the model by which electrode thickness is determined. In most cases this results in somewhat thinner electrodes than would have been projected in the version used for the 2012 FRM analysis. This is expected to result in a slightly higher cost per kWh for most battery packs, all other things being equal.[312]

Electrode aspect ratio is important because it determines how far current must travel on average between where ions reside in the active materials and the current collector tabs. Longer distances are associated with greater resistance and heat generation. If the length is much greater than the width, and the current collector tabs reside on the short dimension rather than the long dimension, current must travel farther on average than in the inverse situation. BatPaC assumes a default aspect ratio of 3:1, with tabs placed on the short dimension. In the FRM, EPA used an aspect ratio of 1.5:1, loosely based on the dimensions of some commonly known cells at the time.

The 3:1 default aspect ratio used in BatPaC appears to be seeing increasing use in the industry. In announcing the 200-mile Chevy Bolt EV[281] at the 2016 NAIAS, GM indicated that its battery cells, supplied by LG Chem, have an aspect ratio of 3.35:1 (measuring 3.9 inches by 13.1 inches). An animation accompanying the announcement shows that the cell tabs reside on the short dimension. The Kia Soul EV battery also uses cells with a nearly identical aspect ratio and tab placement, supplied by SK Innovation.[313,253] These examples lend support to the validity of the default 3:1 aspect ratio and tab placement assumed by BatPaC. GM describes this aspect ratio as "landscape format," presumably to highlight the low-profile design of the pack that allows the entire pack to reside within the floor space of the vehicle.

Also at the 2016 NAIAS, Samsung SDI introduced a family of cells ranging from 26 to 94 Ampere-hours,[314] some of which have a similar aspect ratio to the GM Bolt cells but with tabs on the long dimension. Samsung also displayed a line of "low height packs," suggesting that it anticipates a trend toward low-profile applications for which these cells would be well suited.[315] In December 2015, Volkswagen also announced plans to pursue flat, low-profile pack designs for future electrified vehicles,[316] which likely will also call for a similar cell aspect ratio.

5.2.4.4.7 *Pack Manufacturing Volumes*

In the 2012 FRM analysis, the agencies assumed that battery pack manufacturing would reach full economy of scale at an annual production volume of 450,000 packs in the year 2025. This volume was based on the annual manufacturing volumes assumed by FEV in the teardown analyses performed for the FRM analysis.

In BatPaC, when the user specifies a production volume of 450,000 for a given battery pack, it means that the cost estimate for that specific pack is based on a dedicated manufacturing plant that manufactures an annual volume of 450,000 of that identical pack. Since all of the packs produced by the hypothetical plant are identical, it implies that the cost estimate is most applicable to a situation in which the packs are intended to be used by a single manufacturer in a single model of electrified vehicle.

The 2015 NAS report noted (p. 4-42, and Finding 7.3, p. 7-23) that the technology penetration levels projected by the agencies for electrified vehicles are lower than the 450,000 annual production volume that the agencies assumed in projecting battery pack costs for the 2022-2025 time frame. Further, it noted that whatever annual production did occur would likely be divided among multiple manufacturers and multiple models, preventing the full economy of scale of 450,000 units from being achieved by any single manufacturer. The report recommended that the agencies use a smaller manufacturing volume for electrified vehicle battery packs to better reflect projected technology penetration, rather than the 450,000 annual production assumed in the 2012 FRM.

Despite the agencies' use of an annual production of 450,000 units, it is unclear whether this results in more optimistic estimates of battery cost than the industry may realize. The following discussion describes several points relevant to this consideration: (a) the potential for a "flex plant" manufacturing approach to realize economy of scale at much lower pack volumes; (b) the potential for economies of scale to fully develop at production volumes at low as 60,000; (c) examples of actual costs that are already lower than the agencies' FRM estimates at a much lower production volume than 450,000; (d) the agencies' placement of estimated costs in the year 2025 instead of 2020; and (e) the potential for consolidation in the battery industry to increase pack manufacturing volumes.

There is evidence that optimizing the approach to battery manufacturing by adopting a "flex plant" approach may allow economies of scale to be realized at pack production volumes much lower than 450,000. According to a recent ANL study,[317] a battery manufacturing plant that is designed to simultaneously manufacture packs for multiple vehicle types (HEVs, PHEVs and BEVs) by standardizing on a single electrode width can significantly reduce the pack manufacturing volumes required to achieve maximum economy of scale. The ANL study calls this approach a "flex plant." Some manufacturers already appear to be adopting a similar approach for production of prismatic cells. For example, at AABC 2015, Samsung SDI described a strategy to build an "ecosystem" of xEV battery products by maintaining a "standard cell format between generations," that is, by maintaining the same cell dimensions and container size and achieving different target capacities by varying the chemistry.[275] At the same conference, Bosch similarly described a goal to produce packs of varying capacity by use of a standard 36 Ampere-hour cell.[284] XALT Energy also described its practice of achieving variable cell capacity (Ampere-hour) sizes by adjusting the electrode count within a cell while maintaining one of two fixed cell footprint areas.[318] Cell standardization also may promote the economics of battery second life applications[319] and so could provide an added motivation for manufacturers to reduce the number of cell formats. The agencies anticipate that the most successful suppliers may continue to adopt similar approaches over time. As this occurs, the production volume of the individual cells that compose the several pack types produced from those cells would increase dramatically, even though pack volume of any single pack type may remain relatively low. This increased cell volume may recapture much of the economy of scale reflected at the pack level in the 450,000 unit assumption.

There is also some evidence to suggest that economies of scale may be achieved at much smaller pack production volumes than 450,000, even without necessarily adopting a flex plant approach. According to the ANL flex plant study, the benefits of a flex plant over a dedicated plant for reducing the cost of BEV batteries levels off past a production level of about 60,000 units per year, suggesting that 60,000 units would approach maximum economy of scale for a dedicated plant. The 2015 NAS report (p. 4-42), in noting that agencies' projected costs for 2012 "seem reasonable" despite the large volume assumed, cites as a possible explanation a TIAX study (referred to as Sriramulu & Barnett 2013 in a National Research Council report on Overcoming Barriers to EV Deployment[222]) that also suggests a 60,000 unit volume at which economies of scale would be realized. This level of production is much closer to the technology penetration levels predicted by the agencies. Individual manufacturers such as Nissan and Tesla are already approaching similar production levels, with Nissan having sold more than 30,000 Leaf EVs in North America in 2014, and Tesla projecting a similar amount in 2015. The BMW i3 and i8 PHEVs are also approaching a global production level of 30,000 units per year.

There is also evidence that actual battery pack costs experienced by some manufacturers are already lower than the agencies' FRM estimates, at a much lower production volume than 450,000. As discussed in more detail below, General Motors has cited its rapidly falling battery cell costs from supplier LG Chem as evidence of their being "able to achieve lower costs earlier with much less capital and volume dependency" than presumably had been expected. The cell-level costs cited by GM for the Chevy Bolt are lower than the BEV pack costs projected by the agencies in 2012. Because it appears to suggest a currently contracted price applicable at the very beginning of the Bolt product cycle, it therefore is likely to be based on an annual production level of far less than 450,000 packs. Production of the 2017 Bolt has been characterized as capable of serving a demand of around 50,000 units per year.[320]

The way the agencies apply the BatPaC-generated costs also treats them conservatively. Although the cost estimates generated by BatPaC are intended by its authors to represent technology being used in the year 2020, the agencies assign these costs to the year 2025 when applying reverse-learning to generate year-by-year cost estimates for earlier years. Although this was a practical choice in order to cover the full time frame of the standards which run to 2025, it has the effect of making the projected costs more conservative by assuming that the technology projected by the BatPaC authors will not take effect for an additional five years.

Consolidation among battery cell suppliers may also improve the ability for individual suppliers to begin approaching the production volumes assumed in the analysis. Since the FRM, there has been significant consolidation among battery manufacturers.[321,322,323] For example, A123 Systems, which at one time competed against LG Chem to supply battery cells for the Chevy Volt and was later chosen to supply the Fisker Karma and Chevy Spark, filed for bankruptcy in late 2012 and was sold to Chinese auto supplier Wanxiang in 2013.[324] Wanxiang has since refocused A123's efforts toward smaller HEV and stop-start batteries as well as grid storage. Johnson Controls, which was ranked in second place as an industry leader by one analysis firm in 2013,[323] also has refocused its effort on smaller batteries. As of late 2015, three xEV cell suppliers appear to have been particularly successful at developing OEM partnerships: LG Chem, Panasonic, and Samsung SDI.[325] LG Chem has grown its customer list to include not only GM but also Renault, Volvo, Daimler, Volkswagen, Audi, and Tesla.[326] Panasonic is also a dominant player through its ongoing partnership with Tesla, as well as supplying smaller contracts with Ford and Volkswagen. Samsung SDI is a supplier to BMW and in 2015 announced plans to acquire the battery division of Magna International.[327] Nissan's joint-venture arm Automotive Energy Supply Corporation (AESC) is also an important player through its battery production for Nissan and Renault vehicles, including the Nissan Leaf. In 2015 it was reported that Nissan is also considering a partnership with LG Chem for its future BEV batteries.[328] Even Tesla, which has long-term plans to source cells from its so-called Gigafactory, is said to be investigating the possibility of sourcing cells from other leading suppliers in order to meet expected demand for the Model 3 in a timely manner.[329]

For the reasons discussed above, and in view of the evaluation of 2012 FRM battery cost projections (described in Section 5.2.4.4.9 below), EPA believes that an assumed manufacturing volume of 450,000 was appropriate as a BatPaC input for the purpose of generating battery pack cost estimates for the 2012 FRM analysis.

5.2.4.4.8 Potential Impact of Lithium Demand on Battery Cost

Controversy has periodically arisen about the adequacy of known lithium reserves to service the potential demand generated by the electrified vehicle industry. However, lithium appears to be plentiful enough at this time to suggest that its availability will not be a constraint in the near term.[330,331]

At circa-2010 prices, the cost of lithium content was said to be only about 1 percent of total material cost at the battery pack level[331] or perhaps 2 percent at the cell level.[332] Lithium comprises a similar percentage by mass, and at time of manufacture resides primarily as ions in the cathode active material and the electrolyte solution.

Lithium used in cell manufacturing is most commonly sourced as lithium carbonate.[333] Lithium carbonate is primarily recovered from ancient continental brines underlying salt lake deposits. These are widespread in the southern Andes (primarily Bolivia, Argentina, Chile) and western China and Tibet, with deposits identified in the southwest United States as well. Lithium may also be recovered from some oilfield brines in the western U.S. Because industrial applications for lithium were relatively few and scattered prior to its use in batteries, known reserves may not be as well enumerated as for other commodities, and may have potential to increase as demand increases and previously unidentified or unexploited sources are recognized.

Recently, concerns about lithium prices have been renewed by a significant increase in the price of lithium, thought to be resulting in part from increased demand for use in electrified vehicles.[334] Pressure also appears to be increasing on manufacturers to secure lithium sources that will be needed to supply increased production capacity.[335] A study released by Carnegie-Mellon University in May 2016[336] addressed this issue directly by examining the sensitivity of battery cell manufacturing cost to the price of lithium carbonate and lithium hydroxide. The study concluded that the effect on battery pricing would be minimal (never more than 10 percent) even for the most extreme lithium price fluctuations considered (about four times the historical average). The researchers also suggested that the primary difficulty imposed by such fluctuations would be felt by cell manufacturers in maintaining profit margins, rather than by vehicle manufacturers or consumers.

5.2.4.4.9 Evaluation of 2012 FRM Battery Cost Projections

In the 2012 FRM, the agencies adopted a bottom-up, bill-of-materials approach to projecting the future DMC of xEV batteries by using the ANL BatPaC battery cost model.[137] As discussed in the Technical Support Document (TSD)[136] accompanying the 2012 FRM, battery pack costs projected by this model were shown to compare favorably with cost projections provided by suppliers and OEMs that were interviewed during development of the rule. In the 2015 NAS report (Finding 4.4, p. 4-43), the committee found that "the battery cost estimates used by the agencies are broadly accurate," providing further support for the use of this model.

At the time of the FRM, few public sources were available to further validate these projections. Since that time, several sources have emerged that provide additional information on the evolution of battery costs since the FRM and potential future trends.

In 2015, a peer-reviewed journal article (Nykvist and Nilsson, 2015) appeared that provides a comprehensive review of over 80 public sources of battery cost projections for BEVs.[142] Based on a statistical analysis of these estimates, it was shown that industry cost estimates for lithium-ion batteries for BEVs have declined 14 percent annually between 2007 and 2014, and that pack costs applicable to leading BEV manufacturers have followed a cost reduction curve of about 8 percent per year, with a learning rate of between 6 percent and 9 percent. The authors concluded that the battery costs experienced by market leading OEMs are significantly lower than previously predicted, and that battery costs may be expected to continue declining.

Figure 5.37 compares the full population of cost estimates reviewed by Nykvist and Nilsson to the battery pack cost projections of the 2012 FRM analysis. Because BatPaC does not produce cost estimates for multiple years, the 2012 FRM analysis applied a learning curve to generate costs for the years 2017 through 2025, with BatPaC output costs assigned to the year 2025. The learning-adjusted FRM costs shown in the figure include those for PHEV40, EV75, EV100 and EV150, which have relatively large capacities similar to those likely included in the review. The plot shows that the battery costs projected in the 2012 FRM fit well with the reviewed estimates, and lie on a similar cost reduction curve.

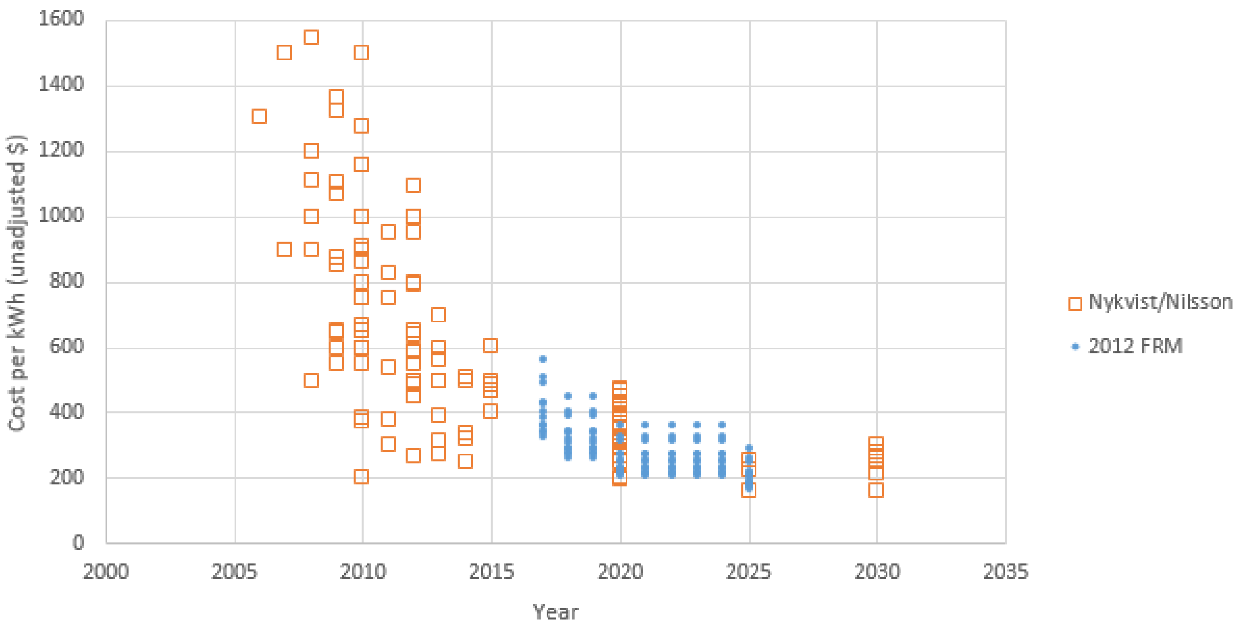


Figure 5.37 Comparison of 2012 FRM Projected Battery Cost Per kWh to Estimates Reviewed by Nykvist & Nilsson

Cost estimates and projections are most useful when they can be validated by comparison to actual costs. Unfortunately, information about actual battery costs paid by manufacturers for production vehicles is rarely disclosed publicly. However, in October 2015, General Motors publicly commented on its battery costs for the Chevy Bolt EV, providing an opportunity to evaluate the FRM projections of BEV battery costs.

At the General Motors Global Business Conference on Oct. 1, General Motors described to an investor audience its current and projected cost per kWh (on a cell basis) for battery cells for the Chevy Bolt EV. Citing partnership with cell manufacturer LG Chem, Executive Vice President of Global Product Development Mark Reuss stated, "When we launch the Bolt, we will have a cost per kWh of $145, and eventually we will get our cost down to about $100. We believe we will have the lowest cell cost with much less capital and volume dependency."[337] An accompanying chart shows the $145 cost continuing to 2019, dropping to $120 per kWh in 2020 and to $100 per kWh in 2022.[338,339]

It is important to note that the costs described above are cell-level costs and not pack-level costs. To compare them to the pack-level costs projected by the agencies requires converting them to that basis using an appropriate methodology. Also, although the context of the announcement suggests that the costs are comparable to a direct manufacturing cost, their exact basis is unknown. Although these factors introduce some uncertainty in comparing the announced costs to the FRM projections, a qualified comparison is possible.

Several sources exist that suggest a cost conversion factor from cell-level costs to pack-level costs for lithium-ion batteries.[340,269,248,341,342,343] These are summarized in Table 5.6. Most of these sources suggest a conversion factor of about 1.25 to 1.4 may be appropriate.

Table 5.6 also shows two estimates derived from the ANL BatPaC model for a liquid-cooled BEV-sized pack at a production volume of 50,000 to 100,000. Outputs from this model suggest that the ratio of pack-level cost to cell-level cost for the pack format modeled by BatPaC may range from about 1.5 for a 16 kWh pack to about 1.3 for a 32 kWh pack, and continuing to decrease for larger pack capacities.

Table 5.6 Examples of Conversion Factors for Cell Costs to Pack Costs

Source	Low	High
Kalhammer et al.[340]	1.24	1.4
Element Energy[269]	1.6	1.85
Konekamp[248]	1.29[BB]	
USABC[341]	1.25[CC]	
Tataria/Lopez[342]	1.26[DD]	
Keller[343]	1.2[EE]	
BatPaC, 16 kWh	1.5	
BatPaC, 32 kWh	1.3	

On the basis of the BatPaC-derived ratios of 1.3 to 1.5, the 2015-2019 cell-level figure of $145 per kWh would translate to approximately $190 to $220 per kWh on a pack level. The future projections of $120 and $100 per cell kWh in 2020 and 2022 would translate to approximately $156-$180 per kWh and $130-$150 per kWh at the pack level, respectively.

On this pack-converted basis the GM cell costs agree well with the BatPaC cost projections that the 2012 FRM analysis applied to 2025. Table 5.7 summarizes the estimated pack-level equivalents of the cell costs disclosed by GM and compares them to the EV150 pack-level BatPaC output costs of the FRM analysis. The pack-converted GM projection for 2020, at $156-$180 per kWh, compares well to the FRM BatPaC output costs for EV150[FF] for 2025, which ranged from $160 to $175 per kWh (at 450,000 units annual volume). The pack-converted GM projection for 2022 at $130-$150 per kWh is significantly lower than the agencies' projection for 2025. This suggests that the 2012 FRM cost projections, at least for EV150, may have been quite conservative.

Table 5.7 Comparison of GM/LGChem Pack-Converted Cell Costs to FRM EV150 Pack Cost

		Pack Cost/kWh (2015$)	
Source of Estimate	Year Applicable	Low	High
EV150 in FRM	**2025**	**$160**	**$175**
GM/LG Global Business Conference	2015-2019	$190	$220
	2020	**$156**	**$180**
	2022	$130	$150

Figure 5.38 compares the pack-converted GM costs to the year-by-year learning-adjusted costs used in the 2012 FRM for Small, Standard, and Large Car EV150. It can be seen that the

[BB] Cell cost = 620 Euros*16 modules = 9,920 Euros; pack cost = 12,800 Euros; 12,800/9,920 = 1.29.

[CC] USABC 2020 goals for advanced EV batteries cite a cost of $125/kWh at pack level and $100/kWh at cell level = 1.25.

[DD] For a 40 kWh pack, cell costs estimated at $258/kWh; pack-related costs at $2,626, or $66 per kWh; (258+66)/258 = 1.26.

[EE] Cites one goal of 21st Century Truck Partnership as "Cost of overall battery pack should not exceed cost of the cells by more than 20% by 2016" (slide 6).

[FF] The Chevy Bolt is anticipated to offer a 200-mile driving range, potentially comparable to the real-world 150-mile range of the EV150 that the agencies modeled in the FRM.

range of the pack-converted GM costs is lower than the costs predicted by the 2012 FRM analysis.

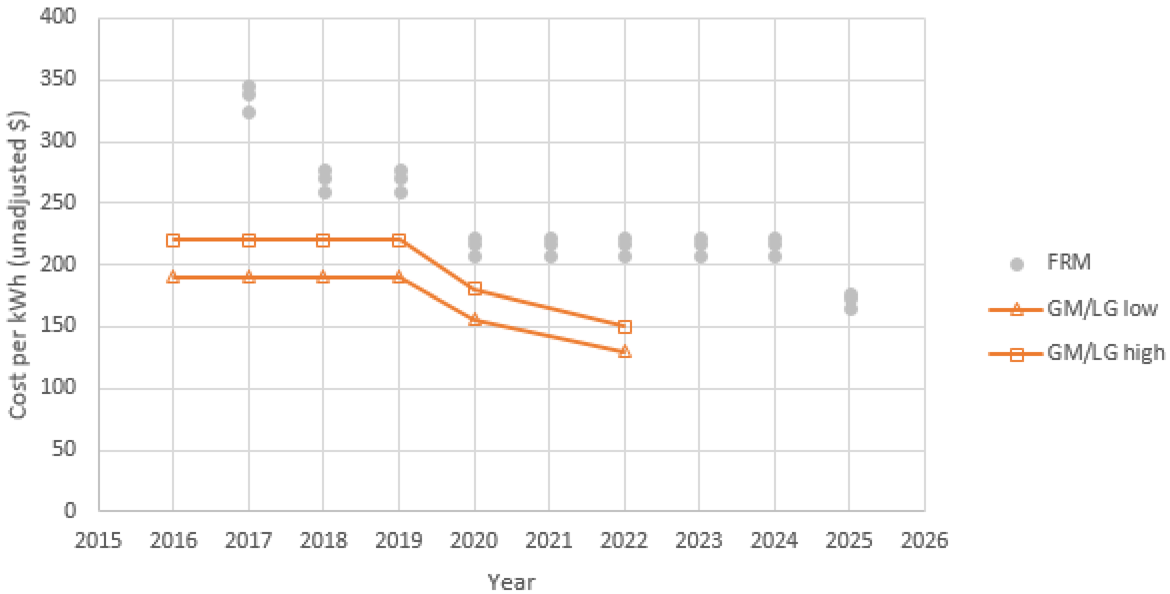


Figure 5.38 Comparison of Estimated GM/LG Pack-Level Costs to 2012 FRM Estimates for EV150

At the time of the FRM, the agencies' battery cost estimates appeared to be lower than costs being reported by many suppliers and OEMs at the time, and also lower than some independent estimates said to be applicable to the time frame of the rule. The agencies chose to place confidence in the peer-reviewed ANL BatPaC model due to its rigorous, bottom-up approach to battery pack costing, and the expertise of leading battery research scientists that contributed to its development. The comparisons described above suggest that this approach was effective and may in fact have been conservative not only with respect to characterizing the pace of reductions in battery cost that have taken place in the time since the FRM but also to projecting future costs for the 2020-2025 time frame. Up to and including the development of this Draft TAR analysis, the agencies have continued to invest significant resources into understanding developments and emerging trends in battery technologies so that these critically important projections of xEV battery cost may be as reliable as possible.

While other public examples of battery costs to manufacturers remain elusive, several suppliers and manufacturers have made battery-related product announcements since the FRM. Some of these include information suggestive of battery costs or pricing. Some manufacturers have published pricing for battery replacement parts or upgrades available to authorized service providers. Others have offered different options, such as battery size or purchase method, the relative pricing of which may suggest a relationship to battery cost. Finally, stand-alone non-automotive Li-ion battery packs are beginning to become available to end users and their pricing may be informative. While the agencies recognize that the pricing of these early-stage product offerings may be subsidized by their manufacturers for competitive and marketing reasons, these announcements may still be relevant to understanding the evolution of battery pack costs as these products increase their presence in the market.

In 2013-2014, Tesla Motors offered the Model S in two battery pack sizes, 60 kWh and 85 kWh, at retail prices of around $69,900 and $79,900, respectively. Assuming no content difference between the two versions, the retail price differential would suggest a battery cost of $10,000 / 25 kWh = $400/kWh. An alternate analysis presented by Nykvist et al.[344] subtracts the estimated value of added content found in the 85 kWh version (Supercharger, premium tires, and associated markup), resulting in a net price difference of $8,500 or $340 per kWh.

In July 2014, Nissan announced the replacement cost of a 24-kWh battery for the Nissan Leaf at $5499 with core return, which amounts to about $229/kWh net. Although Nissan requires return of the original battery (core), a $1000 credit is then applied for the core, suggesting a full retail price of $6499, or $271/kWh.[345,346,347] Later the same month, Nissan followed up by pointing out that the quoted price is in fact subsidized by Nissan, although they declined to report the amount of subsidy or the actual manufacturing cost.[348] Nissan does not allow purchase of the battery except as a Leaf battery replacement.

In 2015, an independent vendor of OEM parts listed the 2011 Chevy Volt battery pack at $10,208 list price, discounted to $7,228, with no mention of core exchange. Assuming a 16 kWh capacity, these prices would value the battery at $638/kWh and $452/kWh, respectively. Although the product was listed and priced by the vendor, it was on restriction from ordering for reasons that remain unclear.[349,350]

In January 2015, it was reported that the MSRP for a BMW i3 battery pack module was listed at $1,805.89, each module being 2.7 kWh (21.6 kWh total divided by 8 modules). This module price would equate to $669/kWh. A specific dealer was reported to be offering the module at a price of $1715.60, or $635/kWh.[351]

In September 2015, Tesla announced the price for a range-increasing battery pack upgrade for the Tesla Roadster at $29,000, including installation and logistics. Tesla indicated that the quoted price is meant to be equal to Tesla's expected cost in providing the pack, and disclaimed any intention to make a profit. Tesla also indicated that the price per kWh is higher than for a Model S battery due to the low volume production expected for the Roadster upgrade pack (only approximately 2,500 Roadsters were produced). Tesla did not list the kWh capacity of the upgrade pack, but describes it as having approximately 40 percent more energy capacity than the original Roadster pack, which is commonly listed as 56 kWh. This suggests that Tesla's cost for low volume production of this pack is around $29,000/(56*1.4) = $370 per kWh.[352] In October 2015, Tesla further announced that the Roadster upgrade packs would be provided through a partnership with LG Chem.[353] This suggests that the price of the pack may not reflect anticipated savings from the Panasonic-Tesla "Gigafactory" partnership.

In August 2013, the Smart ED was offered with a 17.6 kWh battery, with the option to either purchase the battery with the car, or lease it separately. The vehicle price was $5,010 lower without the battery when the battery was leased at a price of $80/mo. If the $5,010 differential was taken to represent the incremental cost of the battery, it would value the battery at $285/kWh. Of course, the present value of the lease payments would also contribute value to the transaction, and it is possible that marketing considerations could also be represented in the pricing.[354,355,356]

In September 2015, Nissan announced pricing in the UK for the 2016 Nissan Leaf. In a press release from Nissan, equivalent versions of the Leaf having a 30 kWh pack instead of a 24 kWh pack were priced at a difference of 1,600 British pounds. This would amount to approximately 267 British pounds per kWh, or U.S. $411 per kWh (assuming an exchange rate of 1.54 U.S. dollars per pound). It should be noted, however, that although the two versions of the pack appear to be designed to install into the same footprint and volume, any cost comparison is potentially complicated by differences in chemistry and construction of the two versions.[357]

In 2014, Tesla Motors began construction of a so-called "Gigafactory" in Nevada in partnership with Panasonic. This factory is commonly cited by Tesla as enabling a potential 30 percent reduction in battery pack costs from the levels Tesla currently pays. According to one analysis,[358] Tesla's current cost is estimated at about $274 per kWh. A 30 percent reduction on that figure would bring costs to about $192 per kWh.

In April 2015, Tesla announced a home battery pack product called Powerwall, pricing a 7 kWh version at $3,000 ($428/kWh) and a 10 kWh version at $3,500 ($350/kWh). Although designed for stationary home use, the pack design bears similarities to automotive packs, being liquid-cooled and using similar chemistries. The 7 kWh version employs NMC chemistry similar to many production BEVs, while the 10 kWh version employs the NCA chemistry like the Tesla Model S. Tesla also announced a similar product called Powerpack for commercial use. Powerpack was said to be priced at $25,000 for 100 kWh capacity, or $250/kWh. These products are expected to take advantage of much of the cell output of the Gigafactory, suggesting that these products may be priced in anticipation of the cost reductions it is expected to achieve. Table 5.8 summarizes the estimated cost or pricing information derived from the foregoing examples.

Table 5.8 Summary of Published Evidence of Battery Pack Cost and Pricing

		Pack Cost or Price per kWh	
Source of Evidence	Year Applicable	High	Low
Tesla Model S 60 kWh vs 85 kWh comparison	2013-2014	$340	$400
Nissan 24 kWh replacement pricing	2015	$229	$271
Vendor pricing for 2011 Volt pack	2015	$432	$638
Dealer pricing for BMW i3 module	2015	$635	$669
Tesla Roadster upgrade pricing	2015	$370	
Smart ED lease vs buy pricing	2013	$285	
Nissan UK price differential 30 kWh vs 24 kWh	2015	$411	
Tesla Lux Research estimate	2014	$274	
Tesla Lux Research estimate modified by Gigafactory	2017	$192	
Tesla Powerwall	2015-2016	$350	$428
Tesla Powerpack	2015-2016	$250	

It is important to remember that the figures derived from these examples should be interpreted with caution. The agencies' cost projections represent direct manufacturing costs and not retail pricing. Also, as previously noted, retail pricing of these early-stage product offerings may be subsidized by their manufacturers and may reflect competitive and marketing considerations that further obscure their true manufacturing cost. Furthermore, some of the estimates are derived from full-product comparisons that may or may not accurately represent the battery portion of the comparison. It should also be noted that the examples presented here represent current pricing, while the FRM applies its BatPaC cost projections to the year 2025.

On the other hand, the existence of these examples shows that the industry has progressed considerably since the FRM, when such examples were almost entirely unknown. The identification and packaging of specific battery products for upgrade, replacement or standalone use is a significant development and suggests that the industry is continuing to gain in maturity and is growing along multiple paths. The establishment of MSRPs for many of these products also suggests that manufacturers are beginning to gain confidence in their understanding of the cost structure of battery products. The examples and estimates derived from this analysis, even if approximate, can serve to ground the various cost estimates and projections that have previously been the primary source of battery costing information (and will continue to play an important role going forward).

5.2.4.5 Fuel Cell Electric Vehicles

5.2.4.5.1 Introduction to FCEVs

Fuel Cell Electric Vehicles (FCEVs) are another potential technology option for implementing electrified drive to achieve zero tailpipe emissions, like the BEV technology presented in Section 5.2.4.3.5. Like BEVs, FCEVs use electricity to turn electric motors onboard the vehicle that provide the motive power for driving. However, unlike a BEV, the FCEV also produces this power onboard. It achieves this by harnessing the energy produced in an electrochemical reaction that combines hydrogen and oxygen to form water. This process occurs within the fuel cell itself, a device that shares a basic structure with batteries; namely, it consists primarily of an anode, a dividing electrolyte, and a cathode. Hydrogen from an onboard tank enters the fuel cell's anode and is separated into its constituent electron and proton. The electron is directed to an external circuit, where it ultimately provides power to the electric motors driving the wheels. The proton is transferred across the fuel cell's electrolyte membrane to the cathode, where it combines with oxygen from air entering the cathode and electrons returning from the external circuit to form water. Thus, the basic reaction in the fuel cell is $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$, with usable electric power (and some amount of heat) produced in the process.

State and national policies have increasingly adopted the perspective that FCEV and BEV technologies will be complementary vehicle technologies that will likely both be needed in order to achieve long-term GHG reduction goals. Well-to-wheel GHG emissions for FCEVs and BEVs vary depending on the method of production for their various fuels (electricity for BEVs and hydrogen for FCEVs), but both technologies hold promise for significant reduction below current and projected future ICE vehicle GHG emission rates (see Chapter 9, Infrastructure Assessment for a more complete presentation of GHG emissions from hydrogen production). Hydrogen energy storage, the conversion of electrical energy into hydrogen gas through the process of electrolysis, has recently gained significant attention for its potential to enable increased renewable penetration in the electric grid, thus potentially playing a significant role in decarbonizing multiple industries in the full US energy system. Although there is potential for FCEVs to play a significant role in reducing GHG emissions, the technology is still relatively new (the first mass-produced vehicles entered the market in 2014) and costs have historically been higher than other options. For this reason, FCEVs were not included in the projections of the future vehicle fleet in the 2012 FRM.

The 2010 Technical Assessment Report (TAR) covered developments and state-of-the-art technology for the FCEV at the time. Since then, researchers and developers in government, academia, and industry have continued to advance the technology's performance capability and cost-competitiveness. This has enabled a transition in recent years away from a pre-commercial technology demonstration phase to the early phases of full commercial product introductions. Additionally, the year 2015 was a critical year in meeting national goals for the development of FCEV technology advancement and commercial deployment. The year has long been an aspirational goalpost, as captured in the Energy Policy Act of 2005.[359]

"To enable a commitment by automakers no later than year 2015 to offer safe, affordable, and technically viable hydrogen fuel cell vehicles in the mass consumer market."

"…to enable a commitment not later than 2015 that will lead to infrastructure by 2020 that will provide— (A) safe and convenient refueling; (B) improved overall efficiency; (C) widespread availability of hydrogen from domestic energy sources…"

The above provisions in the Act directly applied to the US Department of Energy (DOE), but have in actuality enlisted active participation by auto manufacturers, state and federal governments, national labs, academic researchers, fuel and energy firms, engineering firms and consultants, hydrogen production and distribution companies, public-private partnerships, and an array of other industry participants. Based on these requirements, the Department of Energy has long set cost and performance targets for FCEVs, hydrogen storage, and hydrogen fueling technologies, and adjusted these goals in accordance with developments in the state-of-the-art technology.

At the time of the 2010 TAR, the FCEVs that were on the road were part of auto manufacturers' research and demonstration programs. Although many of these cars were operated by private lessees, the models were not fully commercial products and the release of the vehicles was much more carefully managed than full commercial sales. As of 2015, a great deal of progress has been made towards the commercialization goals and the directives of the Act. Two auto manufacturers, Hyundai and Toyota, have begun selling and/or leasing FCEVs directly to the mass market. The first Hyundai Tucson Fuel Cell Crossover vehicles were delivered to customers in June 2014[360] and the first Toyota Mirai sedans began delivery in October of 2015.[361] Other auto manufacturers have announced imminent plans for release of their own mass-market, mass-produced FCEVs; Honda has made indications that it will be the next auto manufacturer to bring a vehicle to market with its Clarity Fuel Cell expected sometime in 2016.[362]

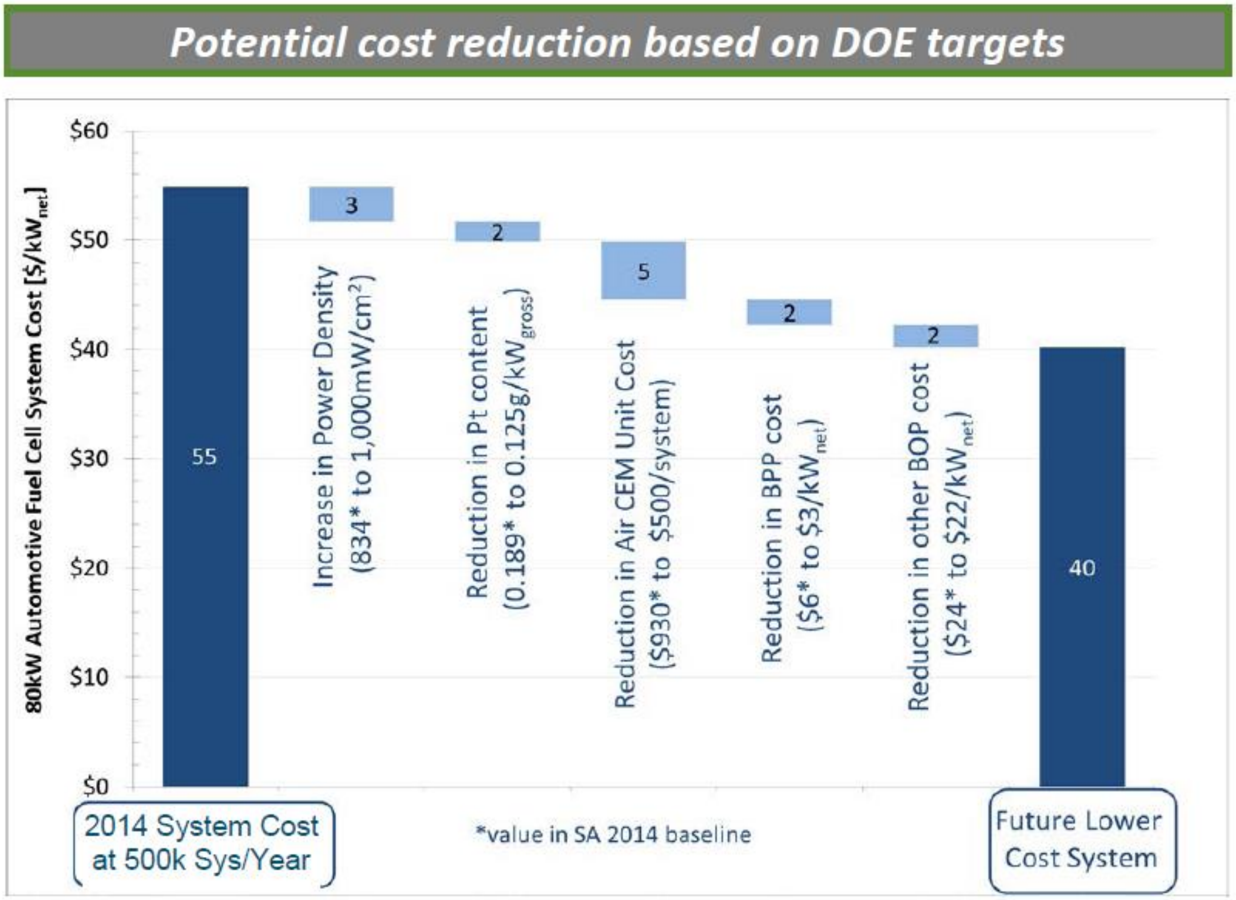
Commercial releases of mass-produced FCEVs intrinsically rely on the availability of a retail hydrogen fueling network to support the needs of the FCEV drivers. California has had the longest experience with deploying and operating fueling stations. However, at the time of the 2010 TAR, the network in California included only a handful of stations with public access, and these stations were primarily research and/or technology demonstration stations. Many retail features were not included in these early stations. Recent progress in the development of station technology and deployment has moved infrastructure development in California towards retail service stations. The recent commercial vehicle releases have been well-timed to the development of this retail fueling infrastructure network; in California there is now a network of 51 stations currently funded and in development, with continued annual State funding expected beyond 2020.[363] For a more complete review of the status of hydrogen fueling infrastructure development, see Chapter 9, Infrastructure Assessment.

Challenges remain in FCEV and fueling station technology and implementation, but progress since the agencies reported in the 2010 TAR has helped the industry mature out of a pre-commercial and demonstration phase into the first stages of the retail, mass-market phase. Many of the previous targets have been met or exceeded and new targets, tied to production volumes rather than specific timeframes, are now in place at the Department of Energy. These developments have also allowed an escalation of the industry-wide dialogue of plans for deployments and development nationwide, as opposed to the singular focus that has historically been placed on the demonstration and nascent pre-commercial market in California alone. Cost remains one of the major challenges for both the vehicles and fueling infrastructure. Federal and State financial incentive programs are currently in place to help meet the cost challenge, and it is likely that these incentives will need to remain and expand as the commercial market develops, similar to the national experience with BEVs.

5.2.4.5.2 FCEV Cost Estimation

Since FCEVs are electric-drive vehicles, they share many of the same types of components as hybrid vehicles and full BEVs. In fact, it is anticipated that auto manufacturers that choose to pursue multiple drive train technologies among these three options may implement similar, if not exactly the same, components whenever possible among HEV, BEV, and FCEVs in order to take advantage of manufacturing efficiencies and benefits of scale in the supply chain. However, there are three main subsystems that the FCEV does not share with other vehicles: the fuel cell stack, air and fuel delivery sub-systems, and the hydrogen storage system. Although exact direct manufacturing costs for individual auto manufacturers' designs are proprietary information, the Department of Energy has for a number of years supported work estimating the direct manufacturing costs of these components. This work was cited in the 2010 TAR, published through Directed Technologies, Inc.[364] Since that time, Directed Technologies has been acquired by Strategic Analysis, Inc. (SA), who continues to publish annual updates to their estimates. These estimates are a critical resource in estimating the potential costs of FCEVs, much in the way that BatPaC is used to estimate the direct manufacturing costs of xEV batteries for the purposes of the Draft TAR. In order to complete its analyses, SA adopts a Design for Manufacturing and Assembly (DFMA[GG]) analysis method that captures optimized material and processing costs at varying production rates.

[GG] DFMA is a registered trademark of Boothroyd Dewhurst Incorporated.



Note: DOE has since published an updated estimate for 2015 of $53/kW at 500k Sys/Year.

Figure 5.39 Projection of Potential Cost Reductions for Fuel Cell System[365]

5.2.4.5.2.1 Fuel Cell System Cost

The SA estimates allow the DOE to measure progress towards its cost reduction goals and provide open and public analysis of the costs of materials and manufacturing processes for fuel cell stacks, hydrogen storage tanks, and related balance of plant. The analyses provide detailed information on the individual processes for nearly all components and estimated costs for conventional and demonstration technologies. The 2014 analysis[366] and 2015 update[367] estimated that current fuel cell system technologies, at high production volumes for a representative 80 kW net power FCEV would cost $55/kW (not including the hydrogen storage system). With advances currently available or anticipated in the near-term, the cost can be potentially reduced to $40/kW, meeting the DOE 2020 system cost target, which is based on achieving cost-parity between FCEVs and hybrid vehicles.[368,369,370] Note: DOE has since published an updated estimate for 2015 of $53/kW at 500k Sys/Year.

Figure 5.39 Figure 5.39 provides an overview of the current system estimate and possible steps to achieve the prospective lower-cost system. The steps shown in the figure should not be interpreted as the only or even the ideal route to a lower cost system; rather, it is a sample pathway for future development and other improvements may provide at least the same improvement in cost. Figure 5.40 provides a breakdown of contributions to cost from raw materials and individual manufacturing steps in the production of the catalyst, one of the most expensive components of the fuel cell stack. The differing responses of each material and process to increased volume production are apparent in the example.

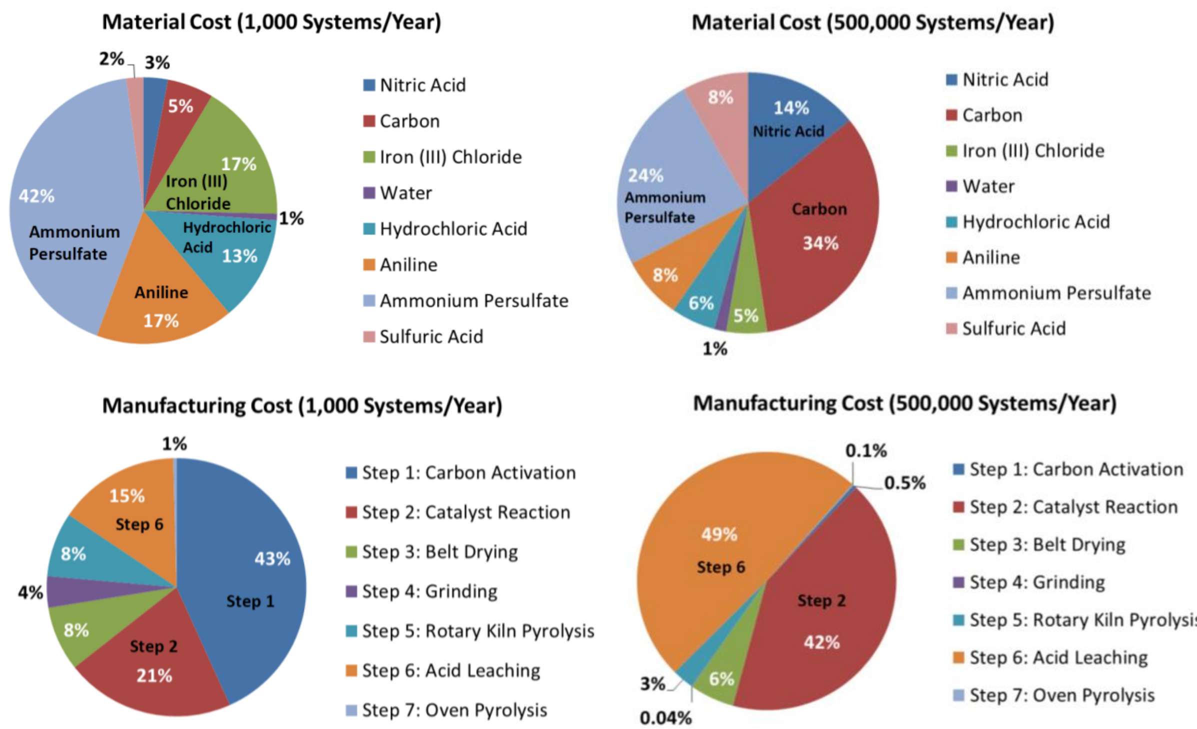


Figure 5.40 Cost Break-Down for Catalyst in an 80kw Fuel Cell System at 1,000 And 500,000 System Annual Production Rates[371]

In addition to the detailed DFMA analysis, SA provided a simplified model of total fuel cell system cost in its 2014 report, based on system design and operational parameters that could be readily determined by a fuel cell system engineer.[372] The simplified cost model was broken down into fuel cell stack, thermal management system, humidification management system, air management system, fuel management system, and balance of plant contributions to total cost (hydrogen storage costs are treated in a separate simplified model, discussed below). Combined, the simplified system's costs require the specification of 14 individual parameters. Baseline values for these parameters that match the cost estimate for SA's 80kW representative system can all be interpreted from the data within the report. However, there are certain details of the 80kW system that do not match well with systems in FCEVs currently available or anticipated in the next few years. Of particular note is the system net power; FCEVs coming to market are nearly uniform in providing a system with 100kW net power.

To evaluate incremental costs for FCEV systems in this Draft TAR, CARB performed a study of FCEV system costs based on the simplified cost model from SA with scaling and re-parameterization in order to generate cost estimates for a 100kW net power system. First, a linear scaling relationship was assumed between net power and many of the 14 variables in the simplified cost model. For example, cell active area was one of the variables assumed to scale with power; however, neither the unit cost of platinum nor the peak air pressure in the system was assumed to scale with power. Fuel cell system costs were then calculated for varying net power and system production volumes (the effect of which was modeled after the trend between the cost and production volume for the 80kW system presented in the SA report). System cost was then parameterized according to best-fit relationships with production volume and net power assumed as independent variables, the contributions of which were multiplicative. It was found that a curve based on a power law relationship best fit the variation in system cost with respect to production volume and an exponential curve best fit the variation with respect to system power. It should be noted that these were derived from a parametric examination for best fit; no underlying mechanism was assumed to lead to these relationships. Thus, system cost was described in the form:

Equation 1. Fuel Cell System Cost

$$Fuel\ Cell\ System\ Cost = A * V_{Production}^{B} * \exp(C * P_{Net})$$

Where A, B, and C are best-fit coefficients, with A, C > 0, B < 0, and $V_{Production}$ is the annual production rate, and P_{Net} is the system net power.

Figure 5.41 shows steps of the re-parameterization process, including the variation in system cost according to annual production rate at various system net powers, the complementary parameterization (variation in system cost according to system net power at various annual production rates), and the surface of projected costs accounting for both variations. Note that these costs are only for the power-producing fuel cell system and its balance of plant components; these costs do not include the hydrogen storage tank(s) and its balance of plant. Due to the use of curve-fitting in the process (A = 70497.1, B = -0.26055, and C = 0.0056), there is some deviation for a specific system from the re-parameterization when compared to the original SA data. However, for an 80kW system at 100,000 systems per year, the deviation is less than 5 percent. Additionally, the results demonstrate the need to re-parameterize the system costs in order to be more in-line with technology seen in today's on-the-road FCEVs. For example, at 100,000 systems per year, an 80kW system is projected by this analysis to cost approximately $5,500; a 100kW system would cost approximately $6,200.

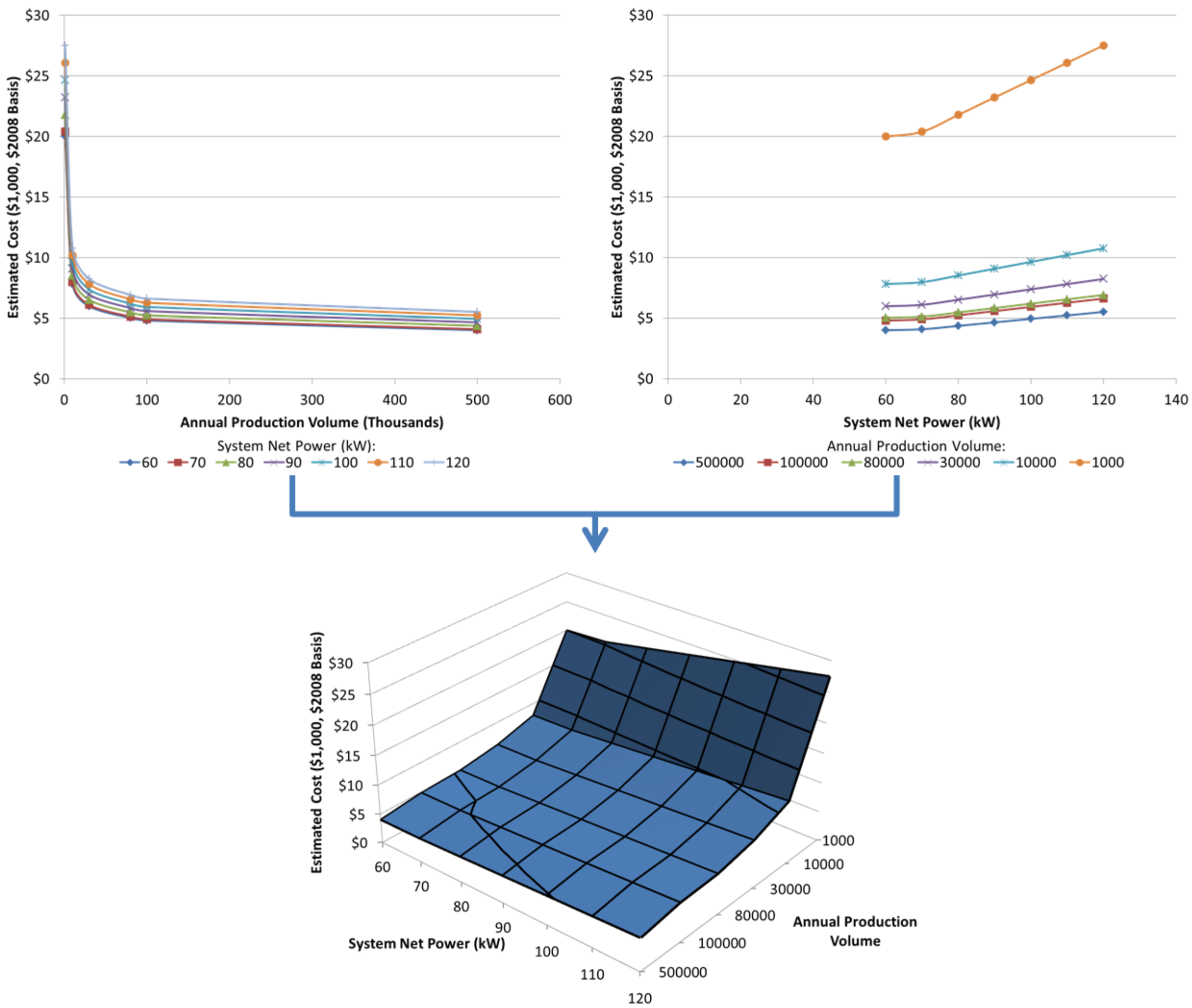


Figure 5.41 Parameterization of SA Fuel Cell System Cost Analysis (Not Including Storage Tanks) According To Production Volume and System Net Power

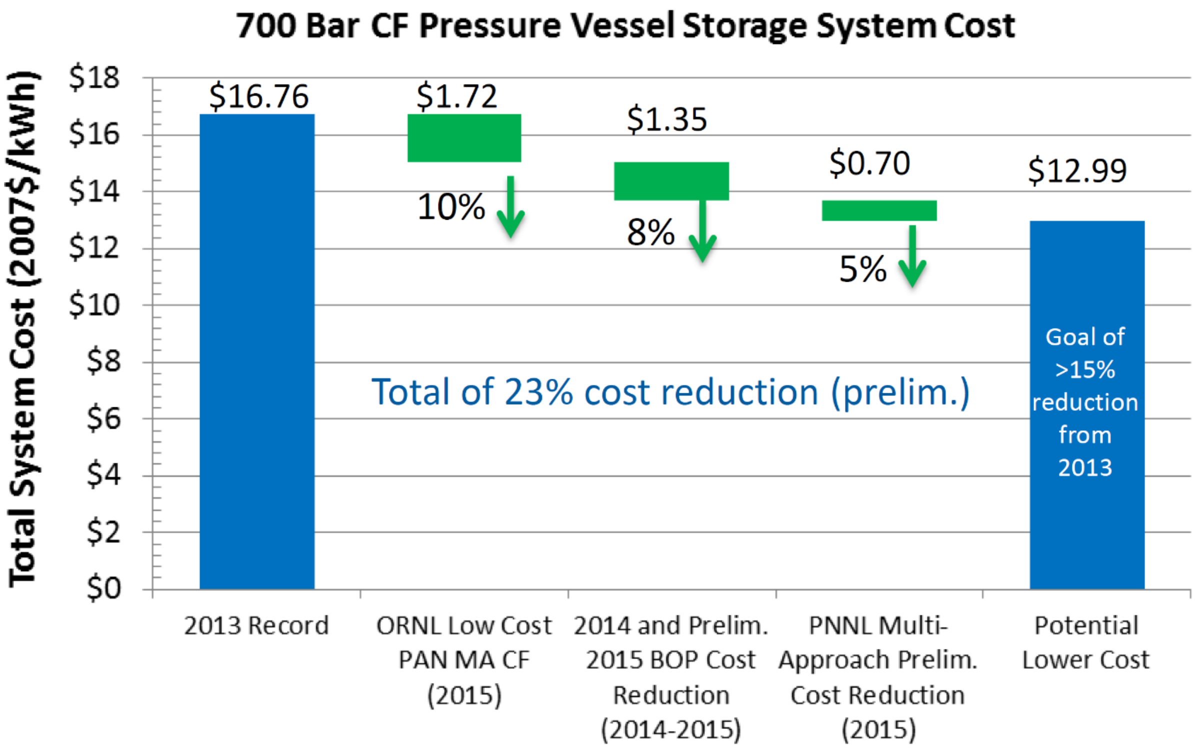


Figure 5.42 Projection of Potential Cost Reductions for 700 Bar Compressed Hydrogen Storage Tank System[373]

5.2.4.5.2.2 Hydrogen Storage Cost

SA also performs a complementary analysis of the costs for the on-board hydrogen storage system and balance of plant. Like the fuel cell system analysis, SA performs a fully detailed analysis of the predominant or conventional technology and provides estimates for emerging or new technologies and compares the costs to DOE goals. As of 2014, SA estimates that 700 bar compressed gaseous storage vessels made from carbon fiber-wrapped polymer cost $16.76/kWh (approximately $660/kg storage capacity).[374] With available or emerging technology improvements, the cost could be reduced to $12.99/kWh (approximately $510/kg). This cost is above the DOE 2020 target[375], but is noteworthy for representing a reduction greater than the DOE's hydrogen storage program's midterm milestone of 15 percent reduction from the 2013 cost estimate. The columns of incremental cost reduction in Figure 5.42 outline the technological advances that may make this lower cost system possible.

In addition to the DFMA analysis reported, SA has developed draft simplified cost models for the hydrogen storage tank and storage balance of plant costs, parameterized according to the tank volume and pressure (for tank costs) and the number of tanks (for storage system balance of plant costs). SA has shared these simplified cost models (for 10k, 200k, and 500k system annual production rates) with CARB.[376]

5.2.4.5.2.3 Combined Fuel Cell and Hydrogen Storage Systems Cost

The cost models for fuel cell and hydrogen storage systems were combined for a FCEV system cost model. CARB adopted the point estimates from the SA work directly and assuming piecewise linear fits between estimates for the 10k to 200k and 200k to 500k portions of the cost curves, separately. CARB then performed a parametric analysis for FCEV costs (stack, tank, and their respective balance of plants) of possible systems within the SA model domain for net power, production volume, number of tanks, and total kg storage to investigate the possible range of costs across the design space available to FCEV system engineers. The ranges for all variables are provided in the “All Possible Designs” column of Table 5.9.

Table 5.9 FCEV System and Production Rate Input Parameters for Assessment of Potential Costs For CARB-Modified SA Simplified Cost Models

	All Possible Designs		TAR Representative Designs	
Parameter	Minimum	Maximum	Minimum	Maximum
System Net Power (kW)	60	120	100	100
Annual Production Volume (1000s/year)	1	500	3	50
Number of Tanks	1	4	1	2
Total Storage (kg)	0.4	11	4	5

Ranges for some of the variables specified in Table 5.9 are wider than realistically expected for production vehicles; however, the wider ranges provide a fuller perspective of the potential sensitivity of total FCEV costs. Calculated full FCEV system cost ranges and average values (incorporating the fuel stack costs shown in Figure 5.41 and the SA-provided tank and tank BOP costs) are provided in Figure 5.43 as a function of annual production rate. The costs shown are indicative of a system with 2014 technology; the range of production volumes are similar to today’s volumes on the lower end and on the high end may be greater than volumes expected in 2025 (as will be discussed further below). As in the SA estimates, there is a strong dependency of total system cost on the annual production volume. Additionally, there is a fairly significant difference between the cost estimates of the most and least expensive vehicle designs; at all production rates, the most expensive system design costs approximately 30 percent more than the least expensive option. However, the distribution of prices at a given production rate was also more heavily weighted towards the higher costs, given that the mean was consistently closer to the maximum rather than the minimum (though this association decreased with increasing system production volume).

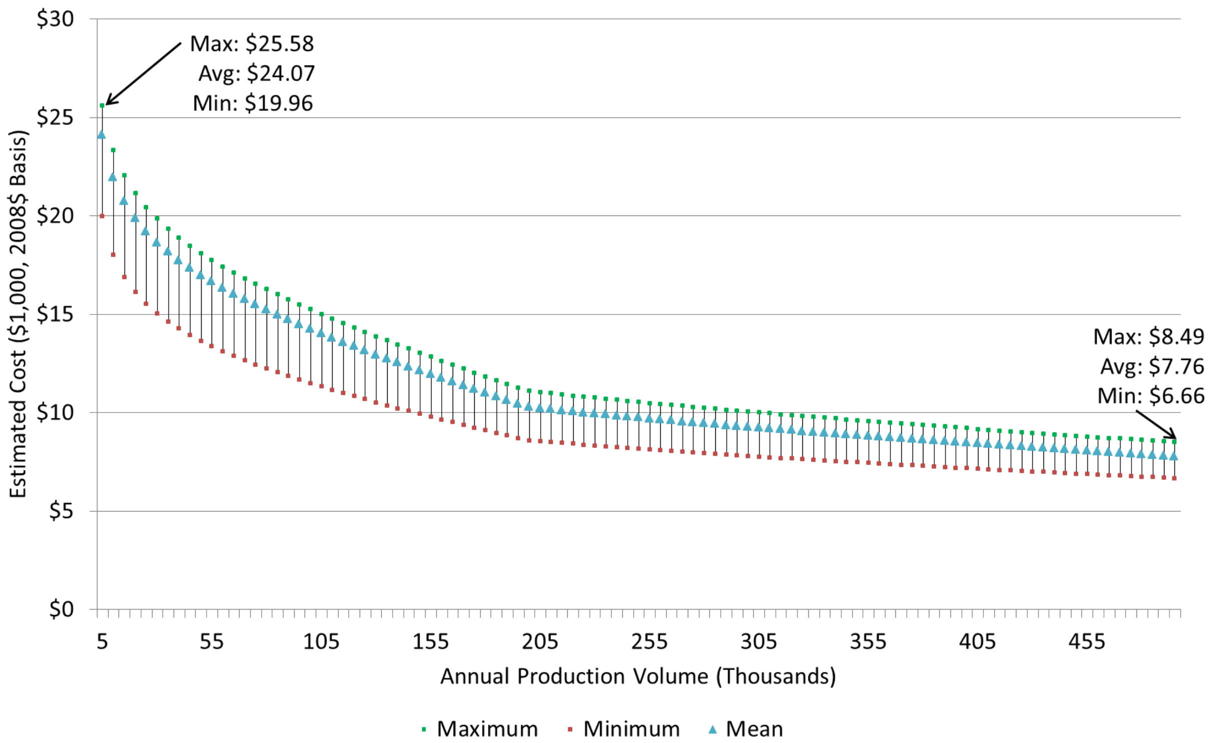


Figure 5.43 Combined Fuel Cell and Tank System Cost Estimates across Design Space of All Possible Systems within Domain of SA Simplified Cost Models

Although the values presented in Figure 5.43 are useful for understanding the potential sensitivities in FCEV system cost to system design parameters and production rates, the estimates are not quite representative of vehicles expected in the near term. For example, no vehicles are yet designed with storage divided between four cylinders; two tanks is the current industry norm. Inclusion of non-representative system designs may skew the aggregate estimates, providing misleading system cost estimates. Therefore, CARB performed a secondary analysis with a narrowed system design space to vehicles more closely matching current expectations, as shown in the "TAR Representative Designs" column of Table 5.9. Figure 5.44 provides the cumulative mean costs from this much narrower set of system designs. In contrast to Figure 5.43, Figure 5.44 does not include the range of values since the variation at a given production volume was very small due to the smaller design space. Additionally, Figure 5.44 provides individual costs for the tank, tank balance of plant, and fuel cell system (inclusive of stack and its balance of plant). According to the parametric study, fuel cell system plus hydrogen storage costs for representative vehicles range from just over $20,000 at 3,000 vehicles per year to $6,730 at 500,000 vehicles per year.

5.2.4.5.2.4 Market Projections

Multiple projections for regional and global FCEV sales (and by inference production) rates have been presented in past literature, including the ORNL[377] and NAS[378] estimates discussed in the 2010 TAR and updated estimates based on continuing work.[379,380] However, as the commercial launch of vehicles has neared and the potential growth rate in necessary supporting infrastructure has become more apparent, new trends have emerged. In particular, CARB's assessments of projected growth in infrastructure and FCEV population in California (one of the larger anticipated early adopter markets) show significant differences from previous in-state estimates like those presented in the California Fuel Cell Partnership Roadmap.[381,382]

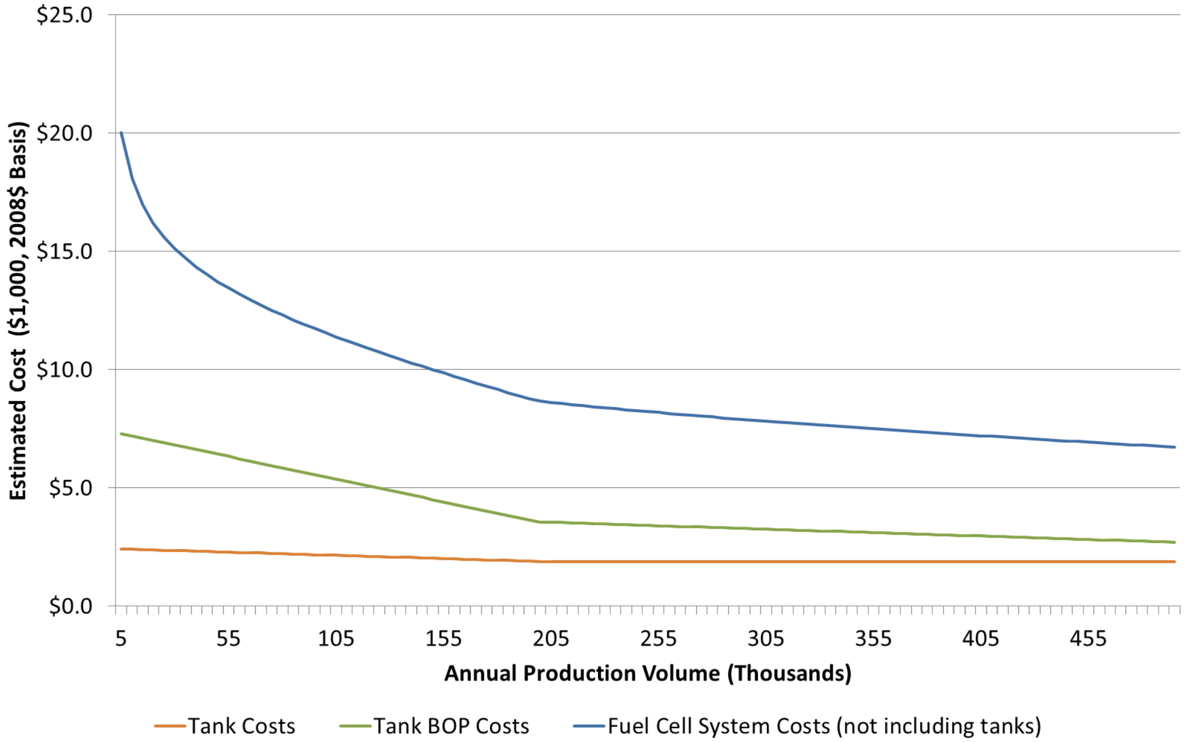


Figure 5.44 Mean Costs for All Possible Delineated Systems With Up To Two Tanks, Between 4 and 5 kg Onboard Storage, 100kW Net Power, And At Least 3,000 Units per Year

Based on its analysis showing a potential power law growth in the California FCEV stock out to 2021, CARB estimated the global early adopter market for FCEVs. First, the power law presented in the report was extrapolated out to 2025 for California. Annual changes in on-the-road vehicles were then assumed to be roughly equal to new car sales (strictly speaking the CARB on-the-road analysis includes vehicle attrition, but at the small volumes for FCEVs the absolute number of vehicles leaving the fleet is not very large). The annual California-specific FCEV sales were then compared to total light duty vehicle sales projections in CARB's EMFAC2014[383] on-road emissions inventory model. For every year from 2014 to 2025, estimates were thus generated for the California FCEV share of new light duty vehicle purchases, which grows to approximately 1.7 percent in 2025.

California, the United Kingdom, Germany, Japan, and Korea are the five main regions that FCEV and hydrogen industry stakeholders generally agree are expected to comprise the majority of the global early FCEV adopter markets. This market identification is also supported by numerous government and industry announcements regarding prospective vehicle launches and investments in supporting infrastructure. For the sake of this analysis, CARB assumed that the FCEV market share would grow in each of these market areas at the same rate calculated for

California. IHS[384,385] and ACEA[386] data and documentation were relied on to estimate the full light duty vehicle sales projections in each region out to 2025. The California-based FCEV market share growth curve was then applied to each region's new vehicle sales projection to estimate the global FCEV sales.

Figure 5.45 shows the CARB-estimated FCEV new vehicle sales in California and globally from 2014 to 2025 and the share of total new sales that these FCEV projections represent in California and globally. Global estimates are based on the IHS projection of new vehicle sales to 2021, and then extrapolated linearly from 2022 to 2025. IHS-based data predict global new auto sales will increase from approximately 86 million in 2014 to 122 million in 2025. Over the same period, California's annual FCEV sales are projected to grow from approximately 25[387] to nearly 37,000 in 2025; global FCEV sales will grow to approximately 273,000 in 2025. In 2021, California and global annual sales are projected to be 10,000 and nearly 83,000 respectively. As a point of comparison, Toyota alone has publicly announced a goal of producing 30,000 FCEVs by 2020; with increasing participation from other manufacturers, the projections of 83,000 in the same timeframe appear consistent. Assuming global production volumes for cost estimates, using the data shown in Figure 5.44 above, 2021 direct manufacturing costs for FCEV systems are projected to be approximately $12,200 which represents a cost in addition to manufacturing the remainder of the vehicle and its systems (such as the body, electric motors, battery, etc.; 2025 FCEV systems are projected to have direct manufacturing costs of approximately $8,000.

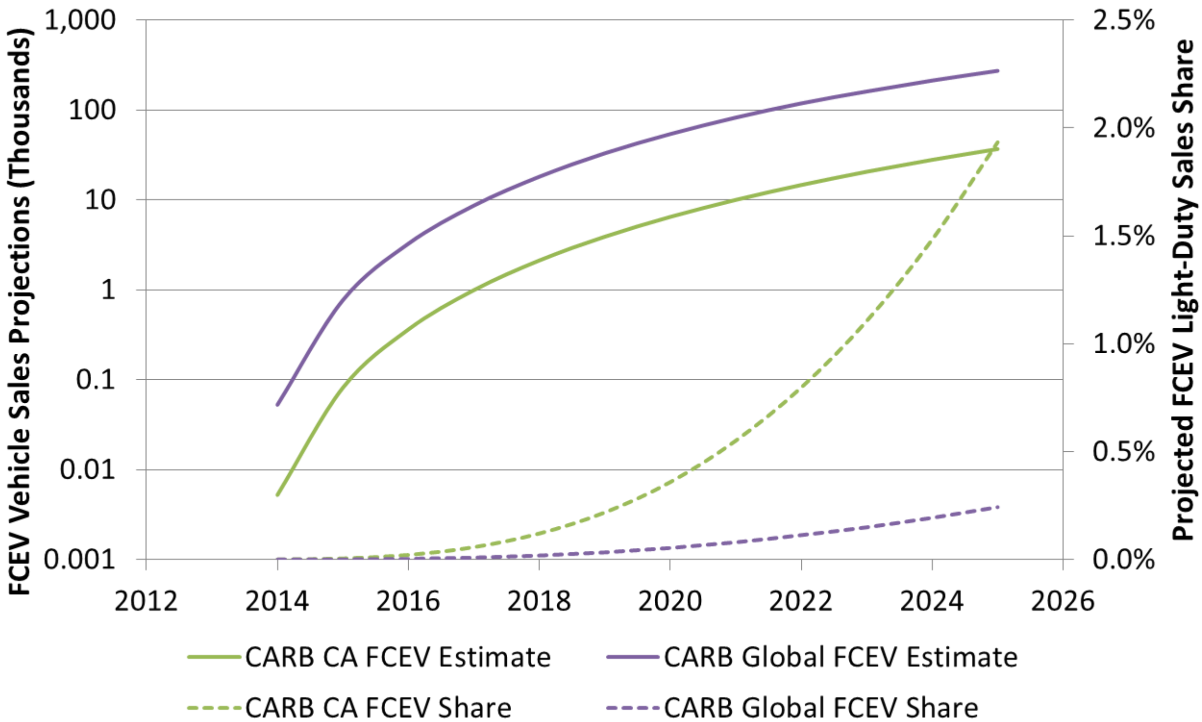


Figure 5.45 CARB Estimates Of California and Global FCEV New Vehicle Sales Estimates and Share of Total New Vehicle Sales

5.2.4.5.3 *FCEV Performance Status and Targets*

Technological status of FCEV components and systems continue to advance as commercial launches begin globally. In the 2010 TAR, then-current technological performance status was presented alongside some of the key targets for 2015 technology as defined by DOE. The status values from the 2010 TAR are reproduced in the "2010 TAR" column of Table 5.10, alongside current status values and current DOE target values. The targets shown in Table 5.10 are those most directly affecting FCEV system-wide performance; DOE additionally sets several more detailed cost and performance metrics that are not shown.

As shown in Table 5.10, the 2014 status demonstrates significant progress since the 2010 TAR. Notably, the previous vehicle range target has been met and exceeded; at the current time, there is no updated range target as commercial FCEV range has achieved relative parity with conventional vehicles. Additionally, costs have improved in the intervening years without any projected loss in system efficiency or durability. New targets have been set for fuel cell system efficiency, indicating a push to achieve performance even beyond the original program goals and maintain the goals' price and performance parity with future hybrid vehicles. Note that the Ultimate DOE Targets are not strictly defined according to a timeframe; they are goals to be achieved in order for full fleet penetration of FCEVs across various manufacturers, models, and vehicle classifications.

Table 5.10 Updated DOE Status and Targets for Automotive Fuel Cell and Onboard Hydrogen Storage Systems[388,389,390]

		2015 TAR		
	2010 TAR	2014 Status	2020 DOE Target	Ultimate DOE Target
System Efficiency	53-59%	60%	65%	70%
System Cost	$61/kW ($51/kw)[i]	$55/kW ($43/kW)[i]	$40/kW	$30/kW
Fuel Cell System Durability	2,500 hrs	3,900 hrs	5,000 hrs	8,000 hrs[iv]
Vehicle Range	254 miles	312 miles[ii]		
H2 Storage Costs	$20/kWh	$15/kWh ($13/kWh)[iii]	$10/kWh	$8/kWh

Notes:
(i) 2010 TAR value includes the then-current 2009 reported status and the 2010 update in parentheses. The 2014 includes the reported current cost status and a potential reduced cost based on available or near-term technologies in parentheses. DOE has additionally reported a 2015 updated estimate of $53/kW.
(ii) Based on US EPA rating for the 2015 Toyota Mirai.
(iii) September 2015 DOE records reports $15/kWh; contact at 2015 AMR indicated the potential for reduction to $13/kWh in very short term with application of technologies within DOE's funded Program.
(iv) Based on March 2016 communication from DOE Fuel Cell Technology Office.

The Hyundai Tucson Fuel Cell (known as the ix35 in the global market) became the first mass-produced fuel cell vehicle to enter the market,[391] indicating the development of manufacturing techniques and methods sufficient for full-scale early production volumes. Announcements from Honda indicate that it has continued to innovate for its planned vehicle release in 2016 by increasing power density more than 60 percent compared to the previously-released FCX Clarity[392] which allows an overall 33 percent reduction in the fuel cell stack volume. For the newly released Mirai vehicle, Toyota was able to eliminate the humidifier necessary in conventional fuel cell system designs by developing a Membrane Electrode Gas

Diffusion Layer Assembly that promotes self-humidification.[393] Key to the development was the design and implementation of a 3-D Fine Mesh Flow Field on the cathode, and a counter-flow field design for hydrogen and coolant on the anode, that promote the necessary exchange of reactant gases and product water within the cell and eliminate the need for the external humidifier. Toyota and Honda have also announced that their vehicles will have the ability to export power generated by the vehicle's fuel cell, allowing owners to power their homes when grid power may not be available for extended periods of time[394,395] and increasing the FCEV customer value proposition.

5.2.4.5.4 Onboard Hydrogen Storage Technology

Current FCEV designs rely on compressed gaseous hydrogen for onboard storage of the fuel. In the past, two pressures had been pursued by the majority of auto manufacturers: 350 bar and 700 bar (equivalent to 35 MPa and 70 MPa, respectively). As development has progressed, the auto industry has predominantly converged on designs for 700 bar storage, as this pressure allows for increased FCEV range. Cost status for onboard storage is presented in Table 5.10. Table 5.11 provides further detail of the technical performance status of 700 bar compressed hydrogen storage, along with other options and the current 2020 and ultimate targets specified by DOE. Although 700 bar compressed storage does not yet meet cost and performance targets, it is the most feasible among the options currently being developed and does provide sufficient range for vehicles. However, for many reasons (including system complexity of refueling stations and reductions in overall fuel lifecycle efficiencies when compressing to high pressures), there is an interest in developing technologies that can achieve the cost and performance targets while avoiding some of the challenges of 700 bar compression. The metal hydride, sorbent, and chemical storage methods all show promise for achieving these goals but are much earlier in their development and not yet implemented today.

Table 5.11 Hydrogen Storage Performance and Cost Targets and Status for Various Technologies[396]

Storage Technology	Cost (\$/kWh),[\$/kg]	Gravimetric Density (kWh/kg), [kgH_2/kg system]	Volumetric Density (kWh/L), [kgH_2/L]
2020 DOE Target	10, [333]	1.8, [0.055]	1.3, [0.04]
Ultimate DOE Target	8, [266]	2.5, [0.075]	2.3, [0.07]
700 Bar Compressed	15	1.5	0.8
350 Bar Compressed	13	1.8	0.6
Metal Hydride	43	0.4	0.4
Sorbent	15-16	1.2	0.6-0.7
Chemical	17-22	1.1-1.5	1.2-1.4

5.2.4.5.5 FCEV Commercialization Status

Currently, three automakers (Hyundai, Toyota, and Honda) have begun to offer fuel cell vehicles to the mass consumer market or announced specific near-term plans for market launch. Hyundai has offered its Tucson Fuel Cell for lease in select regions of southern California since 2014. Toyota offers its Mirai sedan in at least eight dealerships across both northern and southern California with options for both lease and purchase. Honda has unveiled its production Clarity Fuel Cell at the Tokyo Auto Show in October 2015 and announced plans for a 2016 release. Other automakers are known to be involved in the development of FCEV technology and expected to be moving towards commercial production, but have not yet made public announcements of production models or release dates.

In addition to the release of the first three mass-market FCEVs, many automakers have made public announcements of other activities related to FCEVs. A number of automakers have signed agreements to cooperatively work on development of their fuel cell systems and vehicles. BMW-Toyota, Daimler-Ford-Nissan, and GM-Honda partnerships have been announced.[397,398,399] Lexus, Toyota's luxury brand label, recently announced that its LF-LC concept is the precursor to the next LS model and is expected to include a fuel cell-powered all-wheel drivetrain.[400] This development is notable for possibly being the first announcement of a brand's flagship vehicle as an FCEV. BMW recently unveiled a fuel cell prototype of its i8 sports coupe.[401] Audi announced a fuel cell version concept, the A-7 Sportback h-tron Quattro, which is unique among current developments for being a fuel cell-powered plug-in hybrid.[402]

Collectively, these releases, partnerships, and announcements signal progress and commitment from the automotive industry towards the launch of a mass-consumer FCEV market. Many automakers and industry experts often caution that the eventual success of the FCEV market will depend heavily on the successful and widespread implementation of hydrogen fueling infrastructure. Automaker FCEV launches and production rates are likely to be closely tied to the deployment rates of fueling infrastructure and will require that fueling infrastructure development precede vehicle launches. There is currently broad support for this strategy, especially among regions where the first adopter market is anticipated to be large (California, UK, Germany, Japan, and Korea). Public and private actions have in recent years helped to accelerate much-needed activity in the fueling infrastructure industry. A more thorough discussion of this dynamic is presented in the Chapter 9 section on Hydrogen Infrastructure.

5.2.4.5.6 *Outlook for National FCEV Launch*

Compared to the status reported in the 2010 TAR, FCEVs have progressed substantially, transitioning from a demonstration and pre-commercial phase into the inception of commercial launches. This has been aided by the technological and business advancements discussed above (as well as many more) and has been reinforced by supporting policy actions, public-private partnerships, and broad stakeholder initiatives toward cleaner transportation choices. California's ZEV Mandate, Alternative and Renewable Fuel and Vehicle Technology Program, and multiple renewable energy and GHG reduction goals have and will continue to incentivize the adoption of FCEVs alongside other alternative vehicle options like BEVs. Nationally, California's ZEV regulations have been adopted by an additional 7 states (Connecticut, Maryland, Massachusetts, New York, Oregon, Rhode Island, and Vermont), collectively developing an Action Plan with the goal of enabling 3.3 million cumulative sales of ZEVs and PHEVs within those states by 2025.[403] Additionally, California, Connecticut, Maryland, Massachusetts, Rhode Island, and Vermont joined with The Netherlands, Norway, the United Kingdom, Quebec, and other jurisdictions in forming the International ZEV Alliance.[404] The Alliance has broad goals of accelerating global adoption of ZEVs, including FCEVs.

Through these actions, the west coast and the northeast states are leading early market adoption efforts for ZEVs broadly. In addition, California's AB 8 ensures funding is available (up to $20 million a year) specifically for investments in hydrogen infrastructure to encourage the role of FCEVs in meeting ZEV goals. A more thorough discussion is presented in Chapter 9, Infrastructure Assessment. Stakeholders have also begun developing plans to support the necessary infrastructure for an FCEV launch in the northeast states. Connecticut has offered grant funding for up to two stations near Hartford and multiple states in the region have leveraged resources available through the DOE-initiated public-private partnership H2USA to develop detailed infrastructure network planning. Well-planned growth of infrastructure in local early markets, that anticipates integration into larger regional and ultimately national networks, will be essential for ensuring FCEVs significantly contribute to the goals outlined by the multiple ZEV-related State initiatives.

5.2.5 Aerodynamics: State of Technology

5.2.5.1 Background

Aerodynamic drag accounts for a significant portion of the energy consumed by a vehicle, and can become the dominant factor at higher speeds. Reducing aerodynamic drag can therefore be an effective way to reduce fuel consumption and GHG emissions.

Aerodynamic drag is proportional to the frontal area (A) and coefficient of drag (C_d) of the vehicle. The force imposed by aerodynamic drag increases with the square of vehicle velocity, accounting for its dominance at higher speeds.

The coefficient of drag C_d is a dimensionless value that essentially represents the aerodynamic efficiency of the vehicle shape. The frontal area A is the cross-sectional area of the vehicle as viewed from the front. It acts with the coefficient of drag as a sort of scaling factor, representing the relative size of the vehicle shape that the coefficient of drag describes. Because the two values are related in this way, the aerodynamic performance of a vehicle is often expressed as the product of the two values, C_dA (also known as drag area).

C_d and A are determined by the design of the vehicle, and so represent the primary design paths for reduction of aerodynamic drag. The greatest opportunity for improving aerodynamic performance is during a vehicle redesign cycle, when the best opportunity exists to make significant changes to the shape or size of the vehicle. Incremental improvements may also be achieved mid-cycle as part of a model refresh through the use of revised exterior components and add-on devices. Some examples of these technologies include revised front and rear fascias, modified front air dams and rear valances, addition of rear deck lips and underbody panels, and low-drag exterior mirrors.

Aerodynamic technologies are divided into passive and active technologies. Passive aerodynamics refers to aerodynamic attributes that are inherent to the shape and size of the vehicle, including any components of a fixed nature. Active aerodynamics refers to technologies that variably deploy in response to driving conditions. These include technologies such as active grille shutters, active air dams and active ride height adjustment.

Significant variations in C_dA can be observed across vehicle classes and among individual vehicles within a class.[405,406,407] Within a class, drag coefficients tend to vary more than frontal areas. Frontal areas are in part a function of interior passenger and cargo space, and therefore tend to track with the interior space expectations associated with a vehicle class. In contrast, drag coefficients are largely a function of body styling and may vary significantly with relatively small changes in shape and exterior treatment.

5.2.5.2 Aerodynamic Technologies in the FRM

Based in part on the 2011 Ricardo study and public technical literature, the FRM analysis projected that a 10 to 20 percent fleet average reduction in aerodynamic drag should be attainable. Based on EPA vehicle modeling and the Ricardo study, each 10 percent reduction was associated with an incremental reduction in fuel consumption and CO_2 emissions of 2 to 3 percent for both cars and trucks.

The FRM considered two levels of aerodynamic improvements, called Aero1 and Aero2. The first level, Aero1, represented a 10 percent reduction in drag from the baseline by means of passive body features such as front/rear bumper air dams, front and/or rear wheel tire spats/dams, minimal underbody panels, and redesigned mirrors or rear spoilers. Aero1 was estimated to result in an effectiveness of 2.3 percent for all vehicle classes. The agencies estimated the DMC of Aero1 at $41 (2010$) applicable in MY2015. The second level, Aero2, represented a 20 percent reduction from the baseline (nominally 10 percentage points incremental to Aero1), and included active technologies such as active grille shutters and active ride height, as well as passive technologies such as rear visors, larger under body panels and low-profile roof racks. Aero2 was estimated to provide an effectiveness of 4.7 percent relative to a baseline vehicle. The agencies estimated the DMC of Aero2 at $123 (2010$) incremental to Aero1, applicable in MY2015.

In the FRM analysis, fleet penetration of Aero1 was uncapped for 2012 through 2025. Fleet penetration of Aero2 was capped at 80 percent for 2021 and uncapped thereafter.

Because the full benefit of active aerodynamic technologies may fail to be reflected in standard test cycles, the agencies provided for active aerodynamic technology to be eligible for credit under the Off-Cycle Credit Program. Off-cycle credits are discussed in a separate chapter of this Draft TAR.

5.2.5.3 Developments since the FRM

Since the FRM, the agencies have taken several steps to further evaluate the feasibility, cost and effectiveness assumptions of Aero1 and Aero2. We followed industry developments and trends in application of aerodynamic drag technologies to light-duty vehicles. We did this by gathering input from stakeholders through meetings with OEMs, suppliers and other interested parties, and also by attending conferences and trade shows and regularly monitoring the press and technical literature.

EPA also participated in a joint test program with Transport Canada, Environment and Climate Change Canada, and National Research Council Canada to examine the aerodynamic performance and effectiveness of various aerodynamic devices and strategies. This program was conducted in four phases over three years, and examined aerodynamic technologies as currently implemented in a selection of production vehicles, and the effectiveness of potential improvements that have yet to be implemented. Results of this program also were used to evaluate the 2012 FRM assumptions about off-cycle benefits of active aerodynamic technologies and the associated default credit values.

Additionally, EPA coordinated with California Air Resources Board (CARB) to share the results of a research study performed for CARB by Control-Tec, a company that specializes in automotive data analytics. This study is described in more detail in Appendix A, "CARB Analysis of Vehicle Load Reduction Potential For Advanced Clean Cars." The study provided information helpful to assess the penetration of aerodynamic and other road load technologies in the MY2014 fleet as represented nationally and in California. EPA also began a process to compare the fleet aerodynamic performance of MY2014 vehicles as represented in the study to those of MY2008 by using EPA certification data to estimate aerodynamic performance of the 2008 fleet (the baseline MY used for the 2017-2025 final rule). EPA also examined the coefficients of drag reported in the Control-Tec data to determine if any vehicle categories are experiencing difficulties in progressing toward the assumed aerodynamic improvements.

The 2015 NAS report (p. 6-3, and Finding 6.1, p. 6-51) also examined the agencies' assumptions for feasibility, cost, and effectiveness of Aero1 and Aero2, and concluded that the assumptions appear to be reasonable for the 2020-2025 time frame (National Research Council, 2015). The additional analyses outlined above further informs this conclusion. Also, the agencies considered redefining the specific technologies assumed for each level to better align with what has been learned about actual fleet implementation since the 2012 FRM.

5.2.5.3.1 Industry Developments

Since the 2012 FRM, the industry is seeing high levels of implementation of many passive aerodynamic technologies. In addition, active aerodynamic technologies are seeing increasing implementation, primarily in the form of active grille shutters, which are now offered by a number of manufacturers. Although relatively low penetration of other active technologies (such as active ride height and wheel shutters) has occurred, this may be the result of a natural focus on the most cost effective technologies in the early years of the program. These active technologies will remain available for implementation in the future as other aerodynamic technologies begin to reach maximum penetration.

In January 2015, EPA staff attended the 2015 North American International Auto Show (NAIAS) in order to gather information about the state of implementation of various aerodynamic technologies in the vehicles represented at the show. A total of 76 vehicles that appeared to employ aerodynamic devices were viewed, across more than a dozen manufacturers. A memorandum[408] describing this informal survey is available in EPA Docket EPA-HQ-OAR-2015-0827. Although the sample was casually collected and therefore was not random, the information gathered informs our understanding of industry activity in application of aerodynamic technology to production vehicles. Table 5.12 shows a breakdown of the aerodynamic devices and technologies that were observed in these vehicles:

Table 5.12 Aerodynamic Technologies Observed in Vehicles Investigated at the 2015 NAIAS

Technology		Number of vehicles equipped	Percentage equipped
Active Grill Shutters		14	18%
Underbody Panels	front (full)	28	37%
	front (partial)	22	29%
	middle or side	27	36%
	rear	2	3%
Wheel Dams	Front	56	74%
	Rear	59	78%
Front Bumper Air Dam		18	24%
Total vehicles inspected		76	

Based on this assessment, it is clear that manufacturers are choosing to implement passive and active aerodynamic devices as permitted by the various levels of vehicle redesign or model refresh represented in the displayed vehicles. Because many of the vehicles displayed at the show are not completely new designs, the bulk of these aerodynamic improvements were likely added in a non-optimized fashion; that is, added to an existing design rather than fully integrated into a new vehicle design. As a result, it is likely that opportunity for better-optimized application of both passive and active aerodynamic technologies will continue to exist as these vehicles gradually enter redesign phases and entirely new designs are introduced.

One example of the potential for optimized application of aerodynamic technologies can be seen in the redesigned MY2015 Nissan Murano. The exterior of this vehicle was completely redesigned from its MY2003-2014 generation with the goal of minimizing aerodynamic drag by combining passive aerodynamic devices with an optimized vehicle shape. [409] The primary passive devices employed include optimization of the rear end shape to reduce rear end drag, and addition of a large front spoiler to reduce underbody air flow and redirect it toward the roof of the vehicle, thus augmenting the rear end drag improvements. Other passive improvements include plastic fillet moldings at the wheel arches, raising of the rear edge of the hood, shaping of the windshield molding and front pillars, engine under-cover and floor cover, and air deflectors at the rear wheel wells. An active lower grille shutter also redirects air over the body when closed. Together, these measures give the 2015 model a drag coefficient of 0.31, representing a 16 to 17 percent improvement over the 0.37 C_d of the previous model.

Another example of aerodynamics improvement can be found in the redesigned 2015 Acura TLX Sedan. According to a 2015 presentation by Acura,[410] this vehicle was redesigned with the help of computational fluid dynamics (CFD) as well as wind tunnel and real-world coastdown testing to achieve a 15 percent lower C_dA compared to the 2012 model year Acura TL. The frontal area was described as having been reduced by 1.5 percent, suggesting that C_d alone was improved by about 13.7 percent to achieve this result. Some of the methods used included eliminating welds from the forward and rearward edges of the wheel arches by use of a roller hem wheel arch design in place of spot welds, and smoothing transitions between body panels in this area. These results were said to be achieved with no compromises in interior space or crash safety by Acura.

Another example of the aerodynamic improvements available in a full redesign is seen in the all-new Ford F-150 pickup truck. An article in Motor Trend[411] highlighted seven distinct tactics by which drag was reduced, including: air ducts added under the headlamps to reduce wheel-generated air wake; trim pieces strategically placed to avoid trapping air; box geometry modified for better airflow without reducing the cargo volume; adding spoiler features to the tailgate; angling of rear and front corners; and a flush mounted windshield. The 2015 model is touted as being slightly larger than the previous model, indicating that the benefit of these improvements was achieved without loss of cargo space.

5.2.5.3.2 *Joint Test Program with Transport Canada*

In 2013 a Joint Aerodynamics Assessment Program was initiated between Transport Canada (TC), Environment and Climate Change Canada (ECCC), National Research Council (NRC) of Canada, and EPA.[405] The participating organizations and their respective programs share mutual interests in the primary goals of the program, which are: (a) to quantify the aerodynamic drag impacts of various OEM aerodynamic technologies, and (b) to explore the improvement potential of these technologies by expanding the capability and/or improving the design of current state-of-the-art aerodynamic treatments.

This program provides an important contribution to the agencies' technical assessment by offering an opportunity to further validate the feasibility and effectiveness estimates for the passive and active aerodynamic technologies assumed for Aero1 and Aero2.

The program also provides an opportunity to further validate off-cycle credits that were assigned to active aerodynamics in the 2012 FRM. Two active aerodynamic technologies were identified for pre-defined credit availability of specified amount: Active Grille Shutters and Active Ride Height. 86.1869-12 (b)(1)(iv). The default value for these credits offered were determined in large part by analysis using an early version of the EPA ALPHA model to simulate aerodynamic improvements for varying C_d inputs. A key assumption in development of these credits was that active technologies only affect the coefficient of drag, which is assumed to be constant over the speed range of the test. Further validation of this assumption, and of the list of creditable active technologies assumed to be available in production vehicles during the time frame of the rule, would strengthen the basis of the program. A total of four project phases consisting of twenty-five test vehicles in all EPA vehicle classes was undertaken by the project partners.[406]

Active technologies evaluated by this program include: active grille shutters (opened, closed, intermediate positions, speed effects, yaw effects, leakage effects); a detailed sealing study (i.e. grille shutter sealing; external grille shutter concept); and an active ride height concept (i.e. manual ride height adjustment on vehicles not necessarily equipped to do so from factory). Passive technologies include: Air dams (front bumper and wheels); active front bumper air dams (concept/prototype); underbody smoothing panels (both OEM and idealized prototypes); larger-than-baseline wheel/tire packages; wheel covers (i.e. solid hubcaps); and miscellaneous improvements (including front license plates, decorative grille features and smoothing, tailgates (opened/closed/removed), and tonneau covers). Significantly, NRC facilities include a 9 meter x 9 meter rolling road/moving floor wind tunnel that allows testing of full scale vehicles for accurate comparison of aerodynamic performance with and without active technologies. Listed technologies were not evaluated on every vehicle due to stock configuration, timing and funding.

One valuable outcome of this testing was further validation of the default credit menu values established in the 2012 FRM for active aerodynamic technologies under the off-cycle credit program. Phase 1 of the Joint Program evaluated the aerodynamic performance of eleven (11) vehicles (3 small cars, 5 midsize cars, 2 sport utility vehicles and 1 pickup truck). The conclusions of the Phase 1 study indicated that the active aerodynamic technologies studied are within the range of the default menu credit values anticipated in the 2017-2025 GHG rule TSD[136] for active aerodynamic off-cycle credits.

The Phase 1 study also concluded that the benefit of active grille shutters is constant across the operating speed range, confirming one key assumption in the FRM analysis. In addition, it concluded that passive technologies may each improve the aerodynamics of future vehicles by 1 to 7 percent depending on the passive technology employed and overall vehicle design. This conclusion was based on individual component installation, and does not account for synergistic component effects, nor the effect of integrating passive technologies into an overall vehicle redesign.

Depending on stock vehicle equipment, sometimes it was necessary to fabricate prototype components to make an A to B comparison possible. Prototype components were constructed by study partners Roechling Automotive and Magna International, both of which are Tier 1 suppliers of various aerodynamic technologies to the industry.

Effectiveness values identified in Phase 1 of the Joint Program are shown in Table 5.13.

Table 5.13 Aerodynamic Technology Effectiveness from Phase 1 of Joint Aerodynamics Program

Aero Feature (A-B Testing)		Aero Drag Reduction (%)	Comments
Fixed Air Dam-Bumper		1 - 6%	OEM stock components
Active Air Dam – Bumper (Conceptual)		4 - 9% (fixed air dam + 3%)	Fixed, prototype parts w/ lowest deployment height used
Fixed Air Dam-Wheels		1% (front)/4.5% (front & rear)	
Underbody Panels		1-7% (stock OEM)	Addtn'l 0.5%-4% w/ full body panels. Dodge Ram prototype: 8%
Increased Tire Size		-2.0 - 3.2%	17"/18" stock OEM rims vs. 22" optional OEM rims
Wheel Covers		1.5 - 3%	Solid wheel covers only; brake cooling affects not considered
Front License Plates		+/- 0.3%	Negligible impact
Decorative Grille Optimization		1.6%	Smoothing of grille features; function vs. styling trade-offs
Pick-up Tailgates	Open	-5.2%	
	Removed	-7.5%	Open tailgate + 2.3%
Pick-up Tonneau Cover		3.7%	

Phase 2 of the Joint Program[412] investigated similar technologies using the same methodology of Phase 1. Vehicles studied in Phase 2 included nine vehicles including one small car (2014

Chevy Spark BEV), one midsize car (2014 Chevy Impala mild hybrid), one large car (2014 Ford Taurus SEL), one minivan (2014 Honda Odyssey), and five SUV/crossovers (2014 Subaru Crosstrek Hybrid, 2014 Ford Edge SE EcoBoost, 2014 BMW X5, 2015 Nissan Pathfinder, and 2015 Chevy Tahoe LS). Active technologies studied included: active grille shutters (including yaw sweep) and active ride height (stock and conceptual). Passive technologies included: underbody panels and air dams, and optional wheel packages. Other technical assessments included turbulent flow impacts and yaw sweep impact. To take into account the fact that vehicles are generally traveling in a windy environment from potentially all wind azimuth angles, the wind averaged drag area was calculated for all cases where a yaw sweep was carried out.

Results of the Phase 1 and Phase 2 studies further support the conclusion that the Aero1 and Aero2 goals appear to be attainable, with many individual technologies that have not yet been implemented on a majority of light-duty vehicles showing capability for significant improvements in drag area.

Phase 3 involved the testing of 4 vehicles: one sedan (2014 Nissan Versa Note Plus), one minivan (2015 Toyota Sienna), and two sport utility vehicles (2014 Jeep Cherokee, 2015 Nissan Murano)[407]. Phase 4 involved the retesting of previous vehicles with a focus on turbulent flow including a small car (2014 Chevrolet Spark) and a pick-up truck (2015 Ford F-150)[HH].

One significant outcome of the study was the identification of several high-impact areas for drag reduction. For example, the study found that lowering the ride height while pitching the vehicle nose down could provide significant drag reduction. Also, it was shown that certain combinations of technologies (such as active grille shutters with air dams) often acted with positive synergy (i.e. more than additive) to result in greater reductions in overall drag than the individual technologies alone would suggest.

It should be noted that the Phase 1 and Phase 2 studies found that some technologies could potentially increase drag area if poorly applied, and that some individual technologies did not appear to be fully additive when combined with certain others. For example, presence of active air dams was seen in some cases to reduce the effectiveness of adding underbody coverings. Further, combination of active air dams or underbody coverings with active ride height tended to reduce the effectiveness of active ride height. This latter result corroborates with information related to EPA in an OEM meeting that suggested that vehicles that already have underbody coverings are not as highly responsive to adjustments in ride height. On the other hand, combining certain aerodynamic technologies (for example, active grille shutters with air dams) often demonstrated higher total drag reduction than individual additive measurements would have suggested.

All phases of the study found that lowering ride height while pitching the vehicle at highway speeds (for example, 40mm in the front and 20mm in the rear) provided significant drag reduction for all vehicles. The highest reduction was observed for the Large Car classification. Additionally, underbody panels that are extended to cover the entire surface area underneath the vehicle (full underbody cover) proved to be an efficient way to reduce drag.

[HH] The Phase 4 report was not yet finalized at the time of Draft TAR publication.

It was also found that yaw angle had a significant effect on measurement. Some technologies that perform well at 0° wind angle were found to perform relatively poorly at different wind angles (for example, at 8° to 10°, the differences were quite significant). It was also found that some technologies that tend to work well for one class of vehicle may not perform well for another vehicle class (for example, air dams in turbulent flow conditions were shown to perform better on SUVs than on Large Cars.

In an effort to better represent real-world aerodynamic performance of aerodynamic technologies, the study also investigated the effect of turbulent flow conditions on aerodynamic measurements. The study produced an extensive data set comparing steady smooth and turbulent flow performance for most of the vehicle classes. The study found that both turbulent flow and yaw angle can be important to understanding the effectiveness of aerodynamic technologies in real-world use.

5.2.5.3.3 CARB Control-Tec Study

In 2013, the California Air Resources Board (CARB) issued a Request for Proposal[413] to solicit research on the potential for vehicle road load reduction technologies to reduce the CO_2 emissions of future vehicles. The work was proposed to support the mutual interests of the California Advanced Clean Cars Program and the agencies' midterm review effort. An automotive research firm called Control-Tec LLC was contracted by CARB to perform this work and the work was completed in March 2015[414].

The objectives of the research included: determining vehicle load reduction technologies included in or applicable to the California light-duty fleet; identifying the extent to which these technologies have been applied to this fleet; developing a "what-if" scenario by applying best-in-class load reduction technologies to the future fleet; and conducting projections to determine the potential GHG reductions if all future vehicles were to adopt the best-in-class technologies. Because aerodynamic technology is one of the components of road load technology, the results of this study are very relevant to evaluating the feasibility and effectiveness of aerodynamic technologies assumed in the FRM.

As described in Appendix A (CARB Analysis of Vehicle Load Reduction Potential For Advanced Clean Cars), the study defined the best-in-class application of aerodynamic technology in the MY2014 fleet as being represented by the 90th-percentile drag coefficient observed in that fleet within a given vehicle class. Depending on vehicle class, this represented an 8 percent to 12 percent improvement in drag coefficient over the median vehicle in the class. Applying this degree of improvement to all of the vehicles in each respective class resulted (by simulation) in an improvement of about 5 g/mi in CO_2 emissions for the fleet overall, or about 2 percent, relative to a 2014 baseline value of 263 g/mi. It should be noted that the study was by its nature limited only to consideration of aerodynamic technologies that existed in the MY2014 fleet, and therefore did not consider any more advanced examples of drag reduction technology that may now be present in MY2015 or 2016 vehicles, nor any further improvements that may be achieved by 2022-2025.

5.2.5.3.4 EPA Study of Certification Data

The CARB/Control-Tec project created additional opportunities for EPA to study aerodynamic technology implementation since the FRM. Control-Tec had based its analysis upon a large database of performance attributes of about 1,350 MY2014 vehicles, including aerodynamic attributes such as drag coefficients and frontal area. This database included C_dA values from various sources such as publicly available information and manufacturer reports. Control-Tec had estimated values that were unavailable from these sources by a proprietary methodology that estimated C_dA values by mathematical analysis of coastdown coefficients found in manufacturer certification data. This resulted in an unusually comprehensive and inclusive picture of aerodynamic performance characteristics of MY2014 light-duty vehicles.

A similar methodology might be used to help track adoption of technologies over time by making it possible to generate fleet-wide estimates of C_dA for any model year using manufacturer certification data as a basis. This would provide a means to estimate the degree of aerodynamic improvement that has been implemented since the 2008 model year baseline, by using such a methodology to generate a database of fleet aerodynamic performance for MY2008 and comparing it to that of MY2014.

While the Control-Tec methodology for estimating drag characteristics from test data is proprietary, an understanding of the basic physics principles involved allowed EPA to study the possibility of developing a similar methodology for estimating drag performance from coastdown performance data contained in certification records. Figure 5.46 shows a frequency distribution of C_dA values for MY2008 and MY2014 derived from a preliminary exploratory analysis. While some improvement in drag performance appears to have occurred, the overall magnitude of change is quite small; particularly noting that estimated C_dA has increased from 0.942 in 2008 to 0.996 in 2014.

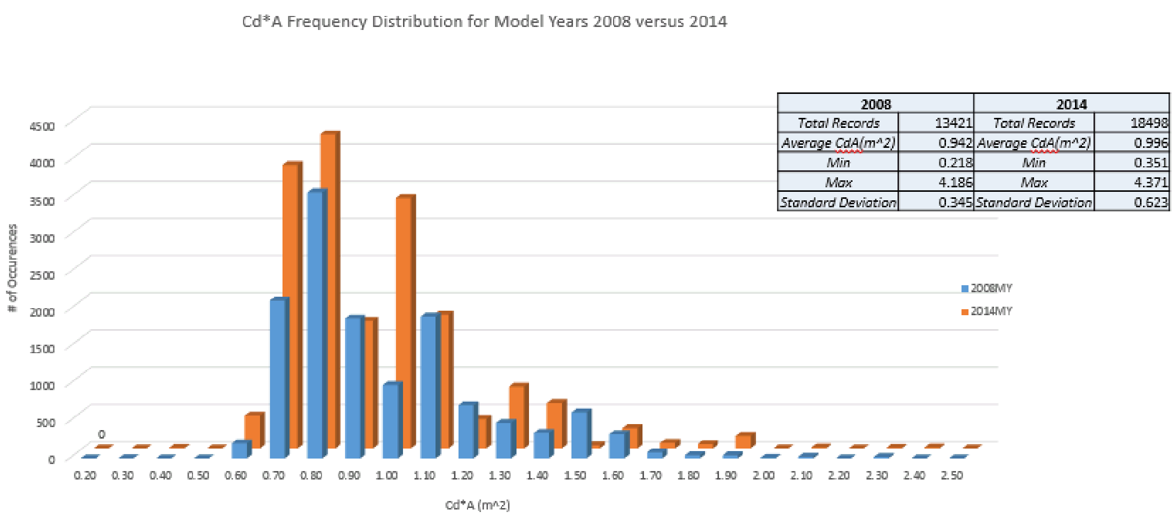


Figure 5.46 Distribution of Estimated CdA for MYs 2008 and 2014 Derived from Certification Data

Since the Control-Tec database relies largely on manufacturer-reported or publicly available information as well as analytically derived figures, EPA sought paths to further validate the proprietary methodology behind the figures. EPA recognized that the Joint Aerodynamic Assessment Program (previously described) could provide a sample of accurately measured C_dA values that could be used to validate the Control-Tec methodology in this application. Although this analysis was not completed in time for publication of this Draft TAR analysis, results may become available to further inform the agencies' analysis.

EPA also plans to more closely examine the Control-Tec database to look at various vehicle categories and examine the span between the best and worst aerodynamically performing vehicles, using C_dA values as a metric. The size of the span as it exists in a given category of current MY vehicles might be suggestive of the remaining potential for aerodynamic improvement within that category. Although this analysis was not completed in time for the publication of this Draft TAR analysis, results may become available to further inform the analysis in the future.

In general, it appears that manufacturers are aggressively pursuing improvements to aerodynamic drag across a wide range of vehicles, particularly for vehicles where the efficiency improvement is highly cost effective. For example, in 2015 Toyota announced[155] that the 2016 Prius would have a drag coefficient of 0.24, which not very long ago was considered to be an extremely low value for a production vehicle. This value is expected to be eclipsed by vehicles such as the Tesla Model 3, which has been described as targeting a drag coefficient of about 0.21. Examples such as these further support the attainability of the aerodynamic technology cases Aero 1 and Aero 2.

5.2.5.3.5 Conclusions

In summary, the agencies evaluated the feasibility, cost and effectiveness of the two levels of aerodynamic technology (Aero1 and Aero2) by the efforts described above. The agencies' analysis of industry developments shows that manufacturers are already implementing many passive and active aerodynamic technologies in MY2015 vehicles, with significant opportunity remaining to further apply these technologies in a more optimized fashion as vehicles enter redesign cycles in the future. The findings of the Joint Aerodynamics Assessment Program and the Control-Tec analysis also lend support to the feasibility of the 10 percent and 20 percent effectiveness levels assumed for Aero1 and Aero2. The NAS report likewise generally supported the assumptions for Aero1 and Aero2 as being applicable to the 2020-2025 time frame.

Some tradeoffs and interactions among specific aerodynamic technologies were identified that suggest there could be value in refining the specific combinations of technologies that are assumed to make up the Aero1 and Aero2 packages.

For the cost and effectiveness assumptions the agencies are adopting for the GHG Assessment and CAFE Assessment for this Draft TAR analysis, see Sections 5.3 and 5.4.

5.2.6 Tires: State of Technology

5.2.6.1 Background

Tire rolling resistance is a road load force that arises primarily from the energy dissipated by elastic deformation of the tires as they roll. Deformation, and hence rolling resistance, for a given tire design is largely a function of vehicle weight and is fairly constant across the normal range of vehicle speeds. Rolling resistance therefore carries an ever-present and often quite significant effect on fuel economy and CO_2 emissions.

Tire design characteristics (for example, materials, construction, and tread design) have a strong influence on the amount and type of deformation and the energy it dissipates. Designers can select these characteristics to minimize rolling resistance. However, these characteristics may also influence other performance attributes such as durability, wet and dry traction, handling, and ride comfort.

Low rolling resistance tires are increasingly specified by OEMs in new vehicles, and are also increasingly available from aftermarket tire vendors. They commonly include attributes such as: higher inflation pressure, material changes, tire construction optimized for lower hysteresis, geometry changes (e.g., reduced aspect ratios), and reduced sidewall and tread deflection. These changes are commonly accompanied by additional changes to vehicle suspension tuning and/or suspension design to mitigate any potential impact on other performance attributes of the vehicle.

5.2.6.2 Tire Technologies in the FRM

In the 2012 FRM, the agencies considered two levels of low rolling resistance technology, known as LRRT1 and LRRT2. The first level, LRRT1, was defined as a 10 percent reduction in rolling resistance from a base tire, made possible by methods such as increased tire diameter and sidewall stiffness and reduced aspect ratios (coupled with reduction in rotational inertia). The second level, LRRT2, was defined as a 20 percent reduction in rolling resistance from a base tire. LRRT2 was associated with more advanced approaches such as use of advanced materials and complete tire redesign.

Based on the 2011 Ricardo study, the agencies estimated the effectiveness of LRRT1 as 1.9 percent and the effectiveness of LRRT2 as 3.9 percent for all vehicle classes. This represents a 2.0 percent incremental effectiveness increase from LRRT1 to LRRT2.

In the 2012 FRM, NHTSA assumed that the increased traction requirements for braking and handling for performance vehicles could not be fully met with the LRRT2 designs in the MYs 2017-2025 timeframe. For this reason the CAFE model did not apply LRRT2 to performance vehicle classifications. However, the agency did assume that traction requirements for LRRT1 could be met in this timeframe and thus allowed LRRT1 to be applied to performance vehicle classifications in the MYs 2017-2025 timeframe.

In the 2012 FRM, the agencies estimated the incremental DMC for LRRT1 at an increase of $5 (2007$) per vehicle, adjusted to 2010 dollars[II]. This included costs associated with five tires per vehicle: four primary and one spare tire. There was no learning applied to this technology due to the commodity based nature of this technology. The agencies considered LRRT1 to be fully learned out or "off" the learning curve (i.e., the DMC does not change year-over-year) and have applied a low complexity ICM of 1.24 through 2018, and then 1.19 thereafter, due to the fact that this technology is already well established in the marketplace.

Prior to the FRM, EPA, NHTSA, and CARB met with a number of the largest tire suppliers in the United States to analyze the feasibility and cost for LRRT2. The suppliers were generally optimistic about the ability to reduce tire rolling resistance in the future without the need to sacrifice traction (safety) or tread life (durability). Suppliers all generally stated that rolling resistance levels could be reduced by 20 percent relative to then-current tires by MY2017. As

[II] We show dollar values to the nearest dollar. However, dollars and cents are carried through each agency's respective analysis. Thus, while the cost for lower rolling resistance tires in the 2012-2016 final rule was shown as $5, the specific value used in that rule was $5.15 (2007$) and is now $5.40 (2010$). We show $5 for presentation simplicity.

such, the agencies agreed, based on these discussions, to consider LRRT2 as initially available for purposes of the FRM analysis in MY2017, but not widespread in the marketplace until MYs 2022-2023. In alignment with introduction of new technology, the agencies limited the phase-in schedule to 15 percent of a manufacturer’s fleet starting in 2017, allowing complete application (100 percent of a manufacturer’s fleet) by 2023.

EPA projected fleet penetration of low rolling resistance technology based on penetration of LRRT2. Because LRRT1 and LRRT2 technology are both defined as incremental to a baseline vehicle, increased use of LRRT2 would displace use of LRRT1. LRRT2 technology was projected to essentially replace LRRT1 technology by the later years of the rule. Penetration of LRRT2 was projected to achieve 73 percent fleet penetration by 2021 and 97 percent by 2025.

For this Draft TAR analysis, the agencies continue to believe that this schedule aligns with the necessary efforts for production implementation, such as system and electronic system calibration and verification.

At the time of the 2012 FRM, LRRT2 technology did not yet exist in the marketplace, making cost estimation challenging without disclosing potentially confidential business information. To develop a transparent cost estimate, the agencies relied on LRRT1 history, costs, market implementation, and information provided by the 2010 NAS report. The agencies assumed LRRT1 first entered the marketplace in the 1993 time frame with more widespread adoption being achieved in recent years, yielding approximately 15 years to maturity and widespread adoption. Then, using MY2017 as the starting point for market entry for LRRT2 and taking into account the advances in industry knowledge and an assumed increase in demand for improvements in this technology, the agencies interpolated DMC for LRRT2 at $10 (2010$) per tire, or $40 ($2010) per vehicle. This estimate was seen to be generally fairly consistent with CBI suggestions by tire suppliers. The agencies did not include a cost for the spare tire because we believe manufacturers are not likely to include a LRRT2 as a spare given the $10 DMC. In some cases and when possible pending any state-level requirements, manufacturers have removed spare tires replacing them with tire repair kits to reduce both cost and weight associated with a spare tire. The agencies continued to consider this estimated cost for LRRT2 to be applicable in MY2021. Further, the agencies considered LRRT2 technology to be on the steep portion of the learning curve where costs would be reduced quickly in a relatively short period of time. The agencies applied a low complexity ICM of 1.24 through 2024, and then 1.19 thereafter. The ICM timing for LRRT2 was different from that for LRRT1 because LRRT2 was not yet being implemented in the fleet.

For the 2012 FRM, the agencies also considered introducing a third level of rolling resistance reduction, LRR3, defined as a 30 percent reduction in rolling resistance from the baseline, but ultimately declined to do so. See 77 FR and the 2012 TSD, p. 3-210.

5.2.6.3 Developments since the FRM

The 2015 NAS report (p. 6-35, and Finding 6.10, p. 6-53) examined the agencies' assumptions for feasibility, cost, and effectiveness for the two levels of rolling resistance, LRRT1 and LRRT2. The report concluded that the feasibility and effectiveness projected by the agencies for a 20 percent reduction in rolling resistance in the 2020-2025 time frame appears to be reasonable. With regard to costs, the Committee substantially agreed with the costs projected by the agencies, while noting that the problem of maintaining tread wear and traction requirements while reducing rolling resistance continues to present engineering challenges that could affect tire costs.

Since the FRM, the agencies have taken several additional steps to further validate the feasibility, cost, and effectiveness assumptions of LRRT1 and LRRT2.

We followed industry developments and trends in application of low rolling resistance technologies to light-duty vehicles. We did this by gathering input from stakeholders through meetings with OEMs, suppliers and other interested parties, and also by attending conferences and trade shows and regularly monitoring the press and technical literature.

EPA is coordinating with Transport Canada (TC) and Natural Resources Canada (NRCan) on a study of the rolling resistance and traction characteristics of low-rolling resistance tires. TC and NRCan originated this study in part to support the development of a Canada consumer information program for replacement tires. The program will study the correlation between rolling resistance performance and safety performance (traction) for winter and all-season tires. As such, it promises to provide concrete input on any tradeoffs between rolling resistance and traction in current production tires, and so will inform the safety concerns noted by NHTSA and the NAS report. A total of 50 randomly selected all-season tires and 5 all-weather tires will be tested under this program. The study is scheduled for completion by December 2016, with testing to be completed earlier that year. Although the analysis was not complete in time for the publication of this Draft TAR analysis, its findings will be incorporated into the agencies' analysis as they become available.

5.2.6.3.1 *Industry Developments*

Tires that achieve the level of improvement of LRRT1 are widely available today, and since the FRM appear to have continued to comprise a larger and larger portion of tire manufacturers' product lines as the technology has continued to improve and mature. Improvements that would reach the level of LRRT2 have also seen significant progress in the industry, with indications of increased availability, improved traction and performance characteristics, and additional cost information.

Since the 2012 FRM and even before, the tire industry has become increasingly focused on improving tire performance. Recent industry momentum in this direction was captured well in a quote by Kurt Berger of Bridgestone, in a 2014 article in Automotive News.[415] "A low-rolling-resistance tire of 2010 would not be considered a low-rolling-resistance tire today. We've really been pushed in a short time to reduce rolling resistance further." Several typical examples of industry research and implementation efforts are outlined in a 2015 report by Auto World[416]. One example of a specific product embodying lower rolling resistance technology is the Falken Sincera SN832 Ecorun Tire, with a 22 percent improvement over its immediately previous generation, while maintaining a 27 percent improvement in braking distance. According to a Continental spokesperson cited in the Auto World report, "…improvements of more than 20 percent from one generation to the next [are possible] by introducing rolling resistance optimized tires. … an additional 5 percent improvement generation-to-generation is possible." According to Indraneel Bardhan, Managing Partner of EOS Intelligence, so-called "green tires" have achieved a global market share of about 30 percent.

The Automotive News article cited above also discussed ongoing challenges for low rolling resistance tires, including issues such as wet traction, tread wear, and the magnitude of real world benefits in comparison to customer expectations. Customers were said to be relatively indifferent about the fuel economy benefits of low rolling resistance tires, but the perception of differences in handling performance between these tires and traditional tires appeared to be stronger. Due to these perceptions, it was suggested that although original equipment fitments of low rolling resistance tires have been increasing, consumers may tend to replace them with more conventional tires after the original tires wear out, potentially reducing the lifetime impact of this tire technology on fuel economy.

Despite the typical perception that reducing rolling resistance sacrifices traction performance, tire designers can exercise a variety of design options to preserve traction characteristics while maintaining low rolling resistance. For example, as shown in Figure 5.47, preliminary results of the Transport Canada/Natural Resources Canada study show that winter tires are available with a wide variety of rolling resistance and wet grip characteristics, including tires with both low rolling resistance and good wet grip. For instance one tire had a rolling resistance coefficient less than 9.0, and a wet grip index greater than 1.1.

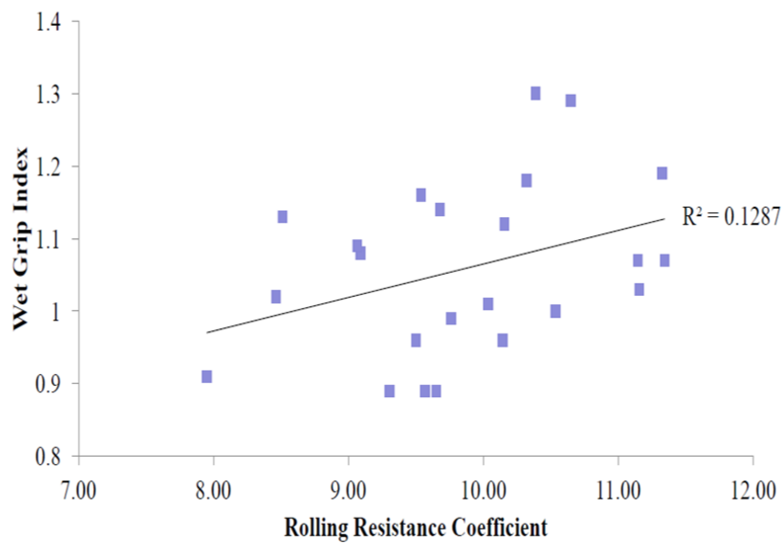


Figure 5.47 Relationship between Wet Grip Index and Rolling Resistance for Winter Tires from Transport Canada/NRCan Study

One example of the potential for careful design to maintain traction in a low rolling resistance tire is seen in the Bridgestone "ologic" design, which appears on the BMW i3 electric vehicle. This tire has a relatively large diameter coupled with a narrow width, reducing rolling resistance by maintaining low deformation through a stiffer belt tension. The larger diameter and unique construction increases the length of the contact patch, which serves to provide improved braking performance and wet and dry traction. An advanced rubber compound and special tread design also contributes.[417] The relatively narrow design is also said to improve aerodynamic performance.[416] The trend toward larger diameter tires with narrower cross-sectional width is also associated with lower tire noise levels, and have been described as one of the likely tire design trends that will continue into the future, particularly for BEVs that value both energy efficiency and quiet performance[416]. As another example, the tire manufacturer Pirelli has projects focusing on development of new tire polymers through joint ventures with chemical suppliers[416].

Research data presented at the 2014 U.S. DOE Merit Review strongly suggests that significant rolling resistance improvements are accessible to much of the tire market. A project involving Cooper Tires, funded by the U.S. Department of Energy, targets a 30 percent reduction in rolling resistance and a 20 percent reduction in tire weight, while maintaining traction performance.[418] By investigating new materials and methods for reducing rolling resistance in ways that maintain wet traction and tread wear capabilities, this project has suggested that potential improvements in rolling resistance of 10 to 20 percent are achievable by selection of appropriate materials and construction, with examples of reduction in rolling resistance from a prevailing 0.08 to 0.10 down to 0.064 to 0.08.

5.2.6.3.2 Control-Tec Analysis of Trends in Tire Technologies

As discussed under Aerodynamics (Section 5.2.5.3.3) and also in Appendix A (CARB Analysis of Vehicle Load Reduction Potential For Advanced Clean Cars), an analysis performed by Control-Tec for the California Air Resources Board[413,414] resulted in a large database of estimated road load parameters for many current vehicles, including estimates of tire rolling resistance. Many of these estimates were analytically derived from input data such as dynamometer road load coefficients. To derive tire rolling resistance, factors representing driveline drag and aerodynamic drag were subtracted from the total road load force, with the remainder being taken as representative of tire rolling resistance.

As described in the CARB Analysis, the study defined the best-in-class application of rolling resistance technology in the MY2014 fleet as being represented by the 75th-percentile rolling resistance coefficient observed in that fleet within a given vehicle class. Depending on the tire category, this represented an 11 percent to 14 percent improvement in rolling resistance over the median vehicle in the class. Applying this degree of improvement to all of the vehicles in each respective class resulted (by simulation) in an improvement of about 5 g/mi in CO_2 emissions for the fleet overall, or about 2 percent, relative to a 2014 baseline value of 263 g/mi. It should be noted that the study was limited only to consideration of rolling resistance technologies represented in the MY2014 fleet, and therefore did not consider more advanced technologies that may now be present in MY2015 or 2016 vehicles, nor any further improvements that may be achieved by 2022-2025.

EPA plans to more closely examine the Control-Tec database for its potential to characterize the penetration of tire rolling resistance technologies in the 2014 fleet. Although this analysis was not completed in time for the publication of this Draft TAR analysis, any results that become available may be used to further inform the agencies' analysis.

5.2.6.3.3 Canada Tire Testing Program

EPA is coordinating with Transport Canada (TC) and Natural Resources Canada (NRCan) on a tire testing program that will provide a large amount of test data relating the rolling resistance of tires to their wet and dry traction performance. The tire testing program was initiated by Transport Canada as part of a Canadian initiative to develop a tire consumer information program to inform consumer selection of aftermarket replacement tires. EPA partnered with the Canadian agencies due to mutual interests in supporting the midterm evaluation.

A major goal of the testing program is to study the correlation between tire rolling resistance and safety performance of winter tires, all-weather tires, and all-season tires. The program will also examine various approaches to the characterization of rolling resistance of tires operating in cold ambient temperatures, a consideration of particular interest to the Canadian market.

To date, a random selection of 23 winter tires have been tested and a random selection of 50 all-season and 5 all-weather tire models have been acquired and are undergoing testing. The previously presented plot of tire rolling resistance and traction performance (Figure 5.47) was derived from preliminary data provided by this program.

Although this testing project will not be completed in time for the June 2016 publication of this Draft TAR analysis, a final report is expected to be completed by the end of 2016 and may be available to further inform the agencies' analysis.

5.2.6.4 Conclusions

In summary, the agencies have revisited the feasibility of the two levels of rolling resistance reduction (LRRT1 and LRRT2) through the efforts described above. The 2015 NAS report generally supported the cost, effectiveness, and feasibility assumptions for LRRT1 and LRRT2 as being appropriate for the 2020-2025 time frame. The agencies' analysis of industry developments shows that tire manufacturers are aggressively pursuing rolling resistance technology capable of achieving a 10 percent and 20 percent reduction in rolling resistance, while OEMs are increasingly specifying low rolling resistance tires in original fitments of their products. Although there is some evidence that consumers have associated low rolling resistance technology with reductions in traction, the ability of tire designers to exercise many design parameters in pursuit of traction performance makes it unclear whether this will continue in the future.

For the cost and effectiveness assumptions the agencies are adopting for the GHG Assessment and CAFE Assessment for this Draft TAR analysis, see Sections 5.3 and 5.4.

5.2.7 Mass Reduction: State of Technology

5.2.7.1 Overview of Mass Reduction Technologies

Mass reduction remains a key technology that vehicle manufacturers are expected to continue to apply to meet the light-duty GHG standards. The reduction of overall vehicle mass can be accomplished through several different techniques. Techniques include CAE optimization of designs, adoption of lighter weight materials, and part consolidation. The cost of reducing vehicle mass is highly variable. Design optimization, consolidation of components along with adoption of secondary mass savings opportunities can result in some cost savings. Secondary mass reduction is weight reduction opportunities that are available as the base vehicle becomes lighter. A smaller engine block, transmission and brakes are examples of secondary mass reduction technologies. Cost increases are often the result of changing from a high density, lower cost material like steel, to a lower density, higher cost material such as certain advanced high strength steels, aluminum, magnesium or composites. The cost for each mass reduction solution depends on the approach and material used. In some cases, the cost savings can offset the cost increases. Benefits from adopting mass reduction technologies, also include increased performance such as improved vehicle dynamics and responsiveness.

For this Draft TAR, which is reviewing technologies for the 2022-2025 standards, EPA reevaluated all aspects of mass reduction including the methodologies described above, mass reduction cost, the FRM conclusions and the amount of mass reduction in the baseline fleet. To support this Draft TAR, EPA and NHTSA have also completed new work including research, stakeholder meetings, supplier meetings, technical conferences and literature searches. Public information from these sources are contained in this section and are the basis of the development of new mass reduction cost curves for technology package modeling. Section 5.3 describes the specific data and assumptions that were used for modeling mass reduction for this assessment and includes the 2014 baseline fleet mass reduction estimates including mass allowances for safety and footprint changes between the 2008 and 2014 vehicles, cost curve development and application, and effectiveness. Specific material (steel, aluminum, magnesium, plastic, glass fiber and carbon fiber composites, glass) and application details addressing Feasibility, Cost, Mass Reduction, Safety and Research, are included in Part B of the Appendices.

The relationship between mass reduction and safety has also been an important consideration and NHTSA performed an updated analysis for which a description and results can be found in Chapter 8.

Current industry trends in mass reduction are to adopt mass reduction technologies in various degrees. From vehicles that have adopted large amounts of lower density materials in their body in white (BIW), as with the MY2015 Ford F150 and MY2014 BMWi3, to vehicles that have adopted smaller changes in vehicle design such as an aluminum hood or a steel clamshell control arm in the suspension such as the MY2014 Silverado 1500. The EPA 2015 Trends report illustrates, in Figure 5.48, how in overall sales weighted basis, vehicles have not yet achieved a notable decrease in curb weight or have continued the trend of using mass reduction to offset increased vehicle content or larger footprint as the mass difference has remained constant over the past 10 years. The detail within the report notes 2014 results show a 0.5 percent mass increase for cars and 0.7 percent mass decrease for trucks, each on a sales weighted basis.

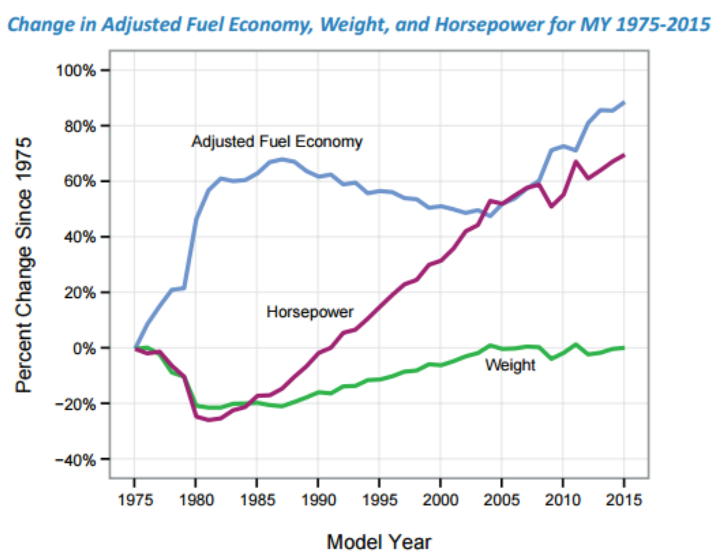


Figure 5.48 Change in Adjusted Fuel Economy, Weight and Horsepower for MY1975-2015[419]

One reason for the current trend of curb weight changes may be the desire to make significant mass reducing design changes during major vehicle redesigns, hence slowing down the release of lightweight vehicles. Other reasons may include the idea that the standards for MYs 2014/2015 don't require high levels of MR, different manufacturers have different compliance strategies, or some vehicles are prioritized for mass reduction for the ancillary benefits that mass reduction provides. Recent announcements, as listed in Table 5.14, indicate that the adoption of mass reduction technologies, and resultant lower curb weights, will continue into the future as vehicle design cycles are revisited and material costs are lowered. One example is the announcement of the MY2017 Acadia by GMC in which it was stated as having a 700lb mass reduction through adoption of high strength steels, smaller engine offering and smaller footprint.[420] The January 2016 announcement of the 2017 Chrysler Pacifica also touted 250lbs of mass reduction through "extensive use of advanced, hot-stamped/high-strength steels, application of structural adhesives where necessary and an intense focus on mass optimization." Magnesium is also used in the instrument panel and the inner structure of the Pacifica’s liftgate, the rest of which is aluminum.[421]

To understand the general trend in the use of lightweight materials we have included Figure 5.49 which shows a comparison of metal material adoption from 2012-2025 included in the 2014 Executive Summary for the Ducker Study.[422] The study notes that there was a slight increase in the use of light-weight materials for BIW and closures between 2012 and 2015. The use of AHSS/UHSS grew from 15 percent to 20 percent of the vehicle body and closure parts. Aluminum sheet also grew from 1 percent to 4 percent and aluminum extrusions made it onto the pie chart in 2015. Overall, the analyses expects that steel will still remain the dominant material in BIW and closures. According to IHS increases in plastics are expected to grow to be 350kg/average car in 2020 which is up from 200 in 2014, as shown in Figure 5.50. Auto manufacturing use of carbon fiber is expected to increase from 3,400 metric tons in 2013 to 9800 metric tons in 2030. According to Ducker Worldwide the use of magnesium is expected to increase through 2025 as over the next 10 years magnesium castings are expected to grow significantly. "Growth is highlighted within "large tonnage" parts like closure inners, IP structures etc. and other body/structural parts."

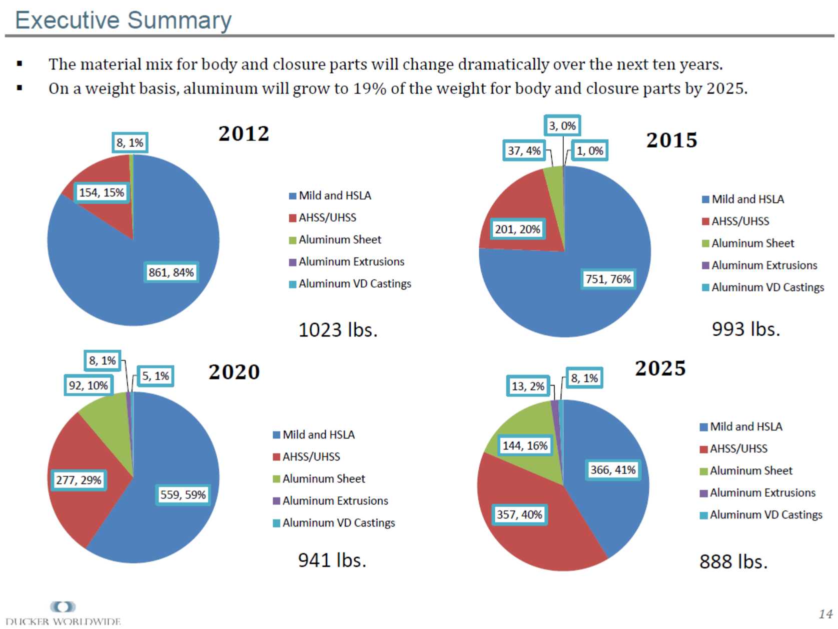


Figure 5.49 Estimated Vehicle Material Change over Time 2012-2025 - Ducker Worldwide[422]

Automotive Market Summary

	2005	2010	2015	2020	2024	Forecasted % CAGR
Vehicle Unit Deliveries	66.5M	77.9M	93.0M	100.7M	109.0M	1.80%
Total Vehicle Wt (MT)	30.2M	35.4M	37.2M	41.1M	44.5M	1.80%
Total FGRP Structures (MT)	79,212	102,371	131,310	167,588	203,704	4.49%
Total CFRP Structures (MT)	3,921	3,771	13,060	37,085	47,011	16.67%
Total CF Demand (MT)	3,666	3,526	10,056	23,456	47,011	13.73%

Figure 5.50 Forecast of Automotive Market Consumption of Composites[423]

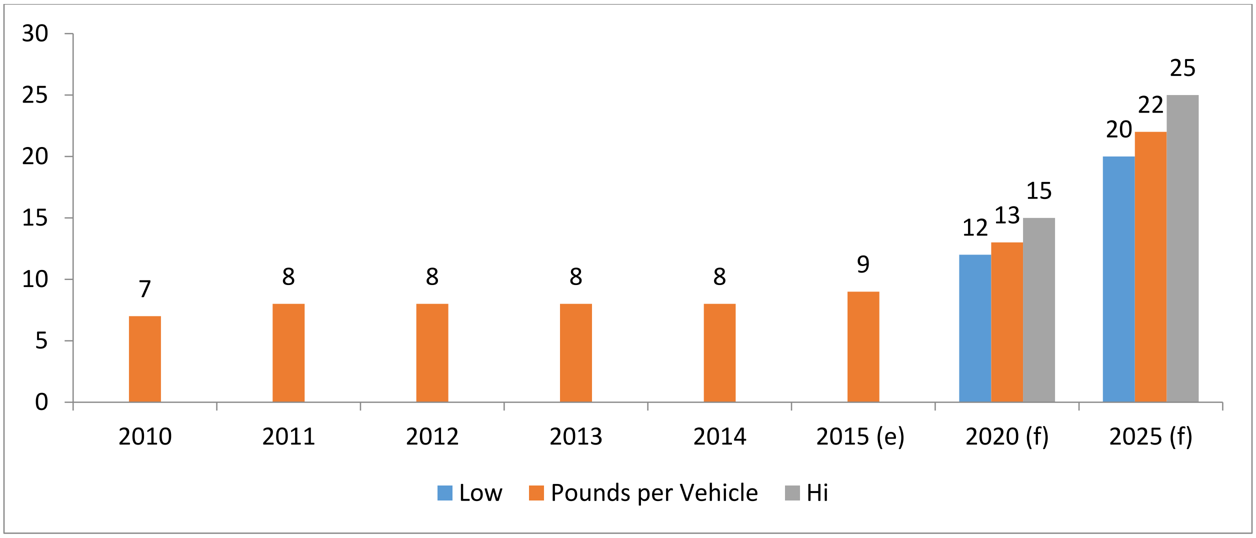


Figure 5.51 Magnesium Growth Expectations through 2025 (Ducker Worldwide)[424]

While a significant amount of work and resources have already been devoted to developing and implementing mass reduction technologies by OEM's and suppliers, the research for new materials and processes continues and some of the research is included in the Appendices' material summaries. The agencies expect that innovative mass reduction solutions will continue to be developed and adopted through 2025 and that mass reduction will be less costly than it is today. Advancements expected include the development of lower cost high strength steel alloys for body structures (3rd generation steels), lower cost and higher quality product (for Class A surfaces) from the aluminum Micromill sheet manufacturing processes and advancements in engineered plastics and composites for structural applications. Additional anticipated developments in design include further development and use of CAE design tools to characterize new material properties and behaviors which will result in material use advances including optimized load pathway analyses in BIW geometries or consolidation of multi-part components resulting in the achievement of mass reduction in the most cost effective way. The agencies will continue to follow the progress of lightweight material adoption.

5.2.7.2 Developments since the 2012 FRM

Since the publication of the FRM, the agencies have been able to gather additional information on technological advancements and application of mass reduction technologies through a variety of resources including conferences, public reports, material association meetings, academic research work, online articles and CBI discussions and materials from manufacturers and suppliers. A snapshot of publicly available information on lightweight materials is included in the Appendices. The agencies also generated two new holistic lightweighting studies for mass reduction and cost data on light duty pickup trucks (MY2011 and MY2014) and updated existing passenger car (EPA Midsize CUV and NHTSA Passenger car) holistic lightweighting studies completed in 2012. The light duty truck holistic reports join the projects currently described in the FRM on a midsize CUV, one funded by EPA and one by ARB, and a passenger car, funded by NHTSA. The Aluminum Association also conducted several projects including a project with EDAG, Inc. to evaluate the EPA Midsize CUV high strength steel BIW CAE model with aluminum material replacement.

DOE also joined forces with Ford/Magna to develop a multi-material lightweight vehicle, through vehicle build and durability tests. In addition to vehicle lightweighting, research projects were performed on the mass adds due to safety requirements by IIHS small overlap test (2012) for their Top Rated Safety Pick. NHTSA funded a CAE passenger car evaluation and Transport Canada funded a CAE light duty truck study evaluation which included a crash test of the baseline vehicle. With respect to mass reduction efficiency, the Aluminum Association funded a study on the impact of mass reduction on fuel economy for various vehicles with Ricardo, Inc. on which the 2015 NAS report comments were based. The EPA and NHTSA (through ANL) also re-evaluated the effectiveness of mass reduction on CO_2 and fuel consumption reductions for several vehicle classes, including standard car and light duty truck. The studies on efficiency will be addressed in Section 5.3.

The following section provides a description of the multi material approach to lightweighting being used by OEM's and presents some examples of current vehicle designs that have adopted notable mass reduction which resulted in curb weight changes. Further sections present an overview of the various holistic mass reduction and cost studies that have been completed since the FRM. The studies provide technology, primary and secondary mass reduction, and cost information in order to create cost curves for application of mass reduction technology for a passenger car and light duty pickup truck.

5.2.7.3 Market Vehicle Implementation of Mass Reduction

Trends of slightly decreased curb weight in the new vehicle fleet are starting to be seen in the data. The 2014 EPA Trends report in Figure 5.48, illustrates that the overall sales weighted vehicle weight has remained steady over the past 10 years. The information in Figure 5.52 illustrates that in 2008, the sales weighted vehicle weight was 4085 lb at 48.9 sq ft while the 2014 sales weighted vehicle weight was 4060 at 49.9 sq ft which is a decrease of 25lbs and an increase of one square foot. At the same time mass increases from additional safety regulations and are accounted for in the 2014 weights. In order to achieve the results of increased size and decreased weight, lightweight technologies/approaches have had to be incorporated into vehicle designs.

Table 2.1

Adjusted CO_2 Emissions, Adjusted Fuel Economy, and Key Parameters by Model Year[1]

Model Year	Production (000)	Adj CO_2 (g/mi)	Adj Fuel Economy (MPG)	Weight (lb)	HP	Footprint (sq ft)	Car Production	Truck Production	Alternative Fuel Vehicle Share of Production
2005	15,892	447	19.9	4059	209	-	55.6%	44.4%	0.0%
2006	15,104	442	20.1	4067	213	-	57.9%	42.1%	0.0%
2007	15,276	431	20.6	4093	217	-	58.9%	41.1%	0.0%
2008	13,898	424	21.0	4085	219	48.9	59.3%	40.7%	0.0%
2009	9,316	397	22.4	3914	208	48.1	67.0%	33.0%	0.0%
2010	11,116	394	22.6	4001	214	48.5	62.8%	37.2%	0.0%
2011	12,018	397	22.4	4126	230	49.5	57.8%	42.2%	0.1%
2012	13,448	375	23.7	3979	222	48.8	64.4%	35.6%	0.4%
2013	15,198	366	24.3	4003	226	49.1	64.1%	35.9%	0.7%
2014	15,512	366	24.3	4060	230	49.7	59.3%	40.7%	0.7%
2015 (prelim)	-	*360*	*24.7*	*4076*	*233*	*49.9*	*59.6%*	*40.4%*	*1.1%*

[1] Adjusted CO_2 and fuel economy values reflect real world performance and are not comparable to automaker standards compliance levels. Adjusted CO_2 values are, on average, about 25% higher than the unadjusted, laboratory CO_2 values that form the starting point for GHG standards compliance, and adjusted fuel economy values are about 20% lower, on average, than unadjusted fuel economy values.

Figure 5.52 Footprint (square feet) Change and Weight 2007-2014

Table 5.14 lists a number of vehicle lightweighting efforts that have been announced over the past few years. Some vehicles adopted high strength steel solutions, up to 2 GPa tensile strength steels, in their BIW such as in the Audi Q7, Acura TLX, Nissan Murano and Cadillac CTS redesigns. The MY2015 F150 and the MY2014 Range Rover by Land Rover have both adopted a number of lightweighting components including aluminum body and cabin structure, aluminum closures, etc.

Table 5.14 Examples of Mass Reduction in Selected Recent Redesigns (Compared to MY2008 Design)[JJ]

Vehicle Make	2008 Model Year curb Weight (kg)	Model Year	Change in Vehicle Curb Weight (kg)	% Change	% Footprint Change
Acura MDX	2070	2014	238	11.5%	+0.5%
Audi Q7	2320	2014	325	14%	0
Land Rover Range Rover	2400	2014	336	14%	+5.2%
Silverado 1500 Crew Cab 4x4	2422	2014	86	3.6%	n/a
Ford F150 2.7L EcoBoost, 4x2 Supercrew	2446	2015	318	13%	n/a
Nissan Murano	1500	2015	30	2%	n/a
Cadillac CTS	1833	2015	110	6%	+1.6%
Honda Pilot	4367	2016	131	3%	+6.1%
Chevy Cruze[425]	1425	2016	114	8%	n/a
Chevy Malibu[426]	1552	2016	136	9.2%	+0.3%
GMC Acadia	2120	2017	318	15%	-7.8%
Chrysler Pacifica	2110	2017	114	5.4%	+8.2%
Cadillac XT5[427]	1893	2017	82	4.5%	+2.7%

The press release by Audi[428] represents the engineering perspective that is needed to achieve notable mass reduction: "Although it (Q7) is shorter and narrower than its predecessor, the cabin is longer and offers more head room. 20 years of experience with lightweight construction flow into the new Audi Q7. Equipped with the 3.0 TDI engine, the new Audi Q7 tips the scales at just 1,995 kilograms (4,398 lb.), which is 325 kilograms (716.5 lb.) less weight…. The Q7 with the 3.0 TFSI engine is even lighter, weighing just 1,970 kilograms (4,343.1 lb.). Lightweight construction has been applied in all areas, from the electrical system to the luggage compartment floor. The key is the body structure, where a new multi-material design reduces its weight by 71 kilograms (156.5 lb.)….Ultra-high-strength parts made of hot-shaped steel form the backbone of the occupant cell. Aluminum castings, extruded sections and panels are used in the front and rear ends as well as the superstructure. They account for 41 percent of the body structure. Other parts made entirely of aluminum are the doors, which shave 24 kilograms (52.9 lb.) of weight, the front fenders, the engine hood and the rear hatch. Audi uses new manufacturing methods for the production and assembly of the parts. The crash safety and occupant protection of the new Audi Q7 are also on the highest level."

In order to achieve the fullest amount of mass reduction from lightweighting efforts, vehicle design and planning are important in order to determine additional secondary mass that may be reduced from the vehicle. Secondary mass savings are identified as a result of primary mass reduction savings. Primary mass savings are those items which are not dependent on a lighter overall vehicle and include such items as aluminum closures and lightweight seats. The most identifiable secondary mass is the adoption of a smaller engine in the light weighted vehicle. Ford mentioned in a 2010 International Magnesium Association article that "Strategic use of lightweight and down-gauged material allows a vehicle's powertrain to be smaller and more

[JJ] Some vehicles were redesigned twice from 2008 and so the changes aren't exactly the same as noted in the articles, from which some of the information was taken, for the table references differences between 2008 and 2014.

fuel-efficient. Combining magnesium with aluminum for the MKT liftgate's panels instead of steel saves 22 pounds in vehicle weight. When coupled with other weight-saving measures, re-matching the vehicle with a smaller powertrain – known as right-sizing of power to weight -- is a key factor in achieving greater fuel economy."[429] The adoption of Ford's EcoBoost engines allow Ford to realize the benefits of secondary lightweighting.

Downsizing is an option not considered for this analyses for lightweighting and not commonly seen in the marketplace to date. GMC designed the MY2017 Arcadia to be 6.4 inches shorter in wheelbase and 3.5 inches narrower than its predecessor and adopted some lightweight solutions for a 700lb reduction in mass in addition to being designed to meet the IIHS small overlap test.[430] The new vehicle achieves 22 city and 28 highway, a 22 percent increase over the original 17/24, with its mass reduction, aerodynamics, new 2.5L Ecotec engine and stop/start technology. "The original Acadia was very truck-inspired, but the new model has a decidedly SUV influence conveyed in sculptural details, softened corners and a sleeker windshield angle."[431]

5.2.7.4 Holistic Vehicle Mass Reduction and Cost Studies

EPA and NHTSA's feasibility assessments for the 2012 Light Duty FRM incorporate mass savings and related costs. The 2017-2025 FRM Joint Technical Support Document contained a linear mass reduction cost curve for direct manufacturing costs (DMC) in the expression of DMC ($/lb.)=$4.36(percent-lb.) x Percentage of Mass Reduction level (percent) as shown in Figure 5.53. This equation starts at $0/kg for no mass reduction and increase at a constant rate of $4.36/(percent-lb.) for each percent mass reduction (ex: $0.44/lb. for 10 percent MR on a 4,000 lb. vehicle and $0.66/lb. for 15 percent on same) and was applied to all 2008/2010 MY vehicles. This cost curve expression was based on a number of available data sources on mass reduction which included a number of papers on individual components.

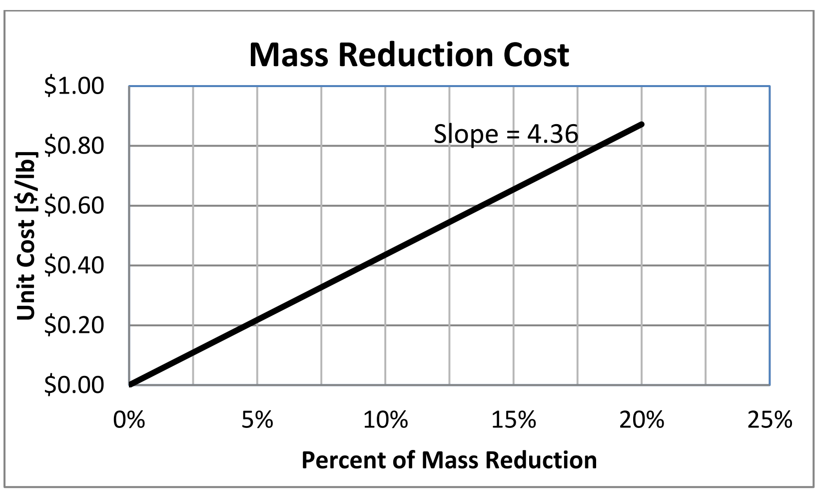


Figure 5.53 Mass Reduction Cost Curve ($/lb.) for 2017-2025 LD GHG Joint Technical Support Document

In order to capture a more complete picture of the potential for mass reduction and related costs, the agencies (EPA, NHTSA, ARB, and DOE) have committed significant resources to acquire mass and cost information through a number of holistic vehicle studies as listed in

Table 5.15. The projects were performed with constant performance in mind and hence the benefits of all lightweighting efforts were put into improving fuel efficiency and lowering CO_2 emissions. Each project includes many steps including baseline vehicle teardown, component/system examination for mass reduction technologies, direct manufacturer cost estimation for mass reduction technology and related tooling, CAE safety crash evaluation, NVH assessment and durability analyses. Mass reduction technologies for these studies are found in a variety of sources including those found on other vehicles, technologies in development at suppliers and material companies, technologies developed in other government funded projects, etc. Cost estimates were made by the project contractors based on their extensive automotive experience and industry contacts. The DOE/Ford/Magna joint project itself did not include a cost study for its two evaluations - Mach 1 (25 percent MR) and Mach 2 (50 percent MR). However DOE did fund two independent cost studies related to this work. One for a 40-45 percent mass reduction vehicle whose results were presented at the DOE Annual Merit Review (AMR) in 2015 and a second independent study was also funded by DOE for a 20-25 percent mass reduced vehicle and results are expected sometime in 2016. The Mach 1 work also included several additions which included the buildup of seven lightweight vehicles for a number of durability and crash analyses as well as testing of some of the project's new technologies. Two other studies provided insights into the mass add for meeting the IIHS small overlap test which is required in order to achieve the IIHS rating of Top Safety Pick. NHTSA funded a follow-up study on their 2012 passenger car work and Transport Canada funded a follow-up study on the EPA 2015 light duty pickup truck. The studies provided a revised final cost and mass reduction to the original works. The agencies also greatly appreciate and acknowledge the work of many individual companies, academia representatives, and material associations to provide information on lightweighting technologies, both in production and in research, to the agency contractors for the holistic vehicle studies. This information was also used as the basis for material information contained in the Appendices to address topics of feasibility, mass reduction, cost, safety, research and recycling. In addition, the agencies greatly appreciate the feedback from OEM's and others on the results of the holistic vehicle studies which formed a basis for revisions to the individual study cost curves for this analysis.

Table 5.15 Agencies Sponsored Mass Reduction Project List since FRM

	Agency	Description	Completion Date	Reference
Pass Car/CUV Studies	US EPA	Phase 2 Midsize CUV (2010 Toyota Venza) Low Development (HSS/Al focus)	2012	Final Report, Peer Review and SAE Paper https://www3.epa.gov/otaq/climate/documents/420r12026.pdf https://www3.epa.gov/otaq/climate/documents/420r12019.pdf SAE Paper 2013-01-0656
	ARB	Phase 2 Midsize CUV (2010 Toyota Venza) High Development All Aluminum	2012	Final Report and Peer Review http://www.arb.ca.gov/msprog/levprog/leviii/final_arb_phase2_report-compressed.pdf http://www.arb.ca.gov/msprog/levprog/leviii/carb_version_lotus_project_peer_review.pdf
	NHTSA	Passenger Car (2011 Honda Accord)	2012	Final Report, Peer Review, OEM response, Revised Report ftp://ftp.nhtsa.dot.gov/CAFE/2017-25_Final/811666.pdf http://www.nhtsa.gov/Laws+&+Regulations/CAFE+-+Fuel+Economy/ci.NHTSA+Vehicle+Mass-Size-Safety+Workshop.print http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/812237_LightWeightVehicleReport.pdf
	DOE/ Ford/ Magna	Passenger Car (2013 Ford Fusion) Mach 1 and Mach 2 projects Cost Study for 40-45% Mass Reduction	2015	http://energy.gov/sites/prod/files/2015/06/f24/lm072_skszek_2015_o.pdf http://energy.gov/sites/prod/files/2014/07/f17/lm072_skszek_2014_o.pdf http://energy.gov/sites/prod/files/2014/07/f17/lm088_skszek_2014_o.pdf http://avt.inl.gov/pdf/TechnicalCostModel40and45PercentWeightSavings.pdf SAE papers include 2015-01-0405..0409 2015-01-1236..1240 2015-01-1613..1616
	NHTSA	Passenger Car small overlap mass add	2016	Final Report http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/812237_LightWeightVehicleReport.pdf
Light Duty Truck Studies	EPA	2011 Silverado 1500	2015	Final Report, Peer Review and SAE Paper https://www3.epa.gov/otaq/climate/documents/mte/420r15006.pdf SAE Paper 2015-01-0559
	NHTSA*	2014 Silverado 1500	2016	Final Report (in peer review)
	Transport Canada	IIHS small overlap mass add on LDT (EPA)	2015	Final Report and Peer Review https://www.tc.gc.ca/eng/programs/environment-etv-summary-eng-2982.html Peer Review (EPA docket)[432]

Note:
*Completion expected May-June 2016

The holistic vehicle studies in Table 5.15 are nearly all focused on 2008/2010 design era vehicles due to the fact that one purpose of the Draft TAR is to evaluate the assumptions utilized in the FRM and perform an updated assessment based on the information available today. The majority of vehicles have not yet incorporated significant mass reduction technologies due to the fact that many vehicle designs were already underway when the rulemakings were finalized and the lead time required to achieve such a transition is influenced by a three year lead time[433] for acquiring aluminum sheet in volume. The MY2014 new generation light duty pickup truck evaluated by NHTSA was a 'next step' approach to evaluate the mass save and cost from converting from a more high strength steel approach (compared to the 2008 design) to other lightweight materials including aluminum and CFRP. It should be noted that the cost curve expression for the EPA and NHTSA projects take different approaches as will be discussed throughout the following sections.

The agencies are using the information in the publicly available government sponsored studies in its modeling of mass reduction and related costs for all the vehicles sold in the US. The vehicles for the holistic vehicle projects were chosen based on their representation of high sales volume vehicles, as the Honda Accord and Chevy Silverado 1500, and/or representative of new vehicle designs that were showing increasing popularity, as the Toyota Venza. The projects were conducted over the past 6 years and were multi-million dollar efforts. The same detailed information collected in these projects were not readily available from any other source - especially cost information and secondary mass effects. Additional mass comparison information was found to be available through the A2Mac1 vehicle databases and that information has been used to supplement our analyses on mass differences - especially on mass add for vehicle footprint increases. Ducker Worldwide executive summaries have also provided insights into aluminum and steel material trends.

To understand how the results from our projects relate to real world lightweighting efforts, staff from the agencies, EPA, NHTSA and ARB, met with OEMs and attended many technical conferences over the past four years. It was observed that there are some cost savings to be achieved from lightweighting MY2008/2010 design vehicles and more is expected as costs are reduced through material recycling and optimization of material use. The agencies agree that some mass reduction technologies will add cost, however recent developments in material processing, as with development of 3rd generation steels and Alcoa's Micromill for aluminum, indicate that these costs may be less than that utilized in the studies. In addition, the decrease in metal material pricing over the past year has not been included in most of the holistic vehicle studies. The agencies understand that OEM's have typically utilized mass reduction technologies to offset the weight of added features or safety measures to remain competitive.

5.2.7.4.1 EPA Holistic Vehicle Mass Reduction/Cost Studies

The U.S. EPA funded two holistic vehicle mass reduction/cost studies for the Midterm Evaluation between 2010 and 2015. The first study was the Phase 2 low development (steel BIW) lightweighting study on a Midsize CUV performed by EPA with FEV North America, Inc., EDAG, Inc. and Munro and Associates, Inc. and was focused on achieving 20 percent mass reduction which resulted in a high strength steel structure with aluminum closures amongst other technologies. This was a follow up to the Phase 1 paper study on the Midsize CUV performed by Lotus Engineering and includes in-depth analyses on cost and CAE safety analyses of the vehicle. The second study was a lightweighting study on a 2011MY light duty pickup truck and was performed by the same contractors using a similar methodology however added in the dynamic vehicle analyses and a number of component evaluations performed in CAE space. The result was an aluminum intensive vehicle with high strength steel/aluminum ladder frame.

EPA's cost curve development methodology for both projects is based on a cumulative additive approach of the best $/kg rated technologies. Primary mass reduction technologies, technologies not dependent on mass savings in other areas of the vehicle, are listed along with the related costs and mass savings. The $/kg for each technology is calculated and then the order of the technologies are sorted from lowest $/kg to highest. The original mass and costs are then each added in a cumulative manner and then the resultant $/kg is calculated at each technology and a related percent mass reduction. Secondary mass savings, those mass savings which are dependent on other mass savings within the vehicle, are noted on a component evaluation basis, summed, and then applied at the solution point for the project. Since the secondary mass savings are based on the size of the component - hence material basis - then this can be proportioned across the whole range of primary mass reduction curve. The cost savings are also proportioned. Two assumptions work into this costs curve methodology: 1) OEM's will adopt cost saving mass reduction technologies first; and 2) secondary mass savings, such as a resized engine, will occur at all percent mass reduction points. This methodology works into EPA's mass reduction modeling methodology for this Draft TAR, however is different from NHTSA's cost curve methodology and assumptions which is described separately.

Other related studies to the Phase 2 Low Development Midsize CUV include the Phase 2 High Development study funded by ARB. ARB hired Lotus Engineering to compete an in-depth look into the aluminum intensive (High Development) Midsize CUV and included CAE safety analyses and an in-depth cost analyses. Both of the Phase 2 studies, High Development and Low Development, are follow-up studies to the Phase 1 paper study by Lotus Engineering on the Midsize CUV. Following the Phase 2 studies, the Aluminum Association Automotive Technology Group contracted with EDAG, Inc. to evaluate aluminum material replacement within EPA's CAE model of the Midsize CUV BIW. A cost analyses was also performed by EDAG for this project.

5.2.7.4.1.1 Phase 2 Low Development Midsize CUV Updated Study and Supplement

The Phase 2 Low Development (steel BIW) Midsize CUV lightweighting study was completed in August of 2012. The results of this work were peer reviewed through an independent contractor as well as through the SAE paper publication process. Feedback was received by OEM's and others independent of the official peer review process.

The MY2010 Toyota Venza was chosen as the base vehicle for this work and vehicle teardown and coupon testing revealed that the base vehicle BIW included high strength steel components made of HSLA 350, HSLA 490, DP500, a 7000 aluminum rear bumper and HF1050 B pillar and side roof rail. After consideration of nearly 150 lightweighting ideas, the project's final lightweighting results stated that 18.5 percent mass reduction was achieved for a cost savings of $0.47/kg. The report also stated that if aluminum doors were included then the mass save would be 20.2 percent with a cost savings of $0.11/kg. To make the non-compounded cost curve, the primary lightweighting ideas were listed with the lowest $/kg to the highest $/kg which reflects an approach where the OEM's would choose the less expensive, or cost saving, technologies first. Then the mass and cost data were individually cumulatively added and a cumulative $/kg was determined at each technology addition to create the non-compounded curve. The compounded curve was developed by determining the secondary mass savings at the primary solution point and then the mass savings were ratio'd across the primary cost curve to yield the final cost curve with compounding. A short summary of this work and the cost curve, see Figure 5.54, were included in the 2012 FRM. The compounded cost curve was not included in the cost curve development in the FRM as the study was not completed in time for the FRM analysis.

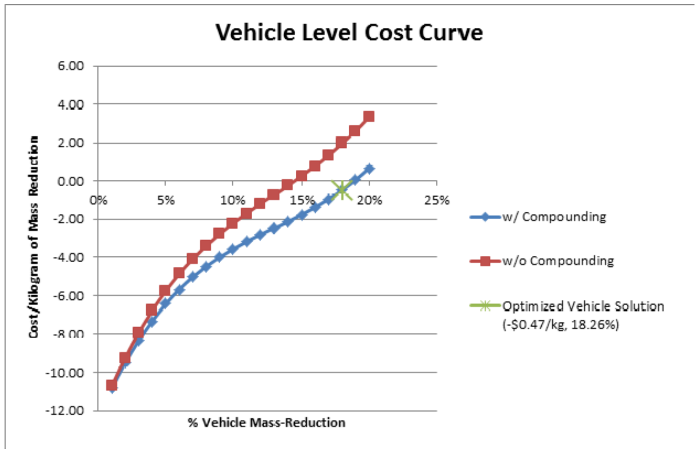


Figure 5.54 Original Phase 2 Low Development Midsize CUV Lightweighting Cost Curve[434]

Additional consideration was given to the feedback EPA and FEV received on the study as well to methodology updates which were made during the 2011MY light duty truck lightweighting study after the FRM. Modifications made to the data for the original curve, shown in Figure 5.54, included adding in the aluminum doors as a lightweight technology, and removing several features including the magnesium engine block and the cost savings for some of the light weighted plastic components. Several customer features were put back into the vehicle including the lumbar and active head rest for the back seat and the cargo cover. A mass and cost allowance for NVH was added as well as the related cost savings for the secondary mass which had not been accounted for in the FRM methodology. The revised cost curve is shown in Figure 5.55 and is 17.6 percent mass reduction at +$0.50/kg. Also included are the $/kg and percent mass reduction solution points for two aluminum BIW Midsize CUV studies. First is the work funded by ARB from Lotus Engineering on the Phase 2 High Development Midsize CUV aluminum intensive project which utilized an aluminum BIW design and results came in at -$0.64/kg for 31 percent MR,[440] per our calculations of study results. Second is the aluminum intensive point from the Aluminum Association work of 27.81 percent mass reduction at $1.12/kg, in which EDAG utilized the same CAE baseline model developed for the EPA Phase 2 Low Development Midsize CUV work.[442]

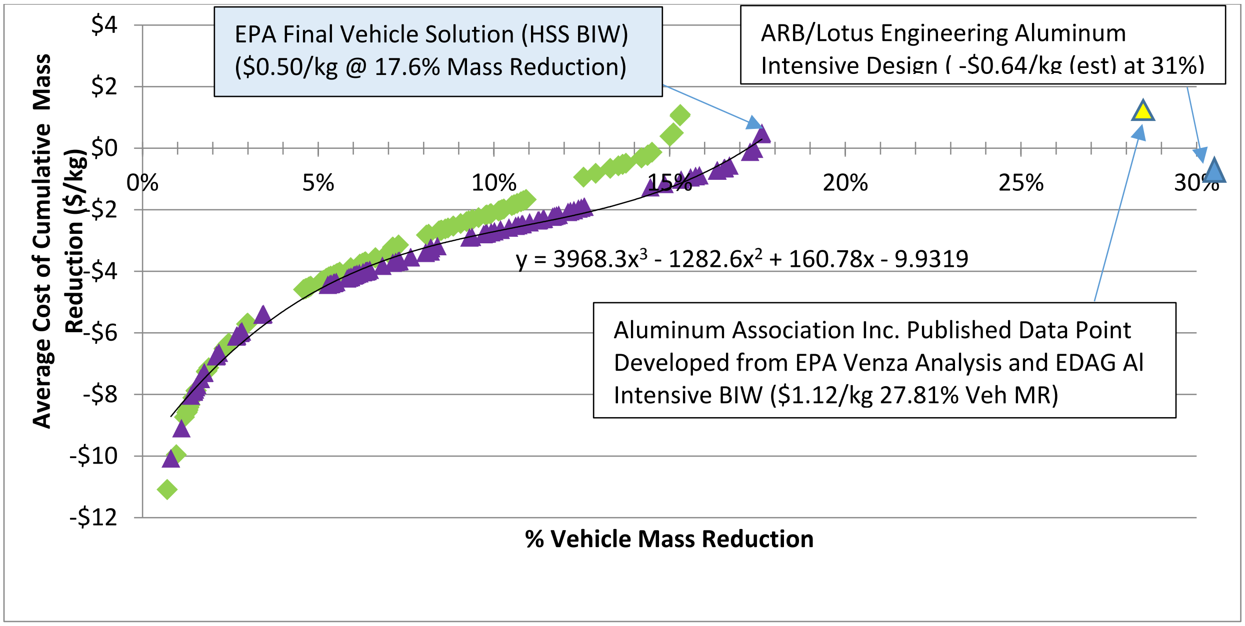


Figure 5.55 Revised Cost Curve for the Midsize CUV Light Weighted Vehicle

This cost curve, in Figure 5.55, is clearly different from the 2012 FRM cost curve for mass reduction, in Figure 5.53, in which all mass reduction points were associated with positive costs. The EPA Phase 2 Low Development Midsize CUV holistic vehicle study is a whole vehicle study which examines nearly every component in the vehicle for mass reduction potential and calculates a related cost and mass save for each and reviews them from most cost/kg save to most costly cost/kg. This methodology was chosen based on the understanding that OEMs will choose the cost saving technologies first and that some cost mass reduction technologies will be paid for by the cost save mass reduction technologies. A vehicle cost curve similar to the FRM expression could be achieved if cost technologies were listed first in the cumulative adding approach and hence losing the appearance of the cost saving technology ideas. However, this is not the approach OEM's are utilizing for lightweighting. For example, a 2016 publication by CAR contains an illustration and caption which states that "(Figure 5.56) illustrates a generic cost curve for lightweighting that is broadly supported.[436] GM has also claimed publically to its potential investors that over $2B[435] was saved in material costs reveals that costs can be saved with mass reduction ideas over several passenger vehicles. It is very likely that some of this savings was due to the decreased material costs over the past year in addition to the cost saving lightweighting approaches.

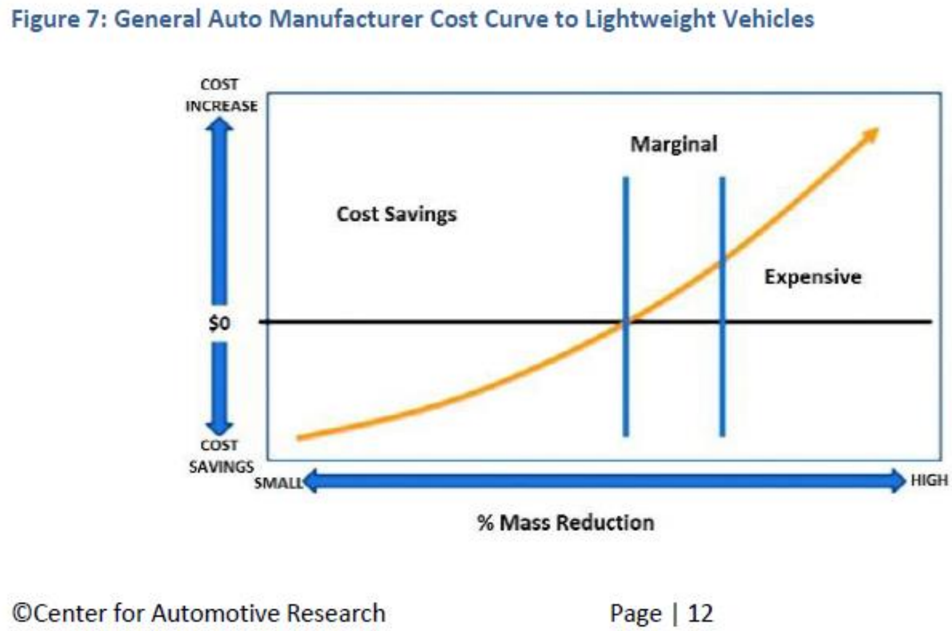


Figure 5.56 Cost Curve Figure from CAR: "A Cost Curve for Lightweighting That Is Broadly Supported"[436]

5.2.7.4.1.2 Light Duty Pickup Truck Light-Weighting Study

The U.S. EPA NVFEL contracted with FEV North America to perform this study utilizing the methodology developed in the Midsize CUV lightweighting effort (2012) and the study was completed in 2015. The results of this work went through a detailed and independent peer reviewed as well as through the SAE paper publication process. Feedback was received by OEM's and others independent of the official peer review process.

For this study a 2011 Silverado 1500 was purchased and torn down. The components were placed into 19 different systems. The components were evaluated for mass reduction potential given research into alternative materials and designs. The alternatives were evaluated for the best cost and mass reduction and then compared to each other. CAE analyses for NVH and safety was completed for the baseline and the light-weighted aluminum intensive vehicle. A high strength steel structure with aluminum closures was the first choice of a solution for this project; however, this was not fully completed for the decision was made by the project team to change course and pursue the aluminum structure solution due to the expected introduction of the aluminum intensive F150 into the marketplace. Durability analyses on both the baseline and light-weighted vehicle designs were performed through data gathered by instrumenting a Silverado 1500 light duty pickup truck and operating it over various road conditions. Included in the durability analyses are durability evaluations on the light weighted vehicle frame, door and other components in CAE space. The crash and durability CAE analyses allowed for gauge and grade determinations for specific vehicle components. Load path redesign of the light duty truck structure (cabin and box structure and vehicle frame) was not a part of this project.

As shown in Figure 5.57, the most mass reduction was achieved in the Body System Group - A- (Body Sheet metal) in which the cabin and box structure and the closures, etc. were converted to aluminum. The suspension system is the second highest system for mass reduction and includes composite fiber leaf springs. Mass reduction technologies with cost save examples include 1) material and design optimization in the connecting rods, 2) material and design through use of vespel thrust washer versus roller bearings, 3) material processing in the Polyone and Mucell applications, 4) material substitution in the thermoplastic vulcanizates (TPV) vs. EPDM static and dynamic weather seals, 5) material and part consolidation in the passenger side airbag housings, and 6) design and processing through incorporation of the half shafts and the Vari-lite® tube process by U.S. Manufacturing Corporation. A complete listing of vehicle technologies can be found in the online report[437] and Figure 5.57 shows that there was a 50kg and $150 allowance for NVH considerations.

			Mass Reduction Impact by Vehicle System (Includes Secondary Mass Savings)						
Item	System ID	Description	Base Mass "kg"	Mass Reduction "kg" (1)	Cost Impact NIDMC "$" (2)	Cost/ Kilogram NIDMC "$/kg" (2)	Cost/ Kilogram NIDMC + Tooling "$/kg" (2)	System Mass Reduction "%"	Vehicle Mass Reduction "%"
1500 Series Chevrolet Silverado Pick-Up Truck									
1	01	Engine System	239.9	31.8	-92.83	-2.92	-2.63	13.3%	1.3%
2	02	Transmission System	145.3	39.4	-96.57	-2.45	-2.47	27.1%	1.6%
3	03A	Body System Group -A- (Body Sheetmetal)	574.7	207.1	-1194.86	-5.77	-5.77	36.0%	8.4%
4	03B	Body System Group -B- (Body Interior)	247.0	34.0	-127.23	-3.74	-3.78	13.8%	1.4%
5	03C	Body System Group -C- (Body Exterior Trim)	40.5	2.1	2.73	1.28	1.28	5.3%	0.1%
6	03D	Body System Group -D- (Glazing & Body Mechatronics)	50.9	4.5	2.30	0.51	0.51	8.9%	0.2%
7	04	Suspension System	301.2	105.4	-154.90	-1.47	-1.48	35.0%	4.3%
8	05	Driveline System	183.8	20.4	38.01	1.86	1.89	11.1%	0.8%
9	06	Brake System	101.0	45.8	-148.92	-3.25	-3.35	45.4%	1.9%
10	07	Frame and Mounting System	267.6	23.7	-54.42	-2.30	-2.30	8.9%	1.0%
11	09	Exhaust System	38.1	6.9	-13.69	-1.97	-1.97	18.1%	0.3%
12	10	Fuel System	26.3	7.3	11.92	1.62	1.77	27.9%	0.3%
13	11	Steering System	32.5	8.5	-147.46	-17.44	-17.45	26.0%	0.3%
14	12	Climate Control System	20.3	1.9	14.71	7.59	7.59	9.5%	0.1%
15	13	Information, Gage and Warning Device System	1.6	0.2	0.66	2.66	2.97	15.7%	0.0%
16	14	Electrical Power Supply System	21.1	12.8	-172.73	-13.49	-13.44	60.6%	0.5%
17	15	In-Vehicle Entertainment System	2.2	0.0	0.00	0.00	0.00	0.0%	0.0%
18	17	Lighting System	9.6	0.4	-2.00	-5.18	-5.18	4.0%	0.0%
19	18	Electrical Distribution and Electronic Control System	33.6	8.5	61.44	7.26	7.27	25.2%	0.3%
20	00	Fluids and Miscellaneous Coating Materials	116.8	0.0	0.00	0.00	0.00	0.0%	0.0%
		a. Analysis Totals Without NVH Counter Measures →	**2454.4**	**560.9**	**-2073.82**	**-3.70**	**-3.69**	**n/a**	**22.9%**
		b. Vehicle NVH Counter Measures (Mass & Cost) →	0.0	-50.0	-150.00	**n/a**	**n/a**	**n/a**	**n/a**
		c. Analysis Totals With NVH Counter Measures →	**2454.4**	**510.9** (Decrease)	**-2223.82** (Increase)	**-4.35** (Increase)	**-4.35** (Increase)	**n/a**	**20.8%**

(1) Negative value (i.e., **-X.XX**) represents an increase in mass
(2) Negative value (i.e., **-$X.XX**) represents an increase in cost

Figure 5.57 Light Duty Pickup Truck Lightweighting Study Results

The individual technology mass and cost saving used to develop the system summaries listed in Figure 5.57 were used to develop EPA's cost curve for the light duty pickup truck lightweighting study, as shown in Figure 5.58. It should be noted that the blue squares are individual solutions and are not based on the cost curve technology points which lead to the red square solution point.

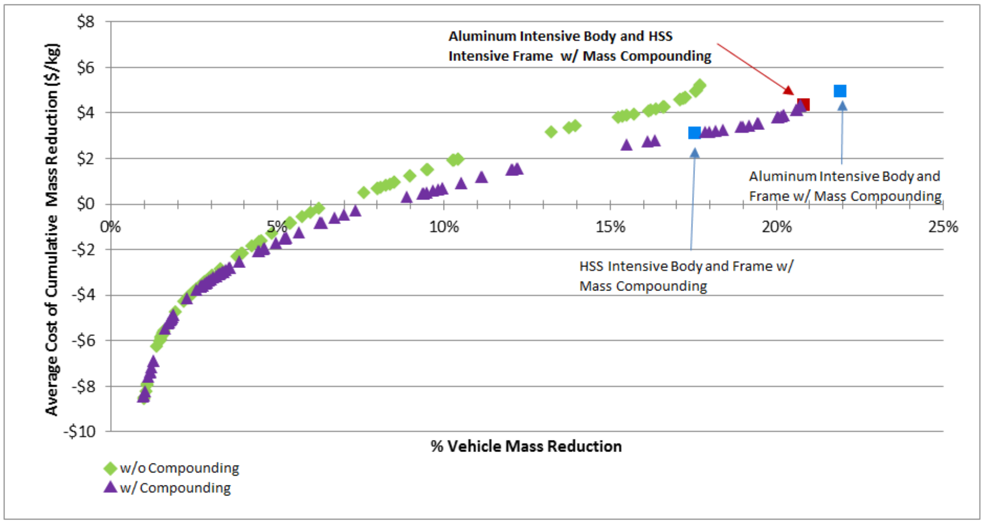


Figure 5.58 Light Duty Pickup Truck Lightweighting Cost Curve

The curve without compounding in Figure 5.58 (green curve) includes primary mass reduction ideas which do not depend on the vehicle being made lighter. The mass reduction ideas based on a resultant lighter vehicle are called secondary mass saving ideas and are based on components decreasing in size and hence material. In this study the engine was able to be downsized 7 percent due to the mass reduction in the vehicle design and still maintain the current towing and hauling capacities. The other systems that were reduced in size, while considering truck performance characteristics, included the transmission, body system group A (bumpers), suspension, brake, frame and mounting systems, exhaust, and fuel systems. The systems considered for secondary mass are included in Figure 5.59 and show the total 83.9kg mass save at $68.74 savings. Overall, the secondary mass savings are 17.6[KK] percent of the primary. The compounded curve in Figure 5.58 is the EPA light duty truck cost curve utilized in the development of the overall cost curve for light duty trucks described in section 5.3.

[KK] % Secondary Mass = 560.9 compounded-83.9secondary =477kg primary, 83.9/477 = 17.6% secondary.

Item	System ID	Description	Base Mass "kg"	Mass Reduction with SMS "kg" (1)	Mass Reduction without SMS "kg" (1)	Incremental Mass Reduction from SMS "kg" (1)	Cost Impact NIDMC with SMS "$" (2)	Cost Impact NIDMC without SMS "$" (2)	Savings from SMS "$" (2)	Cost/ Kilogram NIDMC with SMS "$/kg" (2)	Cost/ Kilogram NIDMC without SMS "$/kg" (2)	Cost Savings/ Kilogram NIDMC from SMS "$/kg" (2)
			Secondary Mass Savings (SMS) Impact by Vehicle System									
1500 Series Chevrolet Silverado Pick-Up Truck												
1	01	Engine System	239.9	31.8	23.8	8.0	-92.83	-114.63	21.81	-2.92	-4.82	1.90
2	02	Transmission System	145.3	39.4	34.2	5.2	-96.57	-128.20	31.64	-2.45	-3.75	1.30
3	03A	Body System Group - A- (Body Sheetmetal)	574.7	207.1	190.7	16.4	-1194.86	-1125.15	-69.71	-5.77	-5.90	0.13
7	04	Suspension System	301.2	105.4	83.1	22.4	-154.90	-260.84	105.94	-1.47	-3.14	1.67
9	06	Brake System	101.0	45.8	43.9	2.0	-148.92	-167.87	18.95	-3.25	-3.83	0.58
10	07	Frame and Mounting System	267.6	23.7	0.0	23.7	-54.42	0.00	-54.42	-2.30	0.00	-2.30
11	09	Exhaust System	38.4	6.9	6.3	0.6	-13.69	-19.54	5.85	-1.97	-3.08	1.11
12	10	Fuel System	26.3	7.3	1.6	5.7	11.92	3.25	8.67	1.62	2.02	-0.40
		a. Analysis Totals Without NVH Counter Measures →	**1694.5**	**467.5**	**383.6**	**83.9**	**-1744.26** (Increase)	**-1813.00** (Increase)	**68.74**	**-3.73** (Increase)	**-4.73** (Increase)	**0.82**

(1) Negative value (i.e., -X.XX) represents an increase in mass
(2) Negative value (i.e., -$X.XX) represents an increase in cost

Figure 5.59 Light Duty Pickup Truck Lightweighting Study Secondary Mass

5.2.7.4.2 NHTSA Holistic Vehicle Mass Reduction/Cost Studies

NHTSA funded two holistic vehicle mass reduction/cost studies for the Midterm Evaluation. The first lightweighting study was performed on a 2011MY Honda Accord as the base vehicle, with Electricore, Inc., George Washington University and EDAG, Inc. and was completed in 2012[438]. EDAG was also rehired to re-evaluate the public study feedback received from Honda on the project as well as evaluate the mass add for IIHS Small Overlap for the passenger car. This study was completed in February 2016. The second was a lightweighting study on a 2014MY light duty pickup truck, Silverado 1500 as the base vehicle, and was performed by EDAG, Inc. using a similar methodology to the passenger car work and is expected to be completed in 2016.

5.2.7.4.2.1 Updated Midsize Car Lightweight Vehicle Study

At the time of the original 2012 passenger car lightweighting study[438], NHTSA did not consider IIHS small overlap test performance as part of overall safety assessment of light-weighted vehicle. Honda commented on the above light-weighted study and highlighted some of the performance, build quality, platform sharing and other customer experience constraints that should be taken into consideration. NHTSA updated the above Honda Accord light-weighted vehicle study in the new report "Update to Future Midsize Lightweight Vehicle Findings in Response to Manufacturer review and IIHS Small-Overlap Testing."[439] The mass and cost adjustments in response to Honda's comments resulted in 21.75kg less mass reduction from the original light-weighted vehicle and an increase cost of $18.13. Further, to address IIHS small overlap test, the mass of the light-weighted vehicle had to be increased by another 6.9kg with $26.88 increased cost on top of $18.13. The resultant cost curve is displayed in Figure 5.60. LWV1.0 is the original AHSS BIW and Aluminum Closures and Chassis Frames solution point. LWV 1.1 includes the corrections based on the Honda feedback and LWV 1.2 includes the Honda feedback as well as the IIHS SOL mass and cost add. This cost curve has been further revised for the Draft TAR as discussed below.

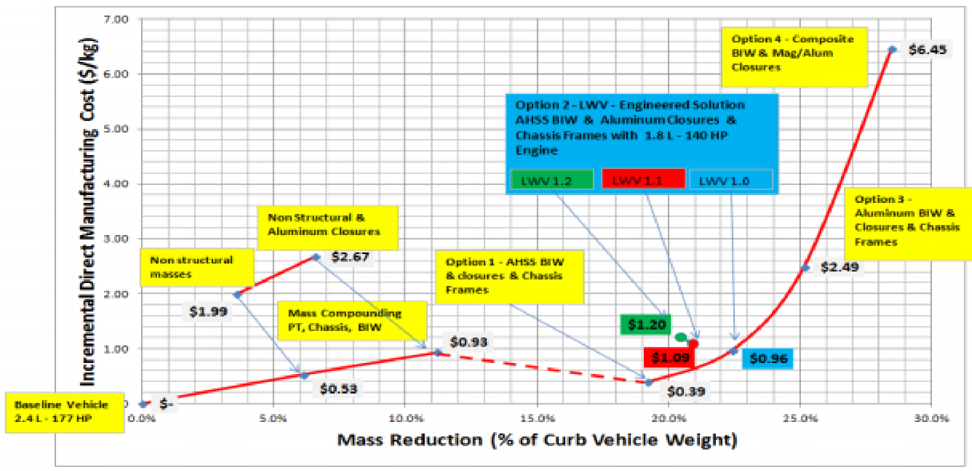


Figure 5.60 NHTSA Passenger Car Updated Cost Curve (DMC($/kg) v %MR)[442]

The final light-weighted vehicle (LWV 1.2 Solution) had mass reduction of 303.65kg compared to the baseline vehicle at the cost of $364.01 after accounting for Honda's recommendation and IIHS small overlap tests. The green point in the cost plot in Figure 5.60 shows revised cost and mass reduction levels after consideration of Honda's recommendations and the mass addition to meet IIHS small overlap test performance. As explained in section 5.2.7.4.2, NHTSA developed cost curve based on the LWV solution point which is explained in detail in section 5.4.

NHTSA realized some limitations in the form of the cost curve in Figure 5.60. Since the cost curve was derived more at the systems level, a more detailed cost curve was developed using cumulative mass savings approach from each of the components considered for mass reduction opportunities. Figure 5.61 shows the cost curve developed from Honda Accord light-weighted vehicle. Table 5.16 shows the list of components considered for mass reduction. Note here the LWV solution is represented as AHSS+AL solution point in the cost curve below.

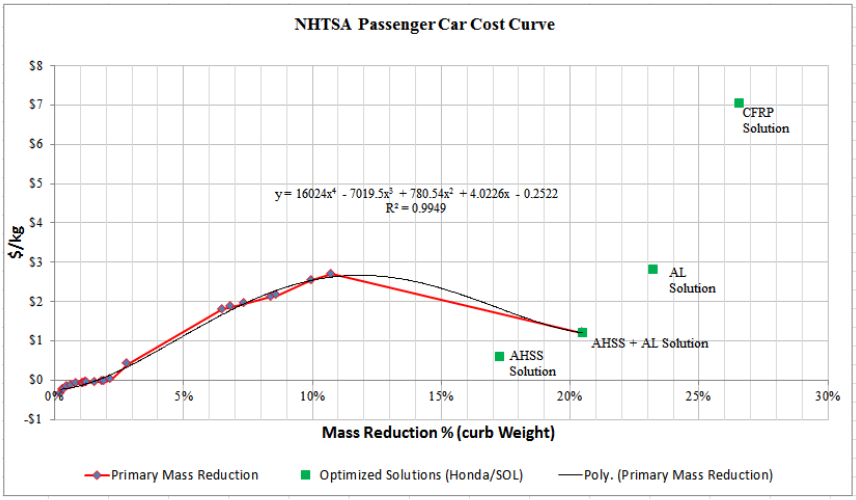


Figure 5.61 NHTSA Revised Passenger Car DMC Curve (($/kg v %MR) and ($/vehicle v %MR))

Table 5.16 shows list of components considered for mass reduction and used for constructing the passenger car cost curve.

Table 5.16 Components for LWV Solution

Vehicle Component/System	Cumulative Mass Saving (kg)	Cumulative MR%	Cumulative Cost ($)	Cumulative Cost $/kg
Front Bumper	3.59	0.24%	-1.23	-0.34
Front Door Trim	4.93	0.33%	-1.23	-0.25
Front Door Wiring Harness	5.23	0.35%	-1.23	-0.24
Head Lamps	6.94	0.47%	-1.23	-0.18
HVAC	9.54	0.64%	-1.23	-0.13
Insulation	12.74	0.86%	-1.23	-0.10
Interior Trim	15.77	1.07%	-1.23	-0.08
Parking Brake	16.76	1.13%	-1.23	-0.07
Rear Door Trim	17.89	1.21%	-1.23	-0.07
Rear Door Wiring Harness	18	1.22%	-1.23	-0.07
Tail Lamps	18.63	1.26%	-1.23	-0.07
Tires	23.08	1.56%	-1.23	-0.05
Wiring and Harness	27.38	1.85%	-1.23	-0.04
Wheels	28.82	1.95%	-$1.23	-0.04
Rear Bumper	32.33	2.18%	$0.53	0.02
Instrument Panel	41.78	2.82%	$17.27	0.41
Body Structure	96.18	6.50%	$173.13	1.80
Decklid	101.39	6.85%	$188.97	1.86
Hood	108.86	7.36%	$211.49	1.94
Front Door Frames	124.26	8.40%	$262.88	2.12
Fenders	127.53	8.62%	$274.98	2.16
Seats	147.56	9.97%	$374.02	2.53
Rear Door Frames	159.02	10.74%	$428.47	2.69
Powertrain components (Engine, transmission, Fuel system, Exhaust system, coolant system), Brakes etc.	302.92	20.5%	364.37	1.20

5.2.7.4.2.2 Light Duty Pickup Truck Light-Weighting Study

The Department of Transportation National Highway Traffic Safety Administration (NHTSA) awarded a contract to an automotive design and engineering company EDAG, Inc., to conduct a vehicle weight reduction feasibility and cost study of a 2014MY full size pick-up truck. The light weighted version of the full size pick-up truck (LWT) used manufacturing processes that will likely be available during the model years 2025-2030 and capable of high volume production. The goal was to determine the maximum feasible weight reduction while maintaining the same vehicle functionalities, such as towing, hauling, performance, noise, vibration, harshness, safety, and crash rating, as the baseline vehicle, as well as the functionality and capability of designs to meet the needs of sharing components across same or cross vehicle platform. Consideration was also given to the sharing of engines and other components with vehicles built on other platforms to achieve manufacturing economies of scale, and in recognition of resource constraints which limit the ability to optimize every component for every vehicle. At the time of writing for this Draft TAR, the report is in peer review and will be finalized by the NHTSA NPRM and EPA Proposed Determination in 2017.

A comprehensive teardown/benchmarking of the baseline vehicle for engineering analysis that included manufacturing technology assessment, material utilization and complete vehicle geometry scanning was performed. The baseline vehicle's overall mass, center of gravity and all key dimensions were determined. Before the vehicle teardown, laboratory torsional stiffness tests, bending stiffness tests and normal modes of vibration tests were performed on baseline vehicles so that these results can be compared with the CAE model of the light weighted design. After conducting a full tear down and benchmarking of the baseline vehicle, a detailed CAE model of the baseline vehicle was created and correlated with the available crash test results. The project team then used computer modeling and optimization techniques to design the light-weighted pickup truck and optimized the vehicle structure considering redesign of structural geometry, material grade and material gauge to achieve the maximum amount of mass reduction while achieving comparable vehicle performance as the baseline vehicle. Only technologies and materials projected to be available for large scale production and available within two to three design generations (e.g. model years 2020, 2025 and 2030) were chosen for the LWT design. Three design concepts were evaluated, a multi-material approach, an aluminum intensive approach and a Carbon Fiber Reinforced Plastics (CFRP) approach. The multi-material approach was identified as the most cost effective. The recommended materials (advanced high strength steels, aluminum, magnesium and plastics), manufacturing processes, (stamping, hot stamping, die casting, extrusions, and roll forming) and assembly methods (spot welding, laser welding, riveting and adhesive bonding) are at present used, some to a lesser degree than others. These technologies can be fully developed within the normal product design cycle using the current design and development methods.

The design of the LWT was verified, through CAE modeling, that it meets all relevant crash tests performance. The LS-DYNA finite element software used by the EDAG team is an industry standard for crash simulation and modeling. The researchers modeled the crashworthiness of the LWT design under the NCAP Frontal, Lateral Moving Deformable Barrier, and Lateral Pole tests, along with the IIHS Roof, Lateral Moving Deformable Barrier, and Frontal Offset (40 percent and 25 percent) tests. All of the modeled tests were comparable to the actual crash tests performed on the 2014 Silverado in the NHTSA database. Furthermore, the FMVSS No. 301 rear impact test was modeled and it showed no damage to the fuel system.

The baseline 2014 MY Chevrolet Silverado was platform shares components across several platforms. Some of the chassis components and other structural components were designed to accommodate platform derivatives, similar to the components in the baseline vehicle which are shared across platforms such as GMT 920 (GM Tahoe, Cadillac Escalade, GMC Yukon), GMT 930 platform (Chevy Suburban, Cadillac Escalade ESV, GMC Yukon XL), and GMT 940 platform (Chevy Avalanche and Cadillac Escalade EXT) and GMT 900 platform (GMC Sierra). As per the National Academy of Sciences guidelines, the study assumes engines would be downsized or redesigned for mass reduction levels at or greater than 10 percent. As a consequence of mass reduction, several of the components used designs that were developed for other vehicles in the weight category of light-weighted designed vehicles were used to maximize economies of scale and resource limitations. Examples include brake systems, fuel tanks, fuel lines, exhaust systems, wheels etc.

Cost is a key consideration when vehicle manufacturers decide which fuel-saving technology to apply to a vehicle. Incremental cost analysis for all of the new technologies applied to reduce mass of the light-duty full-size pickup truck designed were calculated. The cost estimates include variable costs as well as non-variable costs, such as the manufacturer's investment cost for tooling etc. The cost estimates include all the costs directly related to manufacturing the components. For example, for a stamped sheet metal part, the cost models estimate the costs for each of the operations involved in the manufacturing process, starting from blanking the steel from coil through the final stamping operation to fabricate the component. The final estimated total manufacturing cost and assembly cost are a sum total of all the respective cost elements including the costs for material, tooling, equipment, direct labor, energy, building and maintenance.

The information from the LWT design study was used to develop a cost curve representing cost effective full vehicle solutions for a wide range of mass reduction levels. The cost curve is shown in Figure 5.54. At lower levels of mass reduction, non-structural components and aluminum closures provide weight reduction which can be incorporated independently without the redesign of other components and are stand-alone solutions for the LWV. The holistic vehicle design using a combination of AHSS and aluminum provides good levels of mass reduction at reasonably acceptable cost. The LWV solution achieves 17.6 percent mass reduction from the baseline curb mass. Further two more analytical mass reduction solutions (all aluminum and all carbon fiber reinforced plastics) were developed to show additional mass reduction that could be potentially achieved beyond the LWV mass reduction solution point. The Aluminum analytical solution predominantly uses aluminum including chassis frame and other components. The carbon fiber reinforced plastics analytical solution predominantly uses CFRP) in many of the components. The CFRP analytical solution shows higher level of mass reduction but at very high costs. Note here that both all-Aluminum and all CFRP mass reduction solutions are analytical solutions only and no computational models were developed to examine all the performance metrics.

An analysis was also conducted to examine the cost sensitivity of major vehicle systems to material cost and production volume variations.

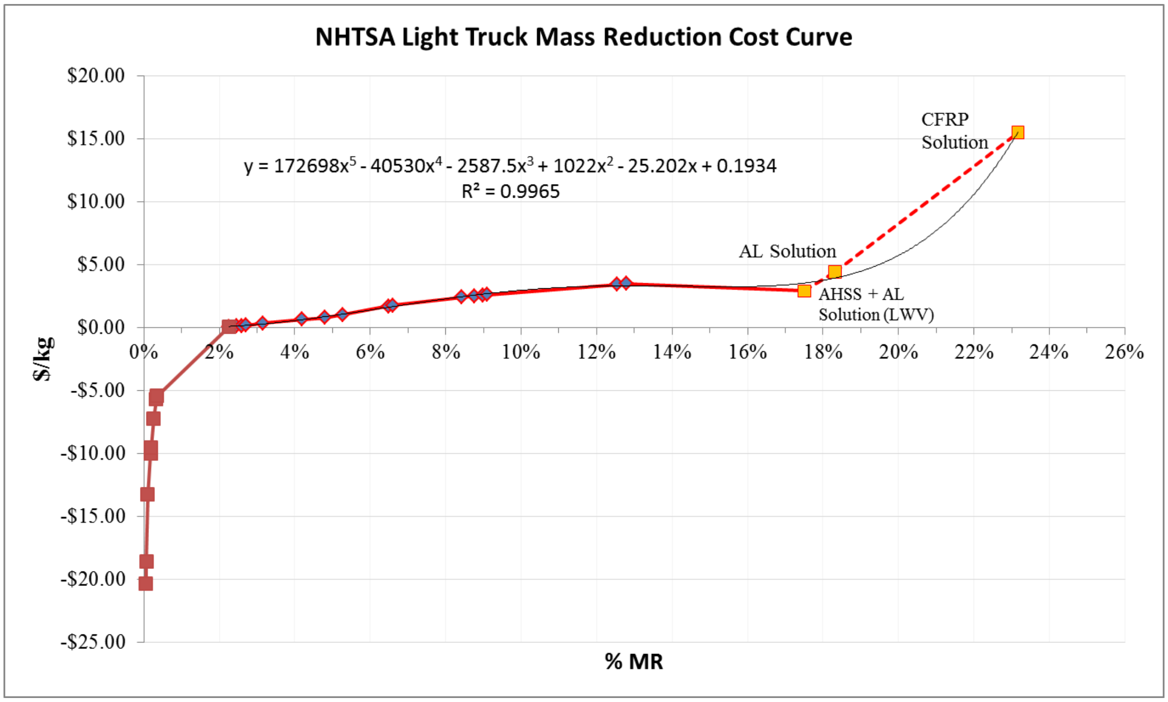


Figure 5.62 NHTSA Draft Light Duty Pickup Truck Lightweighting (AHSS Frame with Aluminum Intensive) Cost Curve (DMC $/kg v %MR)

Table 5.17 Components for LWV Solution, below lists the components included in the various levels of mass reduction for the LWV solution. The components are incorporated in a progression based on cost effectiveness.

Table 5.17 Components for LWV Solution

Vehicle Component/System	Cumulative Mass Saving	Cumulative MR%	Cumulative Cost	Cumulative Cost $/kg
Interior Electrical Wiring	1.38	0.06%	($28.07)	-20.34
Headliner	1.56	0.06%	($29.00)	-18.59
Trim - Plastic	2.59	0.11%	($34.30)	-13.24
Trim - misc.	4.32	0.18%	($43.19)	-10.00
Floor Covering	4.81	0.20%	($45.69)	-9.50
Headlamps	6.35	0.26%	($45.69)	-7.20
HVAC System	8.06	0.33%	($45.69)	-5.67
Tail Lamps	8.46	0.35%	($45.69)	-5.40
Chassis Frame	54.82	2.25%	$2.57	0.05
Front Bumper	59.93	2.46%	$7.89	0.13
Rear Bumper	62.96	2.59%	$11.04	0.18
Towing Hitch	65.93	2.71%	$14.13	0.21
Rear Doors	77	3.17%	$28.09	0.36
Wheels	102.25	4.20%	$68.89	0.67
Front Doors	116.66	4.80%	$92.53	0.79
Fenders	128.32	5.28%	$134.87	1.05
Front/Rear Seat & Console	157.56	6.48%	$272.57	1.73
Steering Column Assy	160.78	6.61%	$287.90	1.79
Pickup Box	204.74	8.42%	$498.35	2.43
Tailgate	213.14	8.76%	$538.55	2.53
Instrument Panel	218.66	8.99%	$565.06	2.58
Instrument Panel Plastic Parts	221.57	9.11%	$580.49	2.62
Cab	304.97	12.54%	$1,047.35	3.43
Radiator Support	310.87	12.78%	$1,095.34	3.52
Powertrain	425.82	17.51%	1246.68	2.93

A fitted curve was developed based on the above listed mass reduction points to derive cost per kilogram at distinct mass reduction points as shown in Table 5.18 below.

Table 5.18 Costs Per Kilogram at Various %MR Points

MR%	$/kg
5.0%	$0.97
7.5%	$2.09
10.0%	$2.98
15.0%	$3.27
20.0%	$5.75

As explained above, the total direct manufacturing costs for the components listed above are shown Figure 5.63 below.

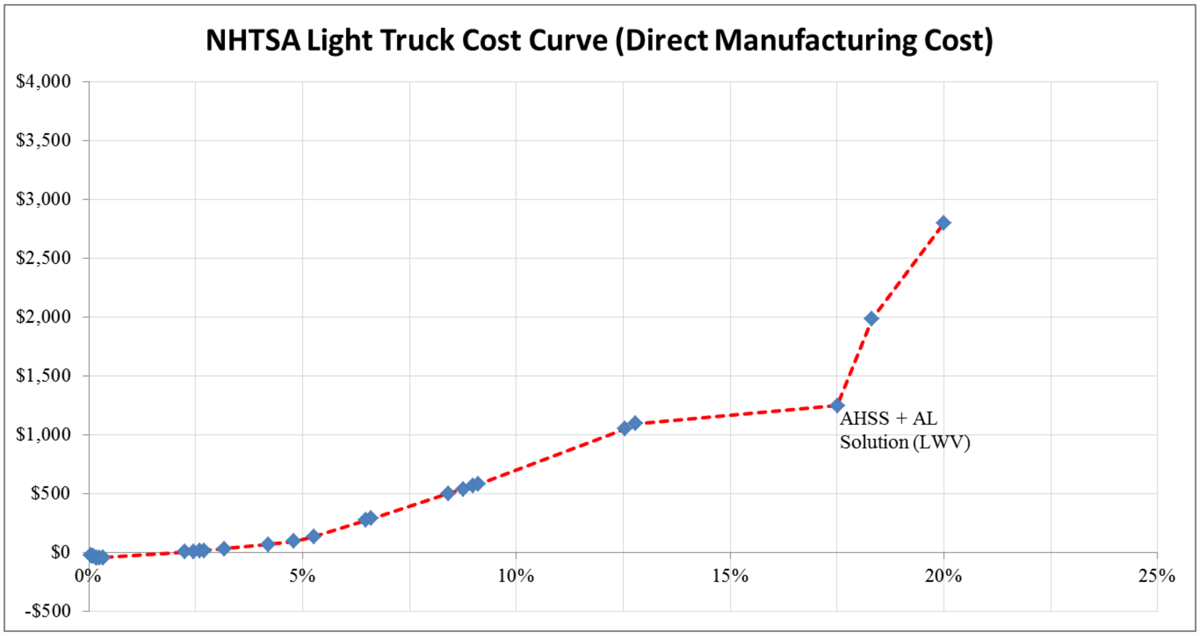


Figure 5.63 NHTSA Light Truck Cost Curve (Direct Manufacturing Costs) $/vehicle vs %MR

Table 5.19 shows the direct manufacturing costs are distinct mass reduction levels.

Table 5.19 Direct Manufacturing Costs at MR0-MR5

LT Baseline Curb Wt. 2432 kg	Mass Reduction (kg)	DMC ($)[LL]
MR0	0	$0
MR1 - 5%	122	$118
MR2 - 7.5%	182	$381
MR3 - 10%	243	$725
MR4 - 15%	365	$1193
MR5 - 20%	486	$2797

5.2.7.4.3 *ARB Holistic Vehicle Mass Reduction/Cost Study*

The California Air Resources Board funded Lotus Engineering on further analysis of in-depth cost and CAE, of the Phase 2 High Development of the Midsize CUV[440]. The project focused on

[LL] Value calculated from best fit curve in previous figure, not from figure above table.

the BIW design through CAE and more in-depth costing of the BIW. A full vehicle solution point was developed by adding the cost and mass save results of the BIW analysis to the cost and mass save information on the other vehicle systems from the Phase 1 work.[441] The report changed the original BIW design of 30 percent magnesium, 37 percent aluminum, 6.6 percent steel and 21 percent composites to one of 12 percent magnesium, 75 percent aluminum, 8 percent steel and 5 percent composites, shown in Figure 5.65. The report states that its BIW design reduced the number of parts from 419 parts in the baseline Venza to 169 parts in the low mass design. Specifically the report states "By factoring in the manufacturability of the materials and designs into the fundamental design process, it is expected that … this type of design [will] be production ready in 2020."

The summary write-up for this work is contained within the LD GHG 2017-2025 FRM Joint Technical Support Document. A cost curve was not developed for this work. Values of cost and overall mass reduction were located in several areas of the report. The overall results, including all of the mass reduction items in the Phase 1 report and including powertrain were taken from Table 4.5.7.2.f. totaling 531.2kg reduced (31 percent of 1711kg) and the total cost was taken from the 4.6.1. Conclusions section of $342/vehicle cost save. The cost per kilogram for this solution is calculated as -$0.64/kg cost save. This point, along with two other all aluminum vehicle solution points - one by NHTSA and the other by the Aluminum Association, helps to indicate the direction for additional mass reduction beyond the AHSS BIW/Aluminum closure solution on which the cost curve for the passenger car/Midsize CUV is based.

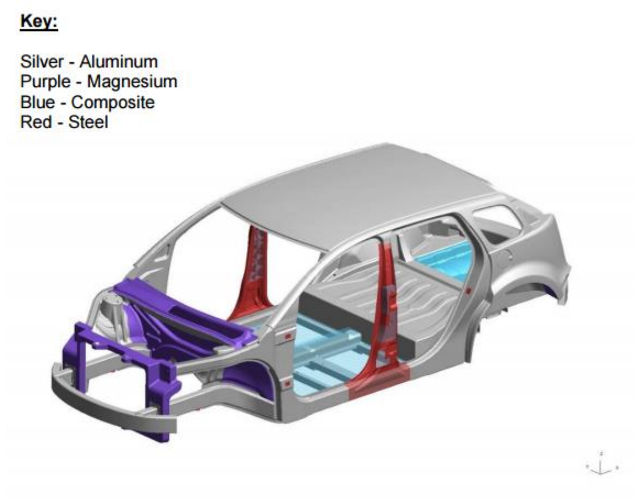


Figure 4.2.3.a: Body-in-white material usage front three-quarter view

Figure 5.64 Phase 2 High Development BIW - Lotus Engineering

5.2.7.4.4 Aluminum Association Midsize CUV Aluminum BIW Study

The Aluminum Association funded a project with EDAG, Inc.[442] in 2012 to perform an aluminum substitution analysis in the BIW of the Midsize CUV work by EPA using the EPA CAE baseline model for the work. The baseline model was also developed by EDAG, Inc. The analyses utilized CAE crash safety and NVH verifications when determining the specifics, gauge and grade, of the aluminum to be utilized in the BIW (Figure 5.65).

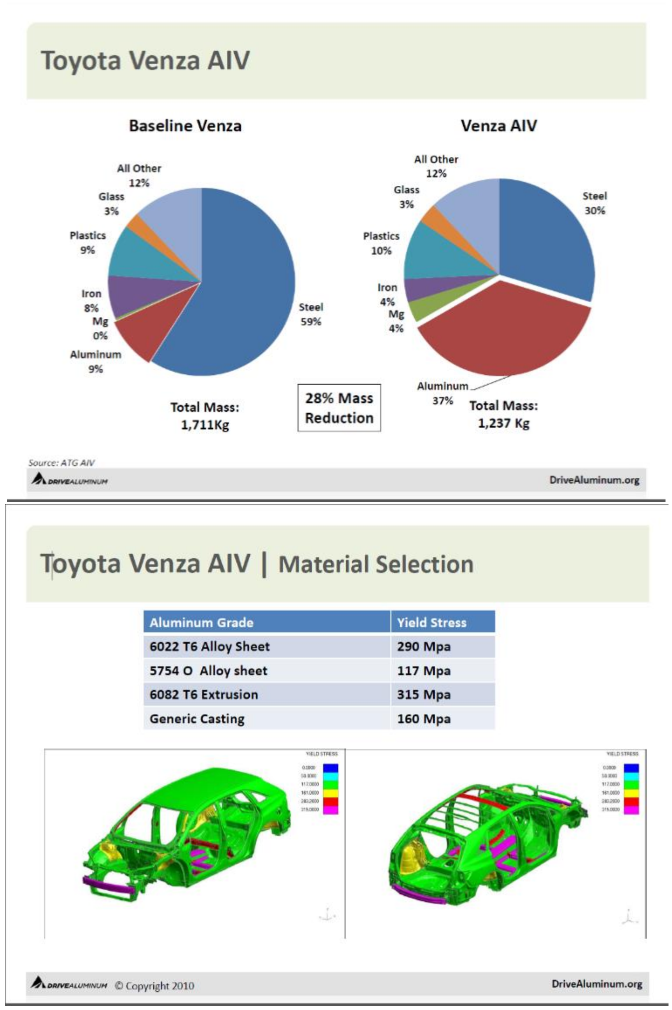


Figure 5.65 Midsize CUV Baseline vs Midsize CUV Aluminum Intensive Vehicle

Description	Estimated Mass Reduction "Kg"	Estimated Cost Impact "$"	Average Cost/ Kilogram "$/Kg"
Body Structure Subsystem			
Underbody Asy	19.8	-67.56	-3.41
Front Structure Asy	14.3	-121.84	-8.49
Roof Asy	14.6	-44.81	-3.07
Bodyside Asy	72.2	-306.60	-4.25
Ladder Asy	38.1	-235.53	-6.19
Bolt on BIP Components	3.2	-3.97	-1.23
Body Closure Subsystem			
Hood Asy	7.7	-27.70	-3.62
Front Door Asy	15.0	-21.65	-1.44
Rear Door Asy	11.3	-19.31	-1.70
Rear Hatch Asy	7.2	-21.21	-2.93
Front Fenders	2.0	-16.22	-8.25
Bumpers Subsystem			
Front Bumper Asy	2.3	-8.60	-3.82
Rear Bumper Asy	0.0	0.00	0.00
Totals	207.7	-895.01	-4.31
"+" = mass decrease, "-" = mass increase			
"+" = cost decrease, "-" = cost increase			

Figure 5.66 Summary Table of Mass Reduction and Cost for Aluminum BIW and Closure Components

Figure 5.66 lists the results from aluminum material substitution into the existing BIW and closures. When combined with the remaining mass and cost saved identified in the U.S. EPA Midsize CUV report, resulted in a $1.12/kg for 27.8 percent mass reduction for the entire vehicle, as shown in Table 5.20. This data point is included in the overall cost curve shown in Figure 5.55.

Table 5.20 Summary of the Automotive Aluminum 2025

	Multi-Material (MMV - EPA low dev)	Aluminum (AIV)
Body and Closure MR	-14%	-39%
Total Vehicle MR	-19.2%	-27.8% (-476kg)
Cost Impact	-$0.23/kg	$1.12/kg (+$534)*

*Note: Full Vehicle Mass Optimization

5.2.7.4.5 *DOE/Ford/Magna MMLV Mach 1 and Mach 2 Lightweighting Research Projects*

The Multi Material Lightweight Vehicle (MMLV) project was initiated in 2012 by the Department of Energy and co-funded by Magna International and Ford Motor Corporation under the project number DE-EE0005574. The objectives of the project included identifying 25 percent (Mach 1) and 50 percent (Mach 2) vehicle mass reduction packages. This work was peer reviewed through the DOE AMR and the SAE publication processes. The "Multi-Material Lightweight Vehicles" presentation, which was a combination of the Mach 1 and Mach 2 projects, was peer reviewed at the 2015 DOE AMR in front of a panel of experts in the field and the results of the peer review were included in the final report for the DOE AMR.[443] The project received a weighted average score of 3.77 out of 4.0 and was measured on reviewer questions related to approach, technical accomplishments, collaborations, and future research. The results were also presented in a number of SAE papers and hence reviewed through the SAE publication process.

The DOE/Ford/Magna developed the lightweight vehicle solutions off of a 2013MY Ford Fusion platform (used to represent a 2002 Ford Taurus). Results include 23.5 percent for the Mach 1 design. Seven vehicles were built and the vehicles, and certain components, were tested under a series of durability tests. New technologies of composite fiber springs, carbon fiber wheels, seat back frame, and the multi-material body structure were included in the durability tests. For the Mach 2 design, 50 percent mass reduction is achieved however the vehicle is not market viable due to extensive de-contenting and use of materials that are not yet ready for full volume production including composite "tub" package tray and roof. A comparison of the MMLV structures weight for BIW, Closure, Chassis and Bumper is displayed in Figure 5.67.

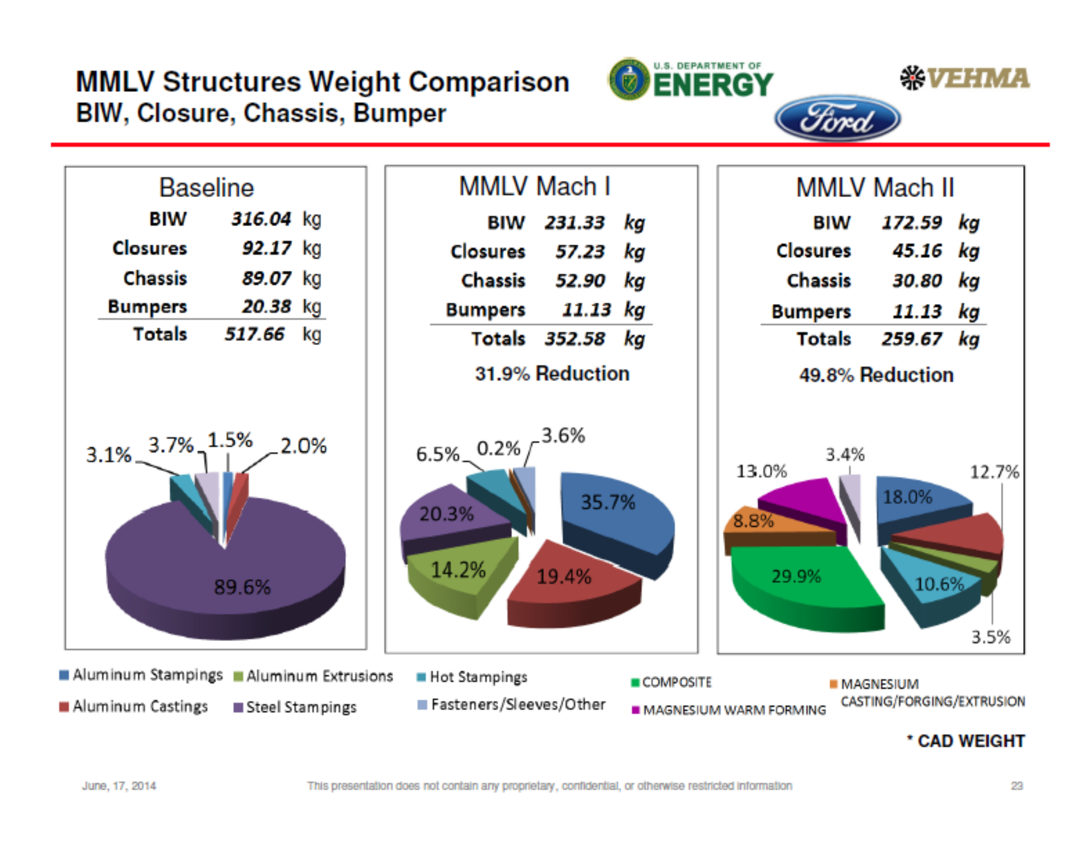


Figure 5.67 MMLV Structures Weight Comparison BIW, Closure, Chassis, Bumper[444]

Gaps identified by the MMLV projects (I and II) include those listed in Table 5.21.

Table 5.21 Gaps Identified by MMLV Project

Topic	GAP
Steel	Improved coatings on ultra-high strength steels for multi material applications
Aluminum	Increased die life and bi-metallic (inserts, etc.) for Al die castings plus low cost 7xxx aluminum sheet and extrusions
Magnesium	High volume warm forming, hemming, class A finish, plus improved die life and bi-metallic inserts in high pressure vacuum die casting
Carbon Fiber Composites	Material characterization for CAE, joining, corrosion, paint, class-A finish
Multi Material Vehicles	Corrosion mitigation strategy including universal equivalent of phosphate (or eqiuv) bath for any mix of steel, aluminum and magnesium before e-coat and paint
	Joining methods with corrosion mitigation
	Aluminum rivet, high hardness, high strength
	Alternative NVH treatments for lightweight panels sheet metal and glazings
	Design for disassembly, end of life, for reclaiming, recycling

No cost analysis was performed for the Mach 1 study. A 40-45 percent MR cost analyses from the base 2013MY vehicle was completed under a separate DOE project, through Idaho National Laboratories performed by IBIS Associates Inc., and results indicate the cost of carbon fiber must decrease in order to make the technology viable for mass market vehicles.[445] This project is described in 5.2.7.4.6.

5.2.7.4.5.1 Mach I

The MMLV Mach I project achieved 364 kg (23.5 percent) mass reduction from the baseline weight of the 2013 Ford Fusion (representing a 2002 Ford Taurus). Seven prototype vehicles were built and these vehicles were used to conduct a number of test such as, corrosion, durability, NVH (noise vibration harshness), and crash. Maintaining performance and capabilities, along with safety and durability were also goals of the MMLV. All parts used in the MMLV are either low volume or high volume production capable up to 250,000 vehicles per year. The Mach I mass reduction was achieved using materials such as aluminum, carbon fibers, magnesium, and high strength steels. Results of the Mach I project were presented in 14 SAE papers.[446],[447],[448],[449],[450],[451],[452],[453],[454],[455],[456],[457],[458]

The Mach I project group presented an estimate of the fuel economy improvement at the 2015 SAE World Congress 2015 as being an increase to 34 mpg from 28 mpg. This change in fuel economy was estimated by taking the fuel economy of a Ford Fiesta (which is the equivalent weight of the lightweight Mach-I) and comparing to the 2013 Ford Fusion. The fuel economy numbers were from fueleconomy.gov. Key requirements of durability, safety, and Noise Vibration Harshness (NVH) were also met within the Mach I design as illustrated in a report presentation at the 2015 DOE AMR.[459] All components of the MMLV were specifically chosen for optimal weight reduction without shorting on performance or technicality.

Five subsystems of the mach-i compared to the baseline 2013 fusion of full body mass reduction.[459]

- The body-in-white (BIW) and closures contributed 76 kg (4.9percent) to the overall vehicle mass reduction. The baseline 2013 BIW is 326 kg and the Mach-I BIW is 250 kg. The 2013 Fusion BIW is steel intensive, and the Mach-I design included advanced high strength steels were integrated for use as primary safety structures like crush rails, B-pillars, and selected cross car beams. Closures in the Mach 1 were aluminum intensive. The transition from steel to aluminum is also the primary design strategy for the light weighting of the deck lid, and front fenders, as well as the side door structures and hinges. Also, chemically foamed plastics were used in the door design as trim.
- Body Interior and Climate Control consists of the seats, floor components, instrument panel/ cross car beam (IP/CCB), and climate control system which contributed 28 kg (1.8 percent) to the overall vehicle mass reduction. The IP/CCB decreased in part count from 71 to 21, new material design involved carbon fiber reinforce nylon from the baseline welded assembly of steel stampings and tubes. The material selection of the seat structures was carbon fiber reinforced nylon composite compared to the baseline steel stampings and tubes.
- Chassis subsystem reduced its total mass by 98 kg (6.3 percent) to the overall vehicle mass reduction. The major components identified in the Mach 1 subsystem include hollow coil springs, carbon fiber wheels, and tires with a tall and narrow design, hollow steel stabilizer bars, aluminum sub frames, control arms and links.
- The powertrain subsystem was reduced by 73 kg (4.7 percent) to the overall vehicle mass reduction. The baseline engine is a 1.6 liter four-cylinder gasoline turbocharged direct injection (EcoBoost) with a six-speed automatic transmission. The Mach-I design has a 1.0 liter three-cylinder gasoline turbocharged direct injection (Fox EcoBoost) with a mass reduced six-speed automatic transmission. The use of carbon fiber within this subsystem encouraged mass reduction and include components such as the engine oil pan.
- The electrical subsystem achieved a 10 kg (0.64 percent overall vehicle mass reduction). A few adjustments were made to accomplish this number. The battery was switched to a lithium ion 12-volt start battery from the baseline lead-acid battery. The change of the battery achieved 5 kg mass reduction. Also, copper electrical distribution wiring was replaced with aluminum conductors meeting a 4 kg mass reduction. The remaining 1 kg mass reduction was achieved by small adjustments to the speakers, alternator, and the starter motor.

DESIGN AND FUNCTION VALIDATION: The Mach-I used computer aided engineering (CAE) for many safety simulations due to low budget, however several vehicles were used to perform a number of actual vehicle safety crashes. Many computer aided designs (CAD) and CAE tests were performed initially before the vehicle components were manufactured and/or physically tested. Seven MMLV Mach-I vehicles were built and selectively tested. Seven different validation tests were completed as listed in Table 5.22.

Table 5.22 Safety Tests Performed on the Mach-I.

VEHICLE	TESTING
Test Buck	Body-in-White + Closures + Bumpers + Glazing + Front Subframe - Body-in-Prime NVH modes, global stiffness, attachment stiffness, selected Durability
Durability A	DRIVABLE, full MMLV content with Fusion powertrain - MPG Structural Durability, Square Edge Chuckhole Test for Wheels and Tires
Corrosion A Traditional Surface Treatments	DRIVABLE, with alternative surface treatment and paint process - MPG Corrosion R-343. Humidity soaks and salt spray etc.
Corrosion B MMLV Alternative Surface Treatments	DRIVABLE, with traditional surface treatment and paint process - MPG Corrosion R-343. Humidity soaks and salt spray etc.
Safety A	NON-Drivable, most MMLV content, without carbon fiber instrument panel - Low Speed Damageability test (front) Right Hand (passenger) side - IIHS Front ODB 40% Offset 40 mph, Left Hand (driver) side - Side Pole Test on Right Hand (passenger) side (FMVSS 214)
Safety B	NON-Drivable, most MMLV content, without carbon fiber instrument panel - NCAP Frontal 35 mph rigid wall, then 70% Offset Rear Impact (FMVSS 301)
NVH + Drives	DRIVABLE, full MMLV content with downsized and boosted powertrain, 1.0-liter I3 EcoBoost, gasoline turbocharged direct injection engine plus six-speed manual transmission - Wind Tunnel, Rough Road Interior Noise, Engine & Tire Noise, Ride & Handling

The overall outcome of the safety and durability tests provided assurance a multi-material lightweight vehicle was successful. Noise Vibration Harshness was tested in a high frequency range of 200-10000 Hz and fell within acceptability but slightly short of requirements. Durability test classified the Mach-I as a durable vehicle and showed no major cracking or durability incidents in the test mileage. Frontal crash safety tests showed that nine parts withstood the test at a good level. Table 5.23 is a list of the parts that performed the best. The carbon fiber wheels had one issue in the durability test with the outer coating on the carbon fiber, however it was solved and the wheel is currently planned for the Shelby Mustang. The composite fiber springs performed better than expected and it is understood that they are in production, or planned for production, in the Audi A6 Ultra Avant and the Renault Megane Trophy RS vehicles. The durability issue for the composite fiber wheels was solved and the improved wheels are being employed in the Shelby Mustang. Some new discoveries were made including the near zero mass add for NVH considerations and corrosion concerns will be better addressed with a correct amount of sealant and the proper choice of nuts and bolts in the multi material vehicle design.

Table 5.23 Mach-I Components to Maintain Frontal Crash Performance.

PART	MATERIAL
Front bumper	Extruded aluminum
Crush Can	Extruded aluminum
Subframe	Cast and extruded aluminum
Shock Tower	Cast aluminum
Coil Spring	Chopped glass fiber composite
Wheel	Woven carbon fiber composite
A-Pillar joint node	Cast aluminum
Windshield	Chemically toughened laminate
Seat frame	Woven carbon fiber composite

5.2.7.4.5.2 Mach 2

The goal of the Mach 2 project was to create a lightweight design that achieved 50 percent mass savings from the 2013 Ford Fusion (representing a 2002 Ford Taurus). This amount of mass reduction is forward looking and of limited use for the time frame considered for this Draft TAR (2022-2025) which has a top application of 20 percent mass reduction.

The project achieved 51.1 percent (798kg) mass reduction with a significant degree of mass reduction using materials and processes that have some initial research but not ready for high volume. Significant vehicle de-contenting was employed which included items from air conditioning to thinning the windows and the resultant vehicle was not marketable.

The vehicle technologies for the BIW and Closures includes carbon fiber and composites as seen in Figure 5.68. However the CAE inputs were not mature for the materials and as a result the outputs were insufficient. CAE information included cards for stiffness, durability, and fatigue analyses. In terms of production, the composite material and manufacturing infrastructure was also not mature for automotive volumes. The carbon fiber and composite panels were not deemed acceptable for Class A surfaces and as a result aluminum or magnesium sheet products were chosen for the BIW and closure applications.

Table 5.24 Mach II Design Vehicle Summary[459]

System	Technology	Material/Approach
Body and Closures	Body	Composite intensive
	Closures	Magnesium
	Windows	Reduced Thickness
Interior & Climate Control	Seats	Carbon fiber seats with reduced function
	IP	Carbon fiber composite
	Reduced content	No bins, center console, air conditioner, etc.
Chassis	Subframes	Cast magnesium
	Coil Springs	Composite
	Reduced capacity	For reduced weight cargo and towing
Powertrain	Engine	1.0L 3 cyl naturally aspirated Remove turbocharger and intercooler Material change
	Transmission	Reduced capacity manual
Electrical		Eliminate content and features
		Reduced battery, alternator, wiring

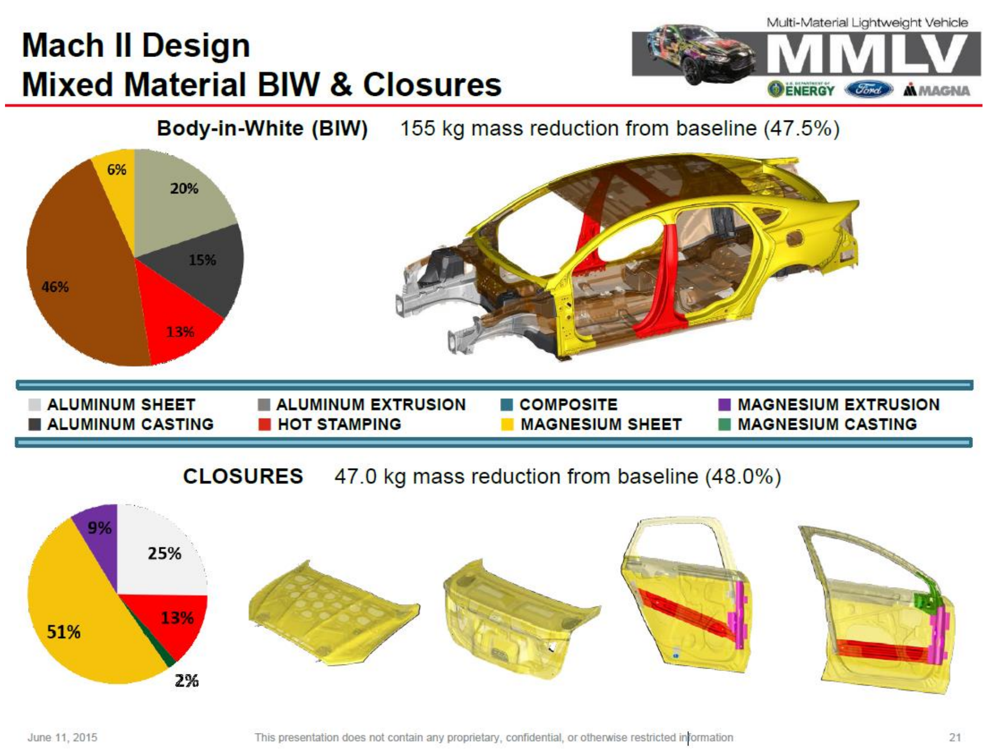


Figure 5.68 Mach II Mixed Material BIW and Closure Design (brown is carbon fiber)[459]

The Mach II design had a number of estimated performance impacts. The CAE based assessments were not complete due to insufficient carbon fiber CAE modeling capabilities and as a result there was low confidence in load cases. There was a large degradation in all metrics for sound and stiffness. Corrosion capability was significantly challenged with mixed material joints that included carbon fiber composites and magnesium. There are some unknown processes for high volume production and challenges with joining, surface treatments, paint, thermal expansion and dimensions and tolerances. Areas identified needing additional research include recyclability and vehicle repair.

5.2.7.4.6 Technical Cost Modeling Report by DOE/INL/IBIS on 40 Percent-45 Percent Mass Reduced Vehicle

The U.S. Department of Energy's Vehicle Technologies Office Materials Area funded a study to provide cost estimates and assessment of a 40 percent and 45 percent weight savings on a North American midsize passenger sedan based on the work of the Mach 1 and Mach 2 lightweighting projects. The title of the report is "Vehicle Lightweighting: 40 percent and 45 percent Weight Savings Analysis: Technical Cost Modeling for Vehicle Lightweighting"[460]. This work was peer reviewed through the 2015 DOE AMR "Technical Cost Modeling for Vehicle Lightweighting" presentation in front of a panel of experts in the field. Results of the peer review were included in the final report for the DOE AMR.[461] The project received a weighted average score of 2.98 out of 4.0 and was measured on reviewer questions related to approach, technical accomplishments, collaborations, and future research.

The goal of the work was to achieve 40 percent-45 percent mass reduction relative to a standard North American midsize passenger sedan at an effective cost of $3.42/lb. This study utilized existing mass reduction and/or cost studies including those from FEV, Lotus Engineering, DOE Mach 1 and Mach 2. The Executive Summary to this report states "The analysis indicates that a 37 to 45 percent reduction in a standard mid-sized vehicle is within reach if carbon fiber composite materials and manufacturing processes are available and if customers will accept a reduction in vehicle features and content, as demonstrated with the Multi-Materials and Carbon Fiber Composite-Intensive vehicle scenarios."

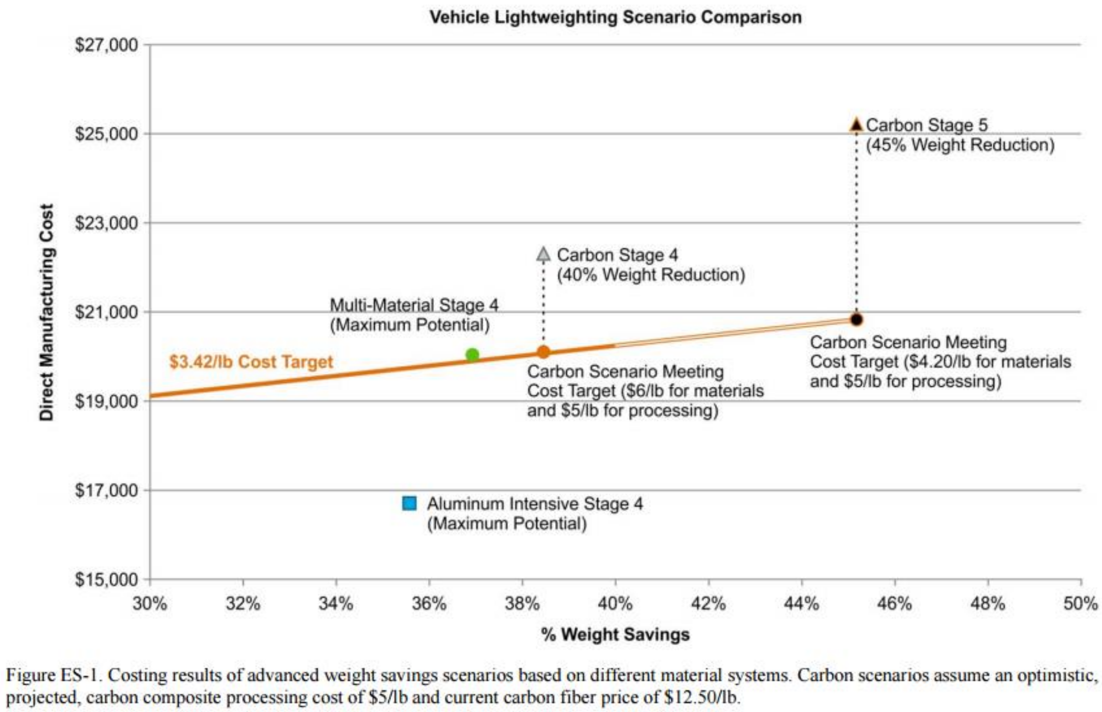


Figure 5.69 Technical Cost Modeling Results for 40 Percent to 45 Percent Lightweighting Scenario (Based on Mach 1/Mach 2 Project Technologies)

5.2.7.4.7 *Studies to Determine Mass Add for IIHS Small Overlap*

The lightweighting analysis within the Midterm Evaluation will give credit for mass adds due to safety regulations and requirements. One of the requirements of the IIHS Top Safety Pick is to meet the IIHS small overlap crash test. The IIHS SOL test is designed to reproduce what happens when the front corner of a vehicle hits another vehicle or an object like a tree or utility pole. Estimating the mass impact to succeed this test can vary widely among different types of vehicles. The structure of the vehicle must be redesigned in order to design load paths such that the passenger compartment remains sound throughout the crash event.

Figure 5.70 Post-test Laboratory Vehicle of IIHS Small Overlap Test

Two studies were funded to examine the mass add to existing vehicle study models. NTHSA funded the passenger car study using their LWV model and Transport Canada funded the light duty truck study using the LDT model from the EPA light duty pickup truck study. All of the CAE modeling, from the base studies to the IIHS small overlap studies were performed by two separate groups within EDAG, Inc. The results of these studies are described in the following sections.

5.2.7.4.7.1 NHTSA Mass Add Study for a Passenger Car to Achieve a "Good" Rating on the IIHS Small Overlap

The analysis of the IIHS Small Overlap resultant mass add for a variety of unibody passenger car vehicle classes are included in the February 2016 report "Update to Future Midsize Lightweight Vehicle Findings in Response to Manufacturer review and IIHS Small-Overlap Testing."[439] In order to improve the structural performance during the IIHS SOL test, several options were considered and implemented using a detailed LS-DYNA crash model that was originally part of the NHTSA LWV study. The CAE model was first updated to address the concerns in performance as identified by Honda. Changes regarding the SOL test include reinforcement of major areas in the body structure and were designed for easy manufacturability and assembly into the body structure. The findings for the IIHS SOL solution was a mass add of 6.9kg and 26.88 in cost.

The report also includes the IIHS mass add results for a range of unibody vehicle classes as shown in Table 5.25 (MY2010) and Table 5.26 (MY2020). Although the IIHS SOL test came out in 2012, the MY2010 refers to the baseline used in the NHTSA work in which it is assumed that all vehicles have no mass reduction technology. The individual mass adds are based on formulas determined for various vehicle classes with unibody design. The overall Light Duty Vehicle Average is based on a straight average of the values for each vehicle class. The report also notes that estimated mass increases for 'body on frame' vehicles should be further reviewed due to a differing body structure design. This was done in Transport Canada's evaluation of the 2011 Silverado 1500 discussed in the section following this section.

Table 5.25 Estimated Mass Increase to Meet IIHS SOL for 2010 Vehicle Classes

	2010 Vehicle Class Average			
Vehicle Class	Curb Vehicle Weight (kg)	Test Vehicle Weight (kg)	Increase in mass to meet IIHS SOL (kg)	Curb Vehicle Weight with IIHS SOL Changes (kg)
Sub-Compact Car	1261	1411	7.4	1268
Compact Car	1345	1495	7.8	1353
Mid-Sized Car	1561	1711	8.9	1570
Small SUV/LT	1592	1742	9.1	1601
Large Car	1752	1902	9.9	1762
Mid-Sized SUV/LT	1916	2066	10.8	1927
Minivans	2035	2185	11.4	2046
Large SUV/LT	2391	2541	13.3	2404
Light Duty Vehicle Average	1732	1882	9.8	1741

Table 5.26 Estimated Mass Increase to Meet IIHS SOL for 2020 Vehicle Classes

	2020 Vehicle Class Average			
Vehicle Class	Curb Vehicle Weight (kg)	Test Vehicle Weight (kg)	Increase in mass to meet IIHS SOL (kg)	Curb Vehicle Weight with IIHS SOL Changes (kg)
Sub-Compact Car	1055	1205	6.3	1062
Compact Car	1119	1269	6.6	1125
Mid-Sized Car	1294	1444	7.5	1302
Small SUV/LT	1318	1468	7.7	1326
Large Car	1453	1603	8.4	1462
Mid-Sized SUV/LT	1632	1782	9.3	1641
Minivans	1689	1839	9.6	1699
Large SUV/LT	1962	2112	11.0	1973
Light Duty Vehicle Average	1440	1590	8.3	1449

5.2.7.4.7.2 Transport Canada Mass Add Study for a Light Duty Truck to Achieve a "Good" Rating on the IIHS Small Overlap

A body on frame 2013MY Silverado 1500 light duty pickup truck (designed in 2007) was evaluated for necessary mass add in order to achieve a “Good” rating on the IIHS small overlap crash test in both current and lightweighted designs. This information was needed in order to evaluate the mass impact from compliance with the safety crash test.

Transport Canada funded the project with EDAG, Inc.[462] in which the light duty pickup truck, utilized in EPA's light-weighting light duty pickup truck study through FEV[437], was evaluated for mass add in the light-weighted aluminum intensive design with the goal of achieving a Good or Acceptable rating. The report and models have been peer reviewed through EPA’s peer review process.

The baseline original CAE model was prepped for the work and then an IIHS small overlap crash test with a 2013MY Silverado 1500 Crew Cab 4x4 was conducted with Transport Canada’s Motor Vehicle Test & Research Centre in Blainville, Québec. This was performed in order to assure that the necessary components for the test were modeled correctly in the baseline model and that the crash could be reproduced in CAE space. A more complete series of CAE tests were conducted at each point in the process to assure that performance was maintained in all crash requirements, NVH, etc. The state of the truck from the barrier impact is shown in Figure 5.71. A number of components were material tested through the assistance of Natural Resources Canada's CanmetMATERIALS facility in Hamilton, Ontario. This was done in order to ensure that the most accurate materials properties were being input into the baseline model at the start of the process and in order that the CAE modeling could reproduce the video from the actual crash test as closely as possible. The baseline model was modified with failure criteria and timing of respective components involved in the IIHS small overlap test. Figure 5.72 shows the baseline model correlating to the baseline truck crash event.

Figure 5.71 MY2013 Silverado 1500 IIHS Small Overlap Test Crash Before and During

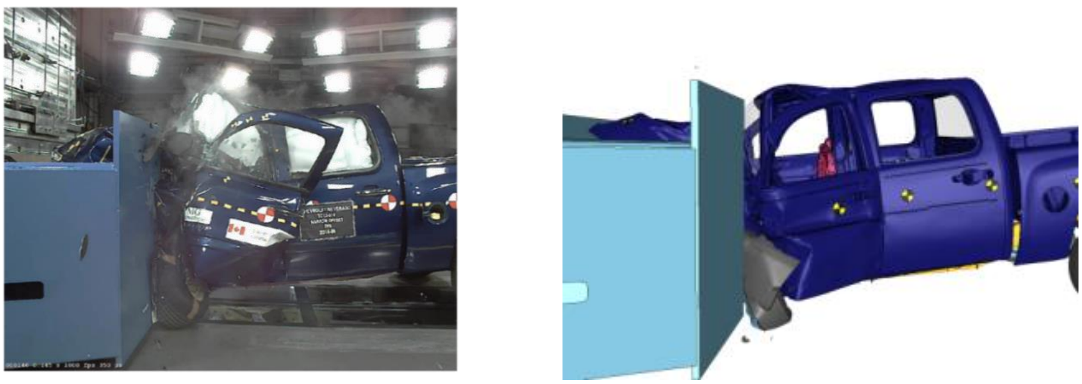


Figure 5.72 Converting the Actual Crash Event to a Model

Development of the light duty truck design modifications to the baseline structure began with research on existing IIHS crash results including those from the GM Equinox, Mercedes ML, and design information on the 2014MY Silverado 1500 and the 2015MY Ford F150 which had been released before the conclusion of this project. A solution for a “Good” rating on the IIHS small overlap crash test was determined for the steel intensive vehicle in order to highlight the areas for improvement in the lightweight model. The mass add for this design was not optimized for the minimum mass add that would still achieve a "Good" rating.

To develop the lightweight model mass add to the “Good” rating on the IIHS small overlap, the vehicle lightweighting ideas from the original U.S. EPA lightweight light duty truck project were first adopted onto the vehicle. The solution from the baseline vehicle was then optimized and the mass add determined. The report states "Like the original EPA Project cab, the T5-LW (light-weighted) cab exploited the low density and manufacturing methods specific to Aluminum, …Extrusions and castings were used to meet and exceed the static bending and torsion requirements with mass efficient solutions." The components in the area of the crash (including suspension and wheel) were not changed to aluminum for the failure information for the aluminum components were not available. The resultant light-weighted model before and after IIHS small overlap crash is illustrated in Figure 5.73. The passenger compartment stays in tact as shown.

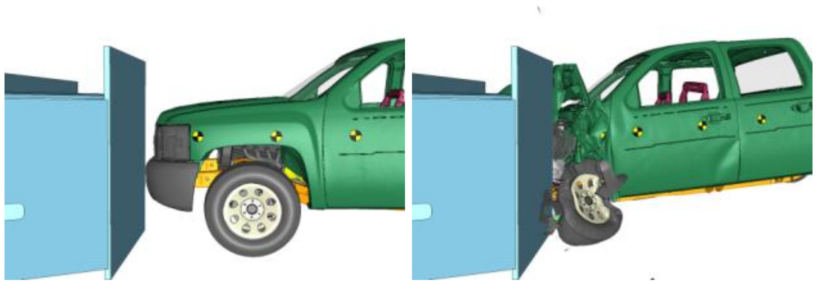


Figure 5.73 Light Weighted Model in the IIHS Small Overlap Crash Test

The accelerations for the dummies will change based on the stiffer passenger compartment which doesn't allow the extreme intrusions in the baseline model. The report contains a comparison of the Velocity (m/s) at CoG X-velocities for the T4-GA LDT model and other production vehicles with "Good" IIHS small overlap results and the results are similar. The T5-LW results are very similar to the T4-GA results. The report concludes that "the pulse response is considered reasonable and it is expected that a modern restraints system could be tuned to manage the vehicle response." [462]

The IIHS Small Overlap Rating is based on dummy injury criteria as well as vehicle intrusion in specified locations within the vehicle. Figure 5.74 illustrates how the light-weighted model (T5-LW) compares to the baseline model (T3-BL) along with the results from the original crash test (TC13-018). The light-weighted model achieves a Good rating in the intrusion part of the evaluation.

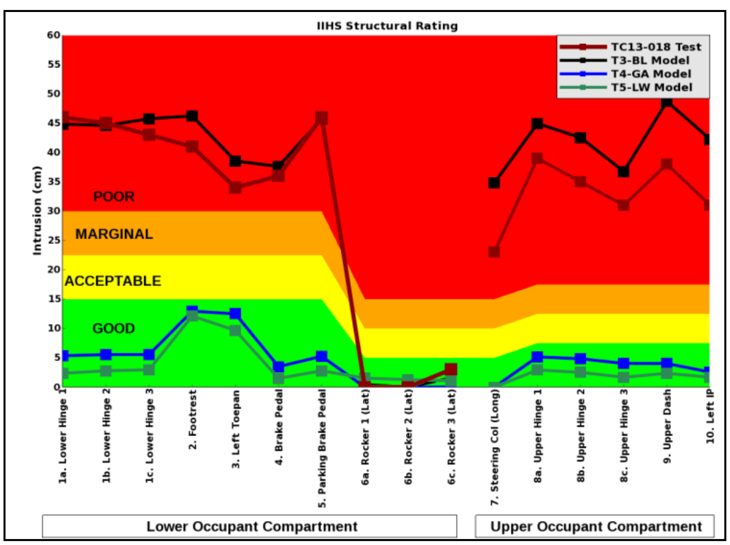


Figure 5.74 Results of the Project Models from Baseline to Light Weighted on the IIHS Small Overlap[462]

The overall mass reduction results for the LDT were 455kg mass reduction for $2115 and included added mass to the light-weighted truck of 17kg mass and removal of the possible 89kg mass reduction which remained to be considered when aluminum components are put into place for the original steel suspension, wheel, etc. One of the peer reviewers for this report provided comments to support a decision of the mass add for the aluminum suspension, wheel, etc. The decision was made that an additional 5kg mass would be needed to assure the aluminum components for the test requirement results. As a result, a mass credit of 22kg is assigned for a light duty aluminum intensive pickup truck to meet the IIHS small overlap test.

5.2.8 State of Other Vehicle Technologies

5.2.8.1 Electrified Power Steering: State of Technology

Compared to conventional hydraulic power steering, electrified power steering can reduce fuel consumption and CO_2 emissions by reducing overall accessory loads. Specifically, it reduces or eliminates the parasitic losses associated with belt-driven power steering pumps which consistently draw load from the engine to pump hydraulic fluid through the steering actuation systems even when the wheels are not being turned. Power steering may be electrified on light duty vehicles with a standard 12V electrical system. Electrified power steering is also an enabler for vehicle electrification since it provides power steering when the engine is off.

Power steering systems can be electrified in two ways. Manufacturers may choose to completely eliminate the hydraulic portion of the steering system and provide electric-only power steering (EPS) or they may choose to move the hydraulic pump from a belt driven configuration to a stand-alone electrically driven hydraulic pump. The latter system is referred to as electro-hydraulic power steering (EHPS).

5.2.8.1.1 Electrified Power Steering in the 2012 FRM

In the 2012 FRM analysis, the agencies estimated a 1 to 2 percent effectiveness of EPS and EHPS for light duty vehicles, based on the 2002 NAS report, Sierra Research Report and confidential OEM data. The 2010 Ricardo study also confirmed this estimate.

For the 2012 FRM, the agencies estimated the DMC at $88 (2007$). Converting to 2010$, this DMC becomes $92 for this Draft TAR. The agencies consider EPS technology to be on the flat portion of the learning curve and have applied a low complexity ICM of 1.24 through 2018 then 1.19 thereafter.

5.2.8.1.2 Developments since the FRM

Since the FRM, EPS has been successfully implemented on all light duty vehicle classes (including trucks) with a standard 12V electrical system eliminating the need to consider EHPS on larger vehicles.

For the cost and effectiveness assumptions the agencies are adopting for the GHG Assessment and CAFE Assessment for this Draft TAR analysis, see Sections 5.3 and 5.4.

5.2.8.2 Improved Accessories: State of Technology

The accessories on an engine, including the alternator, coolant and oil pumps are traditionally mechanically-driven. A reduction in CO_2 emissions and fuel consumption can be realized by driving them electrically, and only when needed ("on-demand").

Electric water pumps and electric fans can provide better control of engine cooling. For example, coolant flow from an electric water pump can be reduced and the radiator fan can be shut off during engine warm-up or cold ambient temperature conditions which will reduce warm-up time, reduce warm-up fuel enrichment, and reduce parasitic losses.

Indirect benefit may be obtained by reducing the flow from the water pump electrically during the engine warm-up period, allowing the engine to heat more rapidly and thereby reducing the fuel enrichment needed during cold starting of the engine. Further benefit may be obtained when electrification is combined with an improved, higher efficiency engine alternator. Intelligent cooling can more easily be applied to vehicles that do not typically carry heavy payloads, so larger vehicles with towing capacity present a challenge, as these vehicles have high cooling fan loads. Both agencies also included a higher efficiency alternator in this category to improve the cooling system.

The agencies considered whether to include electric oil pump technology for the rulemaking. Because it is necessary to operate the oil pump any time the engine is running, electric oil pump technology has insignificant effect on efficiency. Therefore, the agencies decided to not include electric oil pump technology for this final rule, consistent with the proposal.

In MYs 2017-2025 final rule, the agencies used the effectiveness value in the range of 1 to 2 percent based on technologies discussed above. NHTSA did not apply this technology to large pickup truck due to the utility requirement concern for this vehicle class.

In the 2017-2025 rule, the agencies estimated the DMC of IACC1 at $71 (2007$). Converting to 2010$, this DMC becomes $75 for this analysis, applicable in the 2015MY, and consistent with the heavy-duty GHG rule. The agencies consider IACC1 technology to be on the flat portion of the learning curve and have applied a low complexity ICM of 1.24 through 2018 then 1.19 thereafter.

Cost is higher for IACC2 due to the inclusion of a higher efficiency alternator and a mild level of regeneration. The agencies estimate the DMC of the higher efficiency alternator and the regeneration strategy at $45 (2010$) incremental to IACC1, applicable in the 2015MY. Including the costs for IACC1 results in a DMC for IACC2 of $120 (2010$) relative to the baseline case and applicable in the 2015MY. The agencies consider the IACC2 technology to be on the flat portion of the learning curve. The agencies have applied a low complexity ICM of 1.24 through 2018 then 1.19 thereafter.

For the cost and effectiveness assumptions the agencies are adopting for the GHG Assessment and CAFE Assessment for this Draft TAR analysis, see Sections 5.3 and 5.4.

5.2.8.3 Secondary Axle Disconnect: State of Technology

5.2.8.3.1 <u>Background</u>

All-wheel drive (AWD) and four-wheel drive (4WD) vehicles provide improved traction by delivering torque to both the front and rear axles, rather than just one axle. Driving two axles rather than one tends to consumes more energy due to additional friction and rotational inertia. Some of these losses may be reduced by providing a secondary axle disconnect function that disconnects one of the axles when driving conditions do not call for torque to be delivered to both axles.

The terms AWD and 4WD are often used interchangeably. The term AWD has come to be associated with light-duty passenger vehicles that provide variable operation of one or both axles on ordinary roads. The term 4WD is often associated with larger truck-based vehicle platforms that provide for a locked driveline configuration and/or a low range gearing meant primarily for off-road use.

Many 4WD vehicles provide for a single-axle (or two-wheel) drive mode that may be manually selected by the user. In this mode, a primary axle (perhaps the rear) will be powered, while the other axle (known as the secondary axle) is not. Even though the secondary axle is not contributing torque, energy may still be consumed by rotation of its driveline components because they are still connected to the non-driven wheels. This energy loss directly results in increased fuel consumption and CO_2 emissions that could be avoided by disconnecting the secondary axle components under these conditions.

Further, many light-duty AWD systems are designed to variably divide torque between the front and rear axles in normal driving, in order to optimize traction and handling in response to driving conditions. Even when the secondary axle is not delivering torque, it typically remains engaged with the driveline and continues to generate losses that could be avoided by a more advanced disconnect feature. For example, Chrysler has estimated that the secondary axle disconnect in the Jeep Cherokee reduces friction and drag attributable to parasitics of the secondary axle by 80 percent when in disconnect mode.[463] Some of the sources of secondary axle parasitics include lubricant churning, seal friction, bearing friction, and gear train losses.[464,465]

Many part-time 4WD systems, such as those seen in light trucks, use some type of secondary axle disconnect to provide shift-on-the-fly capabilities. In many of these vehicles, particularly light trucks, the rear axle is permanently driven and the front axle is secondary. The secondary axle disconnect is therefore part of the front differential assembly in these vehicles. Light-duty passenger cars that employ AWD may instead permanently power the front wheels while making the rear axle secondary, as currently in production in the Jeep Cherokee 4WD system.

As part of a shift-on-the-fly 4WD system, the secondary axle disconnect serves two basic purposes. First, in two-wheel drive mode, it disengages the secondary axle from the driveline so the wheels do not turn the secondary driveline at road speed, reducing wear and parasitic energy losses. Second, when shifting from two- to four-wheel drive “on the fly” (while moving), the secondary axle disconnect couples the secondary axle to its differential side gear only after the synchronizing mechanism of the transfer case has spun the secondary driveshaft up to the same speed as the primary driveshaft.

4WD systems that have a disconnect typically do not have either manual- or automatic-locking hubs. To isolate the secondary wheels from the rest of the secondary driveline, axle disconnects use a sliding sleeve to connect or disconnect an axle shaft from the differential side gear.

5.2.8.3.2 Secondary Axle Disconnect in the FRM

At the time of the FRM, the agencies were not aware of any manufacturer offering secondary axle disconnect in the U.S. on AWD unibody-frame vehicles. Secondary axle disconnect was included in the FRM analysis with the expectation that this technology could be introduced by manufacturers within the MYs 2017-2025 time period.

The 2012 FRM analysis assigned an effectiveness of 1.2 to 1.4 percent for secondary axle disconnect. The agencies estimated the DMC at $82 (2010$). The agencies considered secondary axle disconnect technology to be on the flat portion of the learning curve and applied a low complexity ICM of 1.24 through 2018 then 1.19 thereafter.

5.2.8.3.3 Developments since the FRM

Since the FRM, the agencies have continued to monitor developments in AWD secondary axle disconnects and their adoption in the light-duty vehicle fleet. We gathered information by monitoring press reports, holding meetings with suppliers and OEMs, and attending industry technical conferences.

EPA coordinated with Transport Canada and Environment and Climate Change Canada on a project to characterize AWD systems present in the market today. The primary objectives of this project are to gain an overview of AWD technology in general and to understand the potential effect of advances in these systems on GHG performance in comparison to their 2WD variants. A comprehensive technical characterization of 17 in-production AWD systems has been completed[465]. It includes characterization of system architecture, operating modes, and current usage in the fleet. It also estimated and compared the mass and rotational inertia of AWD components and parts to those of 2WD variants in order to better understand the weight increase associated with AWD. Additionally, the all-wheel-drive components of three AWD vehicles (the 2015 Jeep Cherokee Limited 4x4, 2015 Ford Fusion AWD, and 2015 Volkswagen Tiguan Trendline 4motion) underwent a teardown in order to accurately characterize their mass and rotational inertia and estimate their approximate cost. One of the teardown vehicles, the Jeep Cherokee, includes a secondary axle disconnect, indicating that this technology has begun to appear in light-duty vehicles since the FRM. In 2014, Chrysler Group LLC presented a very positive outlook on the advantages of this system for improving fuel efficiency while retaining a highly competitive off-road capability.[466] This suggests that the addition of secondary axle disconnect systems need not be accompanied by loss of traction and handling capability.

The study reinforced the perception that AWD is rapidly increasing in popularity in the vehicle fleet, with about one-third of all vehicles sold in North America in 2015 having AWD capability. The prevalence of AWD varies significantly between vehicle segments and trim levels. Sedans have the lowest AWD availability, while AWD versions outnumber 2WD versions in the SUV and pickup segments, particularly among the higher trim levels in each segment.

The study identified several areas of potential efficiency improvement for AWD systems. These included system level improvements such as: use of a single shaft Power Transfer Unit (PTU), which can save up to 10kg in mass compared to a two-shaft unit; careful integration into vehicle architecture; downsizing the driveline to further reduce mass while providing sufficient traction in adverse conditions; and use of electric rear axle drive (eRAD). Component level improvements were also identified, including: use of fuel-efficient bearings, low drag seals, improved lubrication strategies, use of high-efficiency lubricants, advanced CV joints, and dry clutch systems. Design improvements such as hypoid offset optimization, bearing preload optimization, use of single-shaft power transfer units (PTUs) and an optimized propshaft gear ratio were also suggested to have potential. Use of weight-reducing metals such as magnesium, and manufacturing improvements such as vacuum die casting and improved hypoid manufacturing were also cited as opportunities. The authors' judgement of the relative potential for AWD efficiency improvements offered by each opportunity are depicted in Figure 5.75.

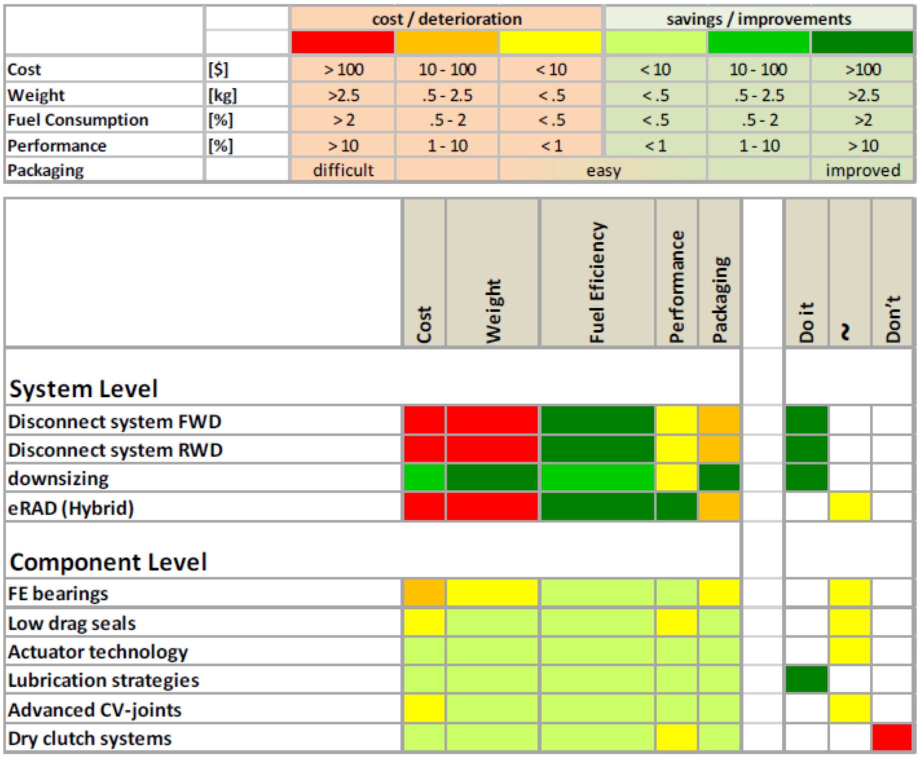


Figure 5.75 Summary of AWD Efficiency Improvement Potentials[465]

Various sources cited in the study suggested that AWD disconnect systems have the ability to lower fuel consumption of AWD vehicles between 2 percent and 7 percent, significantly higher than the estimates of 1.2 percent to 1.4 percent used in the 2012 FRM. However, it should be noted that a disconnect strategy must balance fuel efficiency with other concerns such as vehicle dynamics, traction and safety requirements, which may act to reduce its actual GHG effectiveness.

The study also identified three primary technological trends taking place in AWD system design, including: actively controlled multi-plate clutches (MPCs), active disconnect systems (ADS), and electric rear axle drives (eRAD). While controlled MPCs appear to be the dominant technology in on-demand systems, ADS is a more recent trend and holds promise for reducing real world fuel consumption. eRAD is the most recent emerging technology with potential for even greater improvements (as seen in the Volvo XC90 Hybrid SUV).

The teardown analysis analyzed three power transfer units (PTUs) and rear drive modules (RDMs) from the Ford Fusion, Jeep Cherokee and VW Tiguan. These were non-destructively disassembled and analyzed with respect to mass, rotational inertia and the presence of specific design features. Figure 5.76 shows the contribution of individual AWD driveline components to the total additional mass of the AWD variant of each vehicle compared to the 2WD variant. Further analysis of rotational inertias of these parts suggested that rotational inertias add very little equivalent mass and therefore probably do not carry a large impact on fuel consumption.

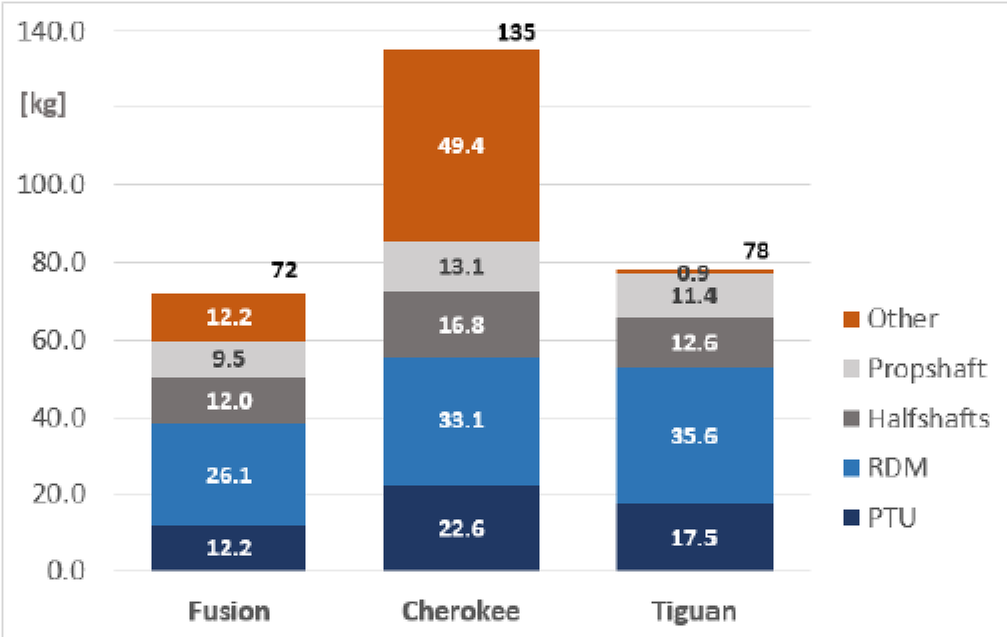


Figure 5.76 Contribution of Individual AWD Driveline Components to Total Additional Vehicle Mass

The study included a high-level cost analysis for these parts, including the mechanical disconnect device and modifications necessary to the torque transfer device (TTD). The total cost of adding secondary axle disconnect to a vehicle was estimated at approximately $90 to $100. Although this cost estimate was informally derived based primarily on the experience and expertise of the authors, it compares well to the total cost (TC) figure attributed to 2017 in the FRM analysis, at $98. The authors noted that the cost for the Jeep Cherokee system would likely be higher because this system was designed to accommodate a planetary low gear, which adds mass and cost not related to the AWD disconnect function.

In addition to the in-production disconnect concepts described in the Transport Canada AWD report, activity continues in the development of innovative secondary axle disconnect concepts. For example, in 2015, Schaeffler presented a novel design for a clutch mechanism for use in AWD disconnect.[467] Suppliers are also designing and marketing modular solutions for integration into existing OEM products.[464] Developments such as these suggest that multiple potential paths will exist for disconnect technology to accompany the increasing growth and popularity of AWD in light-duty vehicles.

In conjunction with the AWD characterization project described above, Transport Canada is also conducting a program of coastdown testing, chassis dynamometer testing, and on-road testing of several Canada-specification AWD vehicles at Transport Canada facilities. This portion of the effort is not yet completed but the results may become available to inform the proposed determination.

For the cost and effectiveness assumptions the agencies are adopting for the GHG Assessment and CAFE Assessment for this Draft TAR analysis, see Sections 5.3 and 5.4.

5.2.8.4 Low-Drag Brakes: State of Technology

Low or zero drag brakes reduce or eliminate the sliding friction of disc brake pads on rotors when the brakes are not engaged. By allowing the brake pads to pull or be pushed away from the the rotating disc either by mechanical or electric methods, the drag on the vehicle is reduced or eliminated.

5.2.8.4.1 Background

The reduction of brake drag is a technology that the vehicle manufacturers have focused on for many years. The ability to allow the brake disc pads to move away from the rotor and thereby reduce friction is a known technology. This has been historically implemented by designing a caliper and rotor system that allows the piston in the caliper to retract. However, if the pads are allowed to move too far away from the rotor, the first pedal apply made by the vehicle operator can feel spongy and have excessive travel. This can lead to customer dissatisfaction regarding braking performance and pedal feel. For this reason, in conventional hydraulic-only brake systems, manufacturers are limited by how much they can allow the pads to move away from the rotor.

5.2.8.4.2 Low Drag Brakes in the FRM

The 2012-2016 final rule and Draft TAR estimated the effectiveness of low drag brakes to be as much as 1 percent. NHTSA and EPA have slightly revised the effectiveness down to 0.8 percent based on the 2011 Ricardo study.

In the 2012-2016 rule, the agencies estimated the DMC at $57 (2007$). This DMC becomes $59 (2010$) for this analysis after adjusting to 2010 dollars. The agencies consider low drag brake technology to be off the learning curve (i.e., the DMC does not change year-over-year) and have applied a low complexity ICM of 1.24 through 2018 then 1.19 thereafter.

5.2.8.4.3 Developments since the FRM

Recent developments in braking systems have allowed suppliers to provide brakes that have the potential for zero drag. In this system the pad is allowed to move away from the rotor in much the same way that is done in today's conventional brake systems, but in a zero drag brake system the pedal feel is separated from the hydraulics by a pedal simulator. This system is very similar to the brake systems that have been designed for hybrid and electric vehicles. In hybrid and electric vehicles, some of the primary braking is done through the recuperation of kinetic energy in the drive system. However, the pedal feel and the deceleration that the operator experiences is tuned to provide a braking experience that is equivalent to that of a conventional hydraulic brake system. These "brake-by-wire" systems have highly tuned pedal simulators that feel like typical hydraulic brakes and seamlessly transition to a conventional system as required by conditions. The application of a pedal simulator and brake-by-wire system is new to non-electrified vehicle applications. By using this type of system vehicle manufacturers can allow the brake pads to move farther away from the rotor and still maintain the initial pedal feel and deceleration associated with a conventional brake system.

In addition, to reducing brake drag, the zero drag brake system also provides ancillary benefits. It allows for a faster brake apply and greater deceleration than is normally applied by the average vehicle operator. It also allows manufacturers to tune the braking for different customer preferences within the same vehicle. This means that a manufacturer can provide a "sport" mode which provides greater deceleration with less pedal displacement and a "normal" mode which might be more appropriate for day-to-day driving. These electrically driven systems also facilitate other brake features such as panic brake assist, automatic braking for crash avoidance and could support future autonomous driving features.

The zero drag brake system also eliminates the need for a brake booster. This saves both cost and weight in the overall system. Elimination of the conventional vacuum brake booster could also improve the effectiveness of stop-start systems. Typical stop-start systems need to restart the engine if the brake pedal is cycled because the action drains the booster of stored vacuum. Because the zero drag brake system provides braking assistance electrically, there is no need to supplement lost vacuum during an engine off event.

Finally, many of the engine technologies being considered to improve efficiency reduce pumping losses through reduced throttle. The reduction in throttle could result in supplemental vacuum being required to operate a conventional brake system. This is situation in many diesel powered vehicles. Diesel engines run without a throttling and often require supplemental vacuum for brake boosting. By using a zero drag brake system, manufacturers may realize the elimination of brake drag as well as the ancillary benefits described above and avoid the need for a supplemental vacuum pump.

For the cost and effectiveness assumptions the agencies are adopting for the GHG Assessment and CAFE Assessment for this Draft TAR analysis, see Sections 5.3 and 5.4.

5.2.9 Air Conditioning Efficiency and Leakage Credits

Air conditioning (A/C) is a virtually standard automotive accessory, with over 95 percent of new cars and light trucks sold in the United States being equipped with mobile air conditioning (MAC) systems. This high penetration means that A/C systems have the potential to exert a significant influence on the energy consumed by the light duty vehicle fleet, as well as to GHG emissions resulting from refrigerant leakage.

The FRM allowed vehicle manufacturers to generate credits for improved A/C systems toward complying with the CO_2 and fuel consumption fleetwide average standards. In the EPA program, manufacturers can generate credits for improved performance of both direct emissions (refrigerant leakage) and indirect emissions (tailpipe emissions attributable to the energy consumed by A/C). In both cases, a selection of "menu" credits in grams per mile are available for qualifying technologies, with the magnitude of each credit being estimated based on the expected reduction in CO_2 emissions resulting from the technology. See 40 CFR 86.1868-12. In the NHTSA program, manufacturers are allowed to generate fuel consumption improvement values for purposes of CAFE compliance based on the use of A/C efficiency-improving technologies. However, manufacturers cannot count reductions in A/C leakage toward their CAFE calculations since these improvements do not affect fuel economy.

Since the FRM, many manufacturers have generated and banked credits through this program and continue to do so today. In the FRM, the agencies estimated that significant penetration of A/C technologies would occur to gain these credits, and this was reflected in the stringency of the standards. See e.g. 77 FR at 62805/3.

EPA and NHTSA projected that the 2017-2025 rule would result in significant improvements in the efficiency of automotive air conditioning (A/C) systems. Also, EPA projected that the program would lead to significant reductions in GHGs from reduced A/C refrigerant leakage and from industry adoption of lower global warming potential (GWP) refrigerants. Additional information that has become available, as well as changes in the overall regulatory environment affecting the A/C technology developments in the light-duty vehicle industry, reinforces our earlier conclusions that these technologies will continue to expand and play an increasing role in overall vehicle GHG reductions and regulatory compliance.

5.2.9.1 A/C Efficiency Credits

5.2.9.1.1 Background on the A/C Efficiency Credit Program

The 2012 FRM established two test procedures to determine eligibility for A/C efficiency credits. The two test procedures are the idle test and the AC17 test. These procedures were assigned to different roles depending on the model year for which the test is conducted.

For model years 2014 to 2016, there were three options for qualifying for A/C efficiency credits: 1) running the A/C Idle Test, as described in the MYs 2012-2016 final rule, and demonstrating compliance with the CO_2 and fuel consumption threshold requirements, 2) running the A/C Idle Test and demonstrating compliance with engine displacement adjusted CO_2 and fuel consumption threshold requirements, and 3) running the AC17 test and reporting the test results.

For model years 2017-2019, the AC17 test becomes the exclusive means manufacturers will have to demonstrate eligibility for A/C efficiency credits, again by reporting the test results. By reporting test results, manufacturers gain access to the credits on the menu based on the design of their AC system. In MYs 2020 and thereafter, however, the AC17 test will be used not only to demonstrate eligibility for efficiency credits, but also to partially quantify the amount of the credit. AC17 test results ("A" to "B" comparison) equal to or greater than the menu value will allow manufacturers to claim the full menu value for the credit. A test result less than the menu value will limit the amount of credit to that demonstrated on the AC17 test. In addition, for MYs 2017 and beyond, A/C fuel consumption improvement values will be available for CAFE in addition to efficiency credits being available for GHG compliance. These adjustments to the utilization and design of the A/C test procedures were largely a result of new data collected, as well as the extensive technical comments submitted on the proposal.

5.2.9.1.2 Idle Test Procedure

Starting in MY2014, manufacturers have been required to demonstrate the efficiency of a vehicle's A/C system by running an A/C Idle Test as a prerequisite to CO_2 credit and fuel consumption improvement value eligibility (the amount of credit determined separately by means of the credit menu). If a vehicle met the emissions threshold of 14.9 grams per minute (g/min) CO_2 or lower on this test, a manufacturer was eligible to receive full credit (CAFE improvement values) for efficiency-improving hardware or controls installed on that vehicle. The vehicle would be able to receive A/C credits based on a menu of technologies specifying the credit amount associated with each technology. For vehicles with a result between 14.9 g/min and 21.3 g/min, a downward adjustment factor was applied to the eligible credit amount, with vehicles testing higher than 21.3 g/min not being eligible to receive credits. The details of this idle test can be found in the MYs 2012-2016 final rule. See 75 FR at 25426-27. This methodology for accessing the credit menu based on the Idle Test results (and threshold requirements) continued to apply for model years 2014-2016. The 2017-2025 FRM did not make any fundamental changes to the previous rule. EPA did, however, provide an optional new threshold requirement for MYs 2014-2016 reflecting the comments submitted on the idle test.

Prior to the 2017-2025 FRM, manufacturers had the opportunity to run the Idle Test on a wide variety of vehicles and discovered that even though there may be a small correlation between engine displacement and the Idle Test result, the trend was important enough that small vehicles had higher A/C idle emissions and were more inclined to fail to meet the threshold for the Idle Test than were larger vehicles. Specifically, vehicles with smaller displacement engines had a higher Idle Test result than those with larger displacement engines, even within the same vehicle platform. This was causing some small vehicles with advanced A/C systems to fail the Idle Test. The load placed on the engine by the A/C system did not seem to be consistent, and in certain cases, larger vehicles perform better than smaller ones on the A/C idle test. These effects were attributed in part to the fact that the brake-specific fuel consumption (bsfc) of a smaller displacement engine is generally lower at idle than that of a larger displacement engine, causing larger engines to move from a less efficient region to a more efficient region when A/C is operated at idle, while smaller engines enjoy less of this effect or may drop into a less efficient region. The 2017-2025 TSD presented additional analyses and adjustments to address these and similar difficulties with the A/C Idle Test.

In the 2012 FRM, the agencies recognized the limitations of the Idle Test and provided for a gradual phasing out of this test in favor of the AC17 Test, to be described below. The primary disadvantage of the Idle Test is that it does not capture the majority of the driving or ambient conditions in the real world when the A/C is in operation, and thus may only encourage the technologies that improve idle performance under narrow temperature conditions. Another limitation is that the narrow range of engine operating conditions present during the Idle Test make it difficult to quantify the incremental improvement of a given technology to generate an actual credit over non-idle operation (without a menu).

5.2.9.1.3 AC17 Test Procedure

In preparation for the 2017-2025 NPRM, the agencies sought to develop a more capable test procedure that could more reliably generate an appropriate credit value based on an “A” to “B” comparison, that is, a comparison of substantially similar vehicles in which one has the technology and the other does not. The result of this effort was the AC17 Test Procedure, which we believe is capable (in part) of detecting the effect of more efficient A/C components and controls strategies during a transient drive cycle, rather than just idle.

To develop this test, EPA initiated a study that engaged automotive manufacturers, USCAR, component suppliers, SAE, and CARB. This effort also explored the applicability and appropriateness of a test method or procedure which combines the results of test-bench, modeling/simulation, and chassis dynamometer testing into a quantitative metric for quantifying A/C system (fuel) efficiency. The goal of this exercise was the development of a reliable, accurate, and verifiable assessment and testing method while also minimizing a manufacturer’s testing burden. For a complete description of the AC17 test, please refer to the 2017-2025 TSD.

The agencies believe that the AC17 test procedure more accurately reflects the impact that A/C use (and in particular, efficiency-improving components and control strategies) has on tailpipe CO_2 emissions and fuel consumption. In the FRM, EPA established this test to be phased in starting in MY2014 as an option and in MYs 2017-2019 as the exclusive means of determining eligibility for A/C efficiency credits (CAFE improvement values), and thereafter as both an eligibility test and as a partial means of determining credit amount. That is, use of the AC17 test procedure to conduct A-to-B comparison tests becomes mandatory in 2020 as the exclusive test means for accessing the A/C efficiency menu and quantifying the credits. If the delta of the A-to-B test is greater than the value in the credit menu, the manufacturer receives the menu value, otherwise the value is scaled. However, an engineering assessment can still be conducted as an alternative to A-to-B testing to build the case for a specific credit value if, for example, a baseline vehicle does not exist on which to base the A-to-B comparison. See 76 FR 74938, 74940.

5.2.9.1.4 Manufacturer Uptake of A/C Efficiency Credits since the 2012 FRM

Many manufacturers have taken advantage of the A/C credit program to generate and bank A/C efficiency credits, which have become an important contributor to industry compliance plans. As summarized in the EPA Manufacturer Performance Report for the 2014 model year[468], 17 auto manufacturers included A/C efficiency credits as part of their compliance demonstration in the 2014 model year. These amounted to more than 10 million Mg of credits, or about 25 percent of the total net credits reported. This is equivalent to about 3 grams per mile across the 2014 fleet. Including the 2012 and 2013 model years, A/C efficiency credits totaled over 24.4 million Mg.

The A/C credit menu includes several A/C efficiency-improving technologies that were well defined and had been quantified for effectiveness at the time of the FRM. The vast majority of A/C efficiency credits were claimed through this mechanism.

The agencies expect that additional technologies for improving A/C efficiency that were not anticipated at the time of the FRM may continue to emerge in the future. Although such technologies will not be added to the design-based credit menu, these technologies will continue to be eligible for credit under the off-cycle credit program.

An off-cycle credit application for this purpose should be supported by results of testing under the AC17 test protocol using an "A to B" comparison, that is, a comparison of substantially similar vehicles in which one has the technology and the other does not. Applications for A/C efficiency credits made under the off-cycle credit program rather than the A/C credit program will continue to be subject to the A/C efficiency credit cap.

To date, the agencies have received one off-cycle credit application for an A/C efficiency technology. In December 2014, General Motors submitted an off-cycle credit application for the Denso SAS A/C compressor with variable crankcase suction valve technology, requesting an off-cycle GHG credit of 1.1 grams CO_2 per mile. EPA evaluated the application and found that the methodologies described therein were sound and appropriate. Therefore, EPA approved the credit application.

5.2.9.1.5 *Evaluation of the AC17 Test Procedure*

Prior to the 2012 FRM, EPA collaborated with several OEMs to conduct independent testing on a variety of vehicles and air conditioning technologies on the AC17 test cycle. The purpose of this test effort was to gain insight regarding the appropriateness of the AC17 test for verifying the reduction in CO_2 emissions which are expected from A/C technologies on the efficiency credit menu. Initially, six vehicles were tested, including three pairs of carlines with some element of difference in their air conditioner systems. The results of these tests were discussed in the 2012 TSD, Section 5.1.3.7, beginning on page 5-44. This collaborative effort continued to include a variety of additional vehicles tested by several OEMs at AC17-capable test facilities.[469] This preliminary testing showed that the AC17 test is capable of low test-to-test variability, and is suitable for evaluating the relative efficiency improvement of A/C technologies, when confounding factors are minimized. In cases where comparison of the AC17 results do not directly demonstrate the effectiveness of a technology, the test results can still be useful within an engineering analysis for justifying the test methodology to determine A/C CO_2 credits.

EPA also initiated a round-robin test program between facilities of several USCAR members in an effort to determine the repeatability of the AC17 test among various test facilities and to identify potential sources of variability. A 2011 Ford Explorer was selected for these tests. Four test sites were utilized, located at Ford, GM, Chrysler, and an EPA-contracted facility at Daimler. Each facility had a full environmental chamber capable of fulfilling all requirements of the test. Four tests were run at each facility, after which the vehicle was returned to Ford for confirmation. Each test measured CO_2 emissions with A/C off and A/C on, to capture the difference (delta) in CO_2 emissions, which represents the GHG effect of A/C usage.

Figure 5.77 through Figure 5.79 compares the results of each test at each test site. Although some variability was observed between test sites, consistency within a given site was good, suggesting that the AC17 test procedure is able to capture the difference in CO_2 emissions between A/C on and A/C off.

Several sources of variation were identified by analysis of these results. Variations in solar load may have resulted from variations in sensor location and soak start time. Temperature control was also a potential issue. Although most labs could maintain temperature within the required tolerance of the test procedure, humidity was more difficult to maintain for the long duration of the test. Overcorrecting may occur, but can be improved by optimizing sensor location to better represent ambient conditions. The complexity and length of the test can lead to an increased potential for voided tests, and may require more frequent calibration of the test cell equipment. Although this test program was not fully described in materials accompanying the FRM, many of the issues observed during this testing were addressed in the final form of the rule.

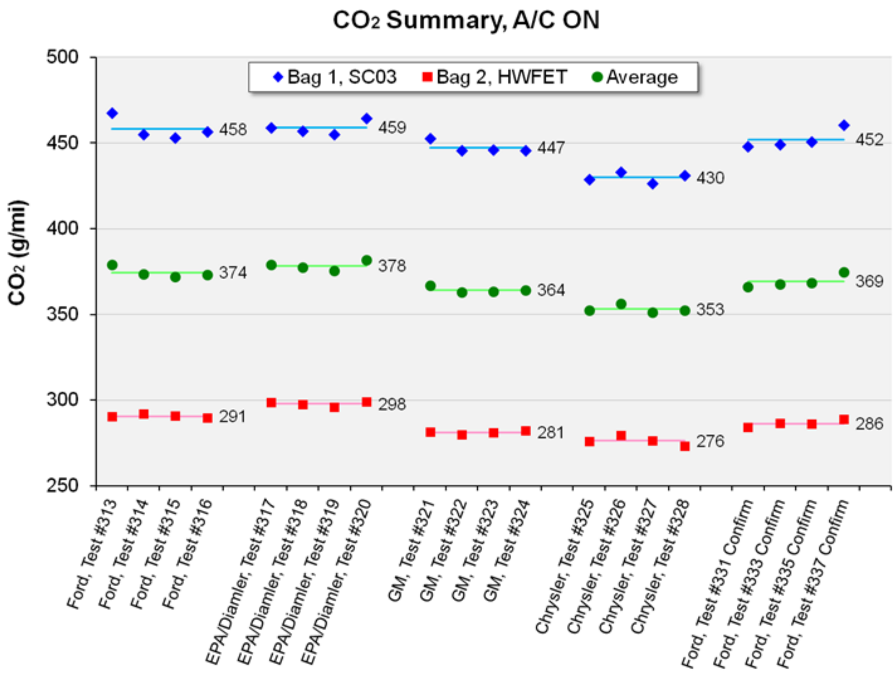


Figure 5.77 Variability of AC17 Round Robin Testing on 2011 Ford Explorer, A/C On

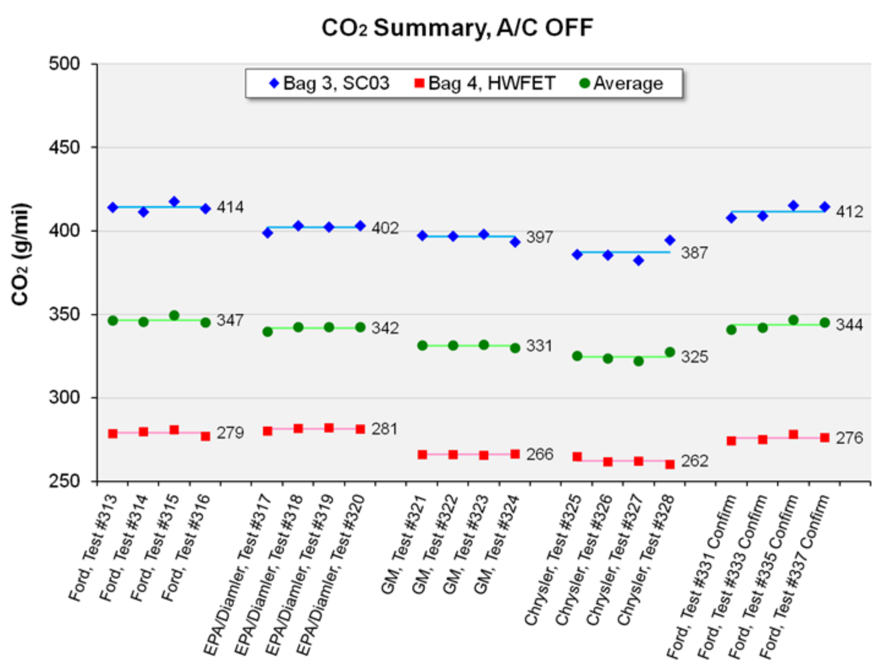


Figure 5.78 Variability of AC17 Round Robin Testing on 2011 Ford Explorer, A/C Off

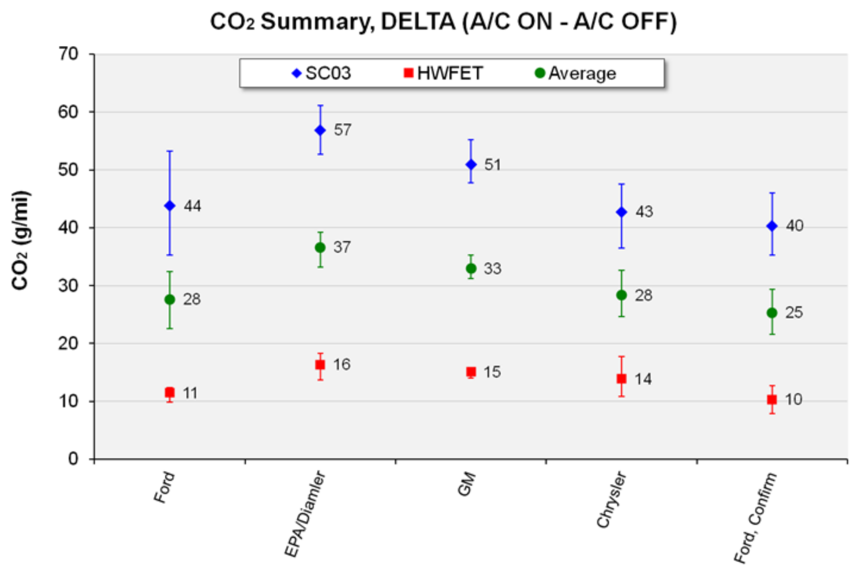


Figure 5.79 Variability of AC17 Round Robin Testing on 2011 Ford Explorer, Delta between A/C on and Off

Although these tests demonstrated that the AC17 test was able to resolve the difference between A/C on and A/C off, they did not address its ability to resolve smaller differences, such as the effect of an individual technology in an A to B test. As the size of an effect diminishes, the difficulty of resolving it against a much larger baseline value becomes more challenging. With the baseline CO_2 g/mi value for most vehicles being in the hundreds, and the effect of a single A/C technology possibly in the low single digits, test-to-test variation must be very small to reliably detect the effect. As the AC17 A-to-B test becomes a requirement beginning in MY2020, this issue is being examined closely by the industry and EPA.

Since the 2012 FRM, USCAR members have conducted an ongoing test program to assess the ability of the AC17 test to resolve the GHG impact of individual A/C efficiency technologies in an A to B test, and thereby function in the role assigned to it in the FRM as a means for quantifying and qualifying for A/C credits. EPA has followed this effort by direct coordination with member OEMs and by participating in meetings of the SAE Interior Climate Control Committee.

At this time, the USCAR test program is not yet complete, and results are not yet conclusive. Preliminary results are encouraging, although uncertainties continue to exist. In general, OEMs have expressed concern about several issues:

a) Difficulty of obtaining or constructing old-technology vehicles, particularly those from earlier model years, on which to base A-to-B comparisons.
b) Factors such as test-to-test variability and the small magnitude of the effect being measured result in the need for multiple tests to be conducted to yield a statistically reliable result, possibly increasing the test burden beyond what the agencies anticipated.
c) Members suggested that bench testing and engineering analysis may be preferable to A-to-B AC17 testing as a means of qualifying for menu credits, if these difficulties are not resolved in further testing.

Overall, members have expressed greater confidence in their ability to conduct A-to-B comparisons of software-related technologies (for example, default to recirculated air) than for hardware-based technologies (for example, compressor design changes) because the former can be implemented by relatively simple changes to software. A-to-B comparisons of hardware technologies would be more difficult because of the requirement to produce test specimens configured with and without the technology.

In January 2016, EPA received additional comment and analysis from several USCAR members regarding their most recent experience with AC17 testing. In this interaction, many of the issues discussed above were further outlined. Manufacturers have continued to experience a significant number of voided tests and are continuing to work to identify the sources of such events, which are commonly associated with long tests that demand careful environmental control. Test-to-test variation is sometimes seen to exceed the magnitude of the credit value that is the subject of the test. Although averaging of the results of multiple tests has shown some success at establishing a reliable outcome, concerns were expressed about the resulting test burden, due to the length of each test, the control requirements, and the limited availability of the required specialized test cells. The availability of base vehicles without the technology being assessed in an A-to-B comparison was also echoed as a concern. Manufacturers suggested that the use of prior year models may be infeasible when several intervening model years are involved, due to the confounding effect of other technologies introduced to the vehicle during that time. This was expressed as being particularly true for the problem of assessing hardware-based technologies, which may require building of prototype installations that may require additional engineering resources to develop. Within individual test efforts, consistency of results was good in some tests but exhibited inconsistencies in others, of which the manufacturers had not yet achieved a full understanding but continue to study. Issues such as the complexity of modern climate control systems and the presence of confounding factors such as powertrain differences were cited as possible factors.

An application for off-cycle credits submitted by General Motors in December 2014 provides an additional source of information on the results of AC17 A-to-B testing, which was used to support the application. GM cited several issues relating to the use of the AC17 test procedure to identify the CO_2 benefit claimed in the application:

a) GM pointed out that the AC17 A-to-B test was enabled by coincidental availability of a valid baseline compressor (a variable compressor without the variable crankcase suction valve technology) in the Holden Commodore and that this compressor coincidentally could be easily bolted into the Cadillac ATS. GM reiterated that this is an uncommon situation and not representative of future expectations;

b) GM stated that this hardware obstacle "prevents ready testing of the benefits of the SAS compressor on other GM models on which it has been implemented;"

c) There were some difficulties with torque and pressure measurement which was cited as example of "control issues that may be expected to arise when attempting to do this type of baseline technology testing for hardware on a vehicle that was never actually designed and optimized to use that hardware."

Despite these difficulties, GM found that the AC17 test procedure was able to resolve a 1.3 g/mile CO_2 improvement, which was in good agreement with the 1.1 g/mile suggested by bench testing. However, because test-to-test variability was greater for the AC17 tests than for the bench tests, GM chose to request the 1.1 g/mile shown by the bench tests, which GM regarded as more precise.

As an alternative to the A-to-B testing requirement, the 2012 FRM provided manufacturers the option to qualify for A/C credits through bench testing supported by engineering analysis. This option continues to be available after the 2020 AC17 requirement goes into effect. EPA has encouraged, and continues to encourage, the use of bench test results and engineering analysis to support applications for A/C efficiency credits.

In 2016, USCAR members initiated a Cooperative Research Program (CRP) through the Society of Automotive Engineers (SAE) to develop bench testing standards for the four hardware technologies in the credit menu (blower motor control, internal heat exchanger, improved evaporators and condensers, and oil separator). The specific standards under development are listed in Table 5.27. The intent of the program is to streamline the process of conducting bench testing and engineering analysis in support of an application for A/C credits by creating uniform standards for bench testing and for establishing the expected GHG impact of the technology in a vehicle application. The AC17 test may continue to have a supporting role in some of these standards. EPA continues to monitor the development of these standards by coordinating with the CRP as well as participating in the applicable SAE standards development committees.

Table 5.27 Hardware Bench Testing Standards under Development by SAE Cooperative Research Program

Number	Title	Status
J2765	Procedure for Measuring System COP of a Mobile Air Conditioning System on a Test Bench	Published
J3094	Internal Heat Exchanger (IHX) Measurement Standard	Work in Progress
J3109	HVAC PWM Blower Controller Efficiency Measurement	Work in Progress
J3112	A/C Compressor Oil Separator Effectiveness Test Standard	Work in Progress

5.2.9.1.6 Conclusions and Future Work

The agencies have evaluated and considered the results of AC17 testing presented by stakeholders. This data suggests that the AC17 test is capable of measuring the difference in CO_2 emissions between A/C on and A/C off, and in some cases, is also capable of resolving differences in CO_2 emissions resulting from hardware and software differences (A-to-B). However, in many of the A-to-B comparisons, test-to-test variability and the small magnitude of the effect to be measured has led to the need for multiple repeated tests to identify the effect with statistical significance, potentially adding to the test burden required to obtain A/C credits.

At this time, the results of USCAR testing of the AC17 test procedure is not yet complete, and not yet conclusive. The agencies await the availability of additional data in order to more fully evaluate the role of the AC17 test procedure under the GHG program. EPA also anticipates that the ongoing test program by USCAR members will result in development of a guidance letter recommending best practices for conducting AC17 testing.

EPA will continue coordination with USCAR to obtain any additional data regarding the effectiveness of the AC17 test in discerning A/C efficiency differences in A-to-B comparisons. Sources of this data may include additional A-to-B testing by USCAR, as well as any future applications for A/C off-cycle credits that are supported by the results of AC17 testing. EPA will also continue to coordinate with manufacturers through meetings with industry stakeholders, participation in the SAE interior climate control committees, coordination with the SAE CRP, and any other applicable venues.

The agencies invite additional comment regarding stakeholder experience with the AC17 test procedure and its ability to resolve GHG emissions differences by A-to-B testing.

Although it is anticipated that new A/C technologies may have emerged since the 2012 FRM that are not represented in the credit menu, the agencies do not have plans to add additional items to the credit menu nor change the values assigned to those that are currently in the menu. Manufacturers may continue to apply for credits for new technologies through the off cycle credit program.

5.2.9.2 A/C Leakage Reduction and Alternative Refrigerant Substitution

5.2.9.2.1 *Leakage*

As we observed in the rule, manufacturers have developed a number of technologies for reducing the leakage of refrigerant to the atmosphere. These include fittings, seals, heat exchanger/compressor designs, and hoses. Vehicle manufacturers consider low-leak technologies to be among the most cost-effective approaches to improving overall vehicle GHG emission performance.

Table 5.28 shows two metrics of the continued industry-wide progress toward durable, low-leak systems. One trend is the annual increase in the generation of leakage credits already apparent in the early years of the program as manufacturers have taken advantage of leakage-reduction incentives. More on this trend, as well as a breakdown of leakage credits by manufacturer, are found in EPA's *Manufacturer Performance Report for the 2014 Model Year*.[470] Specifically, 15 manufacturers reported A/C leakage credits in the 2014 model year, amounting to more than 16.5 million Megagrams (Mg) of credits, or more than 40 percent of the total net credits reported for the model year. This equates to GHG reductions of about 5 grams per mile across the 2014 vehicle fleet. The table also shows the trend toward more leak-proof A/C systems in terms of refrigerant leakage scores across the industry, as indicated by the average industry-wide A/C system leakage scores that the State of Minnesota requires automakers to report (using the SAE J-2727 method).[471]

Table 5.28 Trends in Fleetwide Mobile Air Conditioner Leakage Credits and Average Leakage Rates

	2009	2010	2011	2012	2013	2014	2015
Credits: (Million Megagrams)	6.2	8.3	8.9	11.1	13.2	16.6	Not Yet Reported
MN SAE J-2727 Leakage Rate (g/yr)	15.1	14.7	14.6	14.5	13.9	13.0	12.1

5.2.9.2.2 *Low-GWP Refrigerants*

In support of the LD GHG rules, EPA projected that the industry would fully transition to lower-GWP refrigerants between Model Year (MY) 2017 and MY2021, beginning with 20 percent transition in MY2017, to be followed by a 20 percent increase in substitution in each subsequent model year, completing the transition by MY2021 (77 FR 62779, 62778, 62805). Put another way, the stringency of the MY2021 and later light duty GHG standards is predicated on 100 percent substitution of refrigerants with lower GWPs than HFC-134a. On July 20, 2015, EPA published a final rule under the Significant New Alternatives Policy (SNAP) program that changes the listing status of HFC–134a to unacceptable for use in A/C systems of newly-manufactured LD motor vehicles beginning in MY2021, except where permitted for some export vehicles through MY2025 (80 FR 42870).[MM] EPA's decision to take this action was based on the availability of other substitutes that pose less overall risk to human health and the environment, when used in accordance with required use conditions. Thus all new LD vehicles sold in the United States will have transitioned to an alternative, lower-GWP refrigerant by MY2021.

The July 20, 2015 SNAP final rule has no effect on how manufacturers may choose to generate and use air conditioning leakage credits under the LD GHG standards. As stated in that final rule, " [n]othing in this final rule changes the regulations establishing the availability of air conditioning refrigerant credits under the GHG standards for MY2017-2025, found at 40 CFR 86.1865-12 and 1867-12. The stringency of the standards remains unchanged…. [M]anufacturers may still generate and utilize credits for substitution of HFC-134a through the 2025 model year." EPA also there noted that the SNAP rule was not in conflict with the Supplemental Notice of Intent (76 FR 48758, August 9, 2011) that described plans for EPA and NHTSA's joint proposal for model years 2017-2025, since EPA's GHG program continues to provide the level of air conditioning credits available to manufacturers as specified in that Notice: "[T]he Supplemental Notice of Intent states that '(m)anufacturers will be able to earn credits for improvements in air conditioning . . . systems, both for efficiency improvements . . . and for leakage or alternative, lower-GWP refrigerants used (reduces [HFC] emissions).' 76 FR at 48761. These credits remain available under the light-duty program at the level specified in the Supplemental Notice of Intent, and using the same demonstration mechanisms set forth in that Notice." 80 FR 42896-97.

EPA has listed three lower-GWP refrigerants as acceptable, subject to use conditions (listed at 40 CFR Part 82, Subpart G), for use in newly-manufactured LD vehicles: HFO-1234yf, HFC-152a, and carbon dioxide (CO_2 or R-744). Manufacturers are currently manufacturing LD vehicles using HFO-1234yf, and they are actively developing LD vehicles using CO_2[472] and considering the use of HFC-152a in a secondary loop A/C systems.[473]

EPA expects that vehicle manufacturers will use HFO-1234yf for the vast majority of vehicles. As discussed in the EPA Manufacturer Performance Report referenced above, the use of HFO-1234yf expanded considerably in the 2014 model year, from two manufacturers and 42,384 vehicles in the 2013 model year, to five manufacturers and 628,347 vehicles in the 2014 model year. Although this is a large increase, it is still a relatively small fraction (less than 5 percent) of the total 2014 model year production. This trend reinforces EPA's projection that the industry will have transitioned 20 percent of the fleet by MY2017, as discussed above. Fiat

[MM] HFC-134a will remain listed as acceptable subject to narrowed use limits through MY2025 for use in newly manufactured LD vehicles destined for export, where reasonable efforts have been made to ascertain that other alternatives are not technically feasible because of lack of infrastructure for servicing with alternative refrigerants in the destination country. (40 CFR Part 82, Subpart G, Appendix B.

Chrysler accounted for 86 percent of these vehicles, introducing HFO-1234yf across a number of models, including the 300, Challenger, Charger, Cherokee, Dart, and Ram 1500 trucks. Jaguar Land Rover achieved the greatest penetration within their fleet, using HFO-1234yf in approximately 80 percent of Jaguar Land Rover vehicles produced in the 2014 model year.

Finally, regarding supply of alternative refrigerants, the July 2015 SNAP final rule stated that EPA "considered the supply of the alternative refrigerants in determining when alternatives would be available. At the time the light-duty GHG rule was promulgated, there was a concern about the potential supply of HFO-1234yf. Some commenters indicated that supply is still a concern, while others, including two producers of HFO-1234yf, commented that there will be sufficient supply. Moreover, some automotive manufacturers are developing systems that can safely use other substitutes, including CO_2, for which there is not a supply concern for the refrigerant. If some global light-duty motor vehicle manufacturers use CO_2 or another acceptable alternative, additional volumes of HFO-1234yf that would have been used by those manufacturers will then become available. Based on all of the information before the agency, EPA believes production plans for the refrigerants are in place to make available sufficient supply no later than MY2021 to meet current and projected demand domestically as well as abroad, including, but not limited to, the EU." (80 FR 42891; July 20, 2015)

5.2.9.2.3 Conclusions

As described in this section, there is strong evidence that auto manufacturers are continuing to improve the leak-tightness of their A/C systems. In addition, many manufacturers are transitioning to the use of low-GWP alternative refrigerants in a number of vehicle models. We believe that the current trends among automakers toward the use of alternative refrigerants to comply with the LD vehicle GHG standards, EPA's change in listing status of HFC-134a to "unacceptable" by MY2021, and the parallel increase in the supply of the leading alternative refrigerant ensure that our earlier projections that a complete transition to alternative refrigerants by MY2021 will in fact become reality.

The MY2017-2025 LD GHG rule also encourages manufacturers to continue to use low-leakage technologies even when using alternative refrigerants. Although some leakage may still occasionally occur, the low GWPs of the new refrigerants, as compared to that of HFC-134a, considerably reduce concerns about refrigerant leakage from a climate perspective.

5.2.10 Off-cycle Technology Credits

5.2.10.1 Off-cycle Credits Program

5.2.10.1.1 Off-cycle Credits Program Overview

EPA and NHTSA provide an opportunity for credits for off-cycle technologies. EPA initially included off-cycle technology credits in the MY2012-2016 rule and revised the program in the MY2017-2025 rule.[474] NHTSA adopted equivalent off-cycle credits for MYs 2017 and later in the MY2017-2025 rule.[475] "Off-cycle" emission reductions and fuel consumption improvements can be achieved by employing off-cycle technologies that result in real-world benefits, but where that benefit is not adequately captured on the test procedures used by manufacturers to demonstrate compliance with and fuel economy emission standards.

The intent of the off-cycle provisions is to provide an incentive for CO_2 and fuel consumption reducing off-cycle technologies that would otherwise not be developed because they do not offer a significant 2-cycle benefit. EPA and NHTSA limited the eligibility to technologies whose benefits are not adequately captured on the 2-cycle test and NHTSA added further limitations on technologies that might otherwise be incentivized through its safety regulations.[476] The preamble to the final rule provided a detailed discussion of eligibility for off-cycle credits.[477] Technologies that are integral or inherent to the basic vehicle design including engine, transmission, mass reduction, passive aerodynamics, and base tires are not eligible. Any technology that was included in the agencies' standard-setting analysis also may not generate off-cycle credits (with the exception of active aerodynamics and engine stop-start systems). EPA established this approach believing that the use of 2-cycle technologies would be driven by the standards and no additional credits would be necessary or appropriate. This approach also limits the program to off-cycle technologies that could be clearly identified as add-on technologies more conducive to A/B testing that would be able to demonstrate the benefits of the technology.

There are three pathways by which a manufacturer may generate off-cycle CO_2 credits. The first is a predetermined list of credit values for specific off-cycle technologies that may be used beginning in MY2014.[478] This pathway allows manufacturers to use conservative credit values established in the MY2017-2025 final rule for a wide range of technologies, with minimal data submittal or testing requirements. In cases where additional laboratory testing can demonstrate emission benefits, a second pathway allows manufacturers to use a broader array of emission tests (known as “5-cycle” testing because the methodology uses five different testing procedures) to demonstrate and justify off-cycle CO_2 credits.[479] The additional emission tests allow emission benefits to be demonstrated over some elements of real-world driving not captured by the GHG compliance tests, including high speeds, rapid accelerations, and cold temperatures. Credits determined according to this methodology do not undergo additional public review. The third and last pathway allows manufacturers to seek EPA approval to use an alternative methodology for determining the off-cycle CO_2 credits.[480] This option is only available if the benefit of the technology cannot be adequately demonstrated using the 5-cycle methodology. Manufacturers may also use this option for model years prior to 2014 to demonstrate off-cycle CO_2 reductions for technologies that are on the predetermined list, or to demonstrate reductions that exceed those available via use of the predetermined list. The manufacturer must also demonstrate that the off-cycle technology is effective for the full useful life of the vehicle. Unless the manufacturer demonstrates that the technology is not subject to in-use deterioration, the manufacturer must account for the deterioration in their analysis.

The pre-defined list of technologies and associated car and light truck credits is shown in the tables below.[481] The regulations include a definition of each technology that the technology must meet in order to be eligible for the menu credit.[482] Manufacturers are not required to submit any other emissions data or information beyond meeting the definition and useful life requirements to use the pre-defined credit value. Credits based on the pre-defined list are subject to an annual manufacturer fleet-wide cap of 10 g/mile.

Table 5.29 Off-cycle Technologies for Cars and Light Trucks

Technology	Credit for Cars	Credit for Light Trucks
	g/mi (gallons/mi)	g/mi (gallons/mi)
High Efficiency Exterior Lighting (at 100W)	1.0 (0.000113)	1.0 (0.000113)
Waste Heat Recovery (at 100W; scalable)	0.7 (0.000079)	0.7 (0.000079)
Solar Roof Panels (for 75 W, battery charging only)	3.3 (0.000372)	3.3 (0.000372)
Solar Roof Panels (for 75 W, active cabin ventilation plus battery charging)	2.5 (0.000282)	2.5 (0.000282)
Active Aerodynamic Improvements (scalable)	0.6 (0.000068)	1.0 (0.000113)
Engine Idle Start-Stop w/ heater circulation system	2.5 (0.000282)	4.4 (0.000496)
Engine Idle Start-Stop without/ heater circulation system	1.5 (0.000169)	2.9 (0.000327)
Active Transmission Warm-Up	1.5 (0.000169)	3.2 (0.000361)
Active Engine Warm-Up	1.5 (0.000169)	3.2 (0.000361)
Solar/Thermal Control	Up to 3.0 (0.000338)	Up to 4.3 (0.000484)

Table 5.30 Off-cycle Technologies and Credits for Solar/Thermal Control Technologies for Cars and Light Trucks

Thermal Control Technology	Credit (g CO_2/mi)	
	Car	Truck
Glass or Glazing	Up to 2.9 (0.000326)	Up to 3.9 (0.000439)
Active Seat Ventilation	1.0 (0.000113)	1.3 (0.000146)
Solar Reflective Paint	0.4 (0.00005)	0.5 (0.00006)
Passive Cabin Ventilation	1.7 (0.000191)	2.3 (0.000259)
Active Cabin Ventilation	2.1 (0.000236)	2.8 (0.000315)

The two other pathways available to generate off-cycle credits require additional data. The 5-cycle testing pathway requires 5-cycle testing with and without the off-cycle technology to determine the off-cycle benefit of the technology. The final pathway, often referred to as the public process includes a public comment period and is available for technologies that cannot be demonstrated on the 5-cycle test. Manufacturers must develop a methodology for demonstrating the benefit of the off-cycle technology and the methodology is made available for public comment prior to an EPA determination whether or not to allow the use of the methodology to generate credits. The data needed for this demonstration may be extensive, especially in cases where the effectiveness of the technology is dependent on driver response or interaction with the technology. As discussed below, all three methods have been used successfully by manufacturers to generate off-cycle credits.

5.2.10.2 Use of Off-cycle Technologies to Date

A wide array of off-cycle technologies were used by manufacturers in MY2014 to generate off-cycle GHG credits using the pre-defined menu.[483] Table 5.31 below shows the percent of each manufacturers' production volume using each of the menu technologies reported to EPA for MY2014 by the manufacturer. Table 5.32 shows the g/mile benefit that each manufacturer reported across its fleet from each off-cycle technology. Like the preceding table, Table 5.32

provides the mix of technologies used in MY2014 across the manufacturers and the extent to which each technology benefits each manufacturer's fleet. Fuel consumption improvement off-cycle credits are not available in the CAFE program until MY2017 and therefore only GHG off-cycle credits have been generated by manufacturers thus far.

Table 5.31 Percent of 2014 Model Year Vehicle Production Volume with Credits from the Menu, by Manufacturer & Technology (%)

Manufacturer	Active Aerodynamics		Thermal Control Technologies				Engine & Transmission Warmup			Other		
	Grill shutters	Ride height adjustment	Passive cabin ventilation	Active cabin ventilation	Active seat ventilation	Glass or glazing	Solar reflective surface coating	Active engine warmup	Active transmission warmup	Engine idle stop-start	High efficiency exterior lights	Solar panel(s)
BMW	0.0	0.0	0.0	85.1	3.9	2.9	0.0	78.5	0.0	0.0	98.1	0.0
Fiat Chrysler	16.4	3.6	99.3	0.0	6.1	99.3	1.3	58.0	11.7	0.0	73.3	0.0
Ford	38.4	0.0	0.0	0.0	2.6	97.2	12.5	9.6	16.2	3.4	52.9	0.0
GM	6.7	0.0	0.0	0.0	1.2	52.3	15.6	0.0	0.0	6.7	28.2	0.0
Honda	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	58.5	0.0	28.2	0.0
Hyundai	2.1	0.0	0.0	0.0	0.8	84.4	0.0	0.0	16.7	0.0	36.2	0.0
Jaguar Land Rover	0.0	0.0	0.0	0.0	5.0	98.1	0.0	0.0	0.0	93.0	100.0	0.0
Kia	1.8	0.0	0.0	0.0	0.9	76.1	0.0	0.0	22.7	0.6	59.5	0.0
Mercedes	0.0	0.0	0.0	0.0	2.2	3.9	0.0	0.0	0.0	65.3	35.7	0.0
Nissan	4.6	0.0	0.0	0.0	1.8	0.0	0.0	19.5	55.7	0.9	50.1	0.2
Subaru	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Toyota	0.0	0.2	11.4	0.0	2.5	52.9	25.5	9.2	53.8	12.5	44.5	0.0
Fleet Total	9.8	0.0	15.0	2.1	2.3	50.7	8.7	14.2	23.2	5.5	43.0	0.0

Table 5.32 Off-Cycle Technology Credits from the Menu, by Manufacturer and Technology (g/mi)

Manufacturer	Active Aerodynamics		Thermal Control Technologies				Engine & Transmission Warmup			Other		
	Grill shutters	Ride height adjustment	Passive cabin ventilation	Active cabin ventilation	Active seat ventilation	Glass or glazing	Solar reflective surface coating	Active engine warmup	Active transmission warmup	Engine idle stop-start	High efficiency exterior lights	Solar panel(s)
BMW	-	-	-	2.0	0.0	0.0	-	1.6	-	-	0.3	-
Fiat Chrysler	0.1	0.0	2.0	-	0.0	1.8	0.0	1.7	0.4	0.0	0.2	-
Ford	0.3	-	-	-	0.2	1.3	0.1	0.2	0.4	0.1	0.1	-
GM	0.0	-	-	-	0.2	0.7	0.1	-	-	0.1	0.1	-
Honda	-	-	-	-	0.0	-	-	-	1.3	-	0.1	-
Hyundai	0.0	-	-	-	0.1	0.3	-	-	0.3	-	0.0	-
Jaguar Land Rover	-	-	-	-	0.8	1.2	-	-	-	2.5	0.5	-
Kia	0.0	-	-	-	0.2	0.3	-	-	0.3	0.0	0.1	-
Mercedes	-	-	-	-	0.1	0.1	-	-	-	1.7	0.4	-
Nissan	0.0	-	-	-	0.1	-	-	0.3	1.2	0.0	0.2	0.0
Subaru	0.0	-	-	-	-	-	-	-	-	-	-	-
Toyota	-	0.0	0.2	-	0.2	0.6	0.1	0.1	1.1	0.2	0.1	-
Fleet Total	0.1	0.0	0.3	0.0	0.1	0.7	0.0	0.3	0.5	0.1	0.1	0.0

0.0" indicates that the manufacturer did implement that technology, but that the overall penetration rate was not high enough to round to 0.1 grams/mile, whereas a dash indicates no use of a given technology by a manufacturer.

The credits shown above are based on the pre-defined credit list. Thus far, GM is the only manufacturer to have been granted off-cycle credits based on 5-cycle testing. These credits are for an off-cycle technology used on certain GM gasoline-electric hybrid vehicles. The technology is an auxiliary electric pump, which keeps engine coolant circulating in cold weather while the vehicle is stopped and the engine is off, thus allowing the engine stop-start system to be active more frequently in cold weather.

The third pathway allows manufacturers to seek approval to use an alternative methodology for determining the off-cycle technology CO_2 credits. Several manufacturers have petitioned for and been granted use of an alternative methodology for generating credits. In the fall of 2013, Mercedes requested off-cycle credits for the following off-cycle technologies in use or planned for implementation in the 2012-2016 model years: stop-start systems, high-efficiency lighting, infrared glass glazing, and active seat ventilation. EPA approved methodologies for Mercedes to determine these off-cycle credits in September of 2014.[484] Subsequently, FCA, Ford, and GM requested off-cycle credits under this pathway. FCA and Ford submitted applications for off-cycle credits from high efficiency exterior lighting, solar reflective glass/glazing, solar reflective paint, and active seat ventilation. Ford's application also demonstrated off-cycle benefits from active aerodynamic improvements (grill shutters), active transmission warm-up, active engine warm-up technologies, and engine idle stop-start. GM's application described the real-world benefits of an air conditioning compressor with variable crankcase suction valve technology. EPA approved the credits for FCA, Ford, and GM in September of 2015.[485] Although EPA has granted the use of alternative methodologies, manufacturers have yet to report credits to EPA based on those alternative methodologies.

As discussed above, the vast majority of credits in MY2014 were generated using the pre-defined menu. Even though the program has been in place for only a few model years, and MY2014 is the first year the pre-defined list may be used, the level of credits achieved has already been significant for some manufacturers. FCA and Jaguar Land Rover generated the most off-cycle credits on a fleet-wide basis, reporting credits equivalent to about 6 g/mile and 5 g/mile, respectively.[NN] Several other manufacturers report fleet-wide credits in the range of about 1 to 4 g/mile. The fleet total across all manufacturers was equivalent to about 2 g/mile for MY2014. The agencies expect that as manufacturers continue to expand their use of off-cycle technologies, the fleet-wide impacts will continue to grow with some manufacturers potentially approaching the 10 g/mile fleet-wide cap applicable to credits that are based on the pre-defined list.

5.3 GHG Technology Assessment

5.3.1 Fundamental Assumptions

5.3.1.1 Technology Time Frame and Measurement Scale for Effectiveness and Cost

The effectiveness and cost associated with applying a technology will depend on the starting technologies from which improvements are measured. For example, two vehicles that start with different technologies will likely have different cost and effectiveness associated with adopting the same combination of technologies. The importance of clearly specifying the point of comparison for cost and effectiveness estimates was highlighted in the 2015 NAS committee's finding "that understanding the base or null vehicle, the order of technology application, and the interactions among technologies is critical for assessing the costs and effectiveness for meeting the standards."

As long as the point of comparison is maintained consistently throughout the analysis for both the baseline and future fleets, the decision of where to place an origin along the scale of cost and effectiveness is inconsequential. For EPA's technology assessment, the origin is defined to coincide with a "null technology package," which represents a technology floor such that all technology packages considered in this assessment will have equal or greater effectiveness, consistent with the FRM approach. While other choices would have been equally valid, this definition of a "null package" has the practical benefit of avoiding technology packages with negative effectiveness values, while also allowing for a direct comparison of effectiveness assumptions with the FRM.

[NN] The credits are reported to EPA by manufacturers in Megagrams. EPA has estimated a g/mile equivalent.

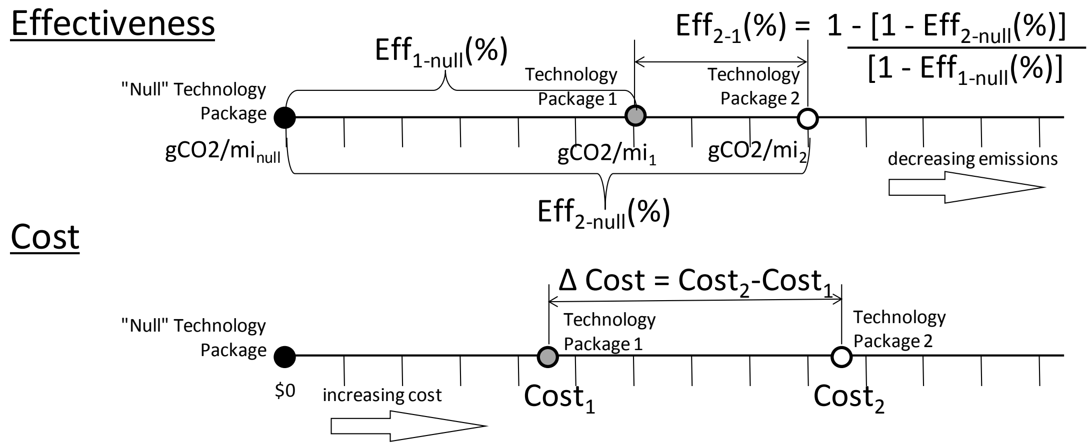


Figure 5.80 The "Null Technology Package" and Measurement Scale for Cost and Effectiveness

When technologies can be specifically identified for individual vehicle models, it is possible to estimate cost and effectiveness values specifically for those models. To the extent possible with the available information, EPA has attempted to consider this. This is the case, for example, with mass reduction and improvements in aerodynamics and tire rolling resistance, where for this assessment EPA has uniquely characterized the various levels of those technologies for individual models based on available road load data. For other technologies, the information that is broadly available across the entire fleet is not detailed enough to distinguish differences that arise to different implementations of the technologies.

5.3.1.2 Performance Assumptions

When determining cost and effectiveness values for specific technologies, it is important to compare the technologies on a consistent basis, so that the relative cost-effectiveness of the technologies can be fairly compared. The National Academy of Science states in their 2011 report: "Estimating the cost of decreasing fuel consumption requires one to carefully specify a basis for comparison. The committee considers that to the extent possible, fuel consumption cost comparisons should be made at equivalent acceleration performance and equivalent vehicle size."[486] This is because "objective comparisons of the cost-effectiveness of different technologies for reducing [fuel consumption] can be made only when vehicle performance remains equivalent."[487] The National Academy of Science engaged the University of Michigan for their 2015 report to perform a set full vehicle simulations. As a ground rule, "Each engine configuration was modeled to maintain, as closely as possible, the torque curve of the baseline naturally aspirated engine so that equal performance, as measured by 0-60 mph acceleration time, would be maintained"[488] The agencies agree that it is appropriate to objectively compare technology costs and effectiveness, that maintaining constant vehicle performance is the appropriate way to achieve that goal, and that the NAS's recommendation of "equivalent acceleration performance" is appropriate. Thus, the costs and effectiveness presented in this document are based on the application of technology packages while holding the underlying acceleration performance constant.

In most cases, equivalent acceleration performance is achieved by "engine downsizing": reducing the size (and thus the output power/torque) of the engine in advanced vehicle packages until a series of performance metrics are maintained within a reasonable range of the target value similar to the methodology used in the FRM. A smaller engine will typically be more efficient at the same speed and torque than a larger engine (as pumping losses are reduced), so this methodology properly accounts for effectiveness that could be used for acceleration performance as fuel consumption reduction, thus allowing an objective and fair comparison of technologies. Our process maintains performance neutrality. As recommended by the NAS (2011), EPA is working under the premise that technology cost assessments should be made under the assumption of equivalent performance. As such, the ALPHA modeling runs generate effectiveness values which maintain a set of acceleration metrics within a reasonably small window.

EPA recognizes that manufacturers have many vehicle attribute and manufacturing constraints. Manufacturers will make many product planning decisions and the final products will have engine displacement which represent the OE's decision in its product plans. As a modeling convenience, when calculating effectiveness, EPA assumes the appropriate component sizing to maintain performance. Even if our model produces a greater variation in technology packages than exists today (for example, by producing two levels of tire rolling resistance on a vehicle platform compared to just one today), this does not require that manufactures actually produce a greater variety of component sizes than exist currently in order for our overall results to be valid. In actual vehicle design, manufacturers will design discretely sized components, and for each vehicle choose the available size closest to the optimal for the given load and performance requirements. For example, in some cases, the chosen engine will be slightly smaller than optimal (and thus lower fuel consumption), and in some cases the chosen engine will be slightly larger than optimal (and thus higher fuel consumption). The same assumption is applied to drivetrain, suspension, chassis components, etc. For example, brake rotors may be sized in 15mm diameter increments, and manufacturers will apply the size that most closely matches the performance and load requirements of that application. Just as the manufacturers are doing today, EPA expects that they will average these product decisions across their entire fleet. In our analysis, on average, the actual fleet of vehicles will use the appropriate component size, and CO_2 emissions and performance of the fleet will average out, with no significant net change compared to the original analysis with unconstrained component sizes.

In gathering information on technology effectiveness, the agencies relied on a wide variety of sources. These sources provided information on the costs and effectiveness of various technologies, but not all comparisons were done on a rigorously performance-neutral basis. Thus, it was often necessary to recalculate the effectiveness of a particular technology when the original comparison was done without the assumption of equivalent performance. For example, the 2011 NAS report, in discussing continuously variable valve lift (CVVL)[489] cites Energy and Environmental Analysis, Inc.,[490] which "estimates a 6.5 to 8.3 percent reduction in fuel consumption at constant engine size and 8.1 to 10.1 percent with an engine downsize to maintain constant performance."

When EPA modeled effectiveness of specific technologies of their combinations, it was careful to maintain a minimum deviation of acceleration performance from the baseline vehicle. As the NAS notes, "truly equal performance involves nearly equal values for a large number of measures such as acceleration (e.g., 0-60 mph, 30-45 mph, 40-70 mph, etc.), launch (e.g., 0-30 mph), grade-ability (steepness of slopes that can be climbed without transmission downshifting), maximum towing capability, and others."[491] However, they furthermore state that "in the usage herein, equal performance means 0-60 mph times within 5 percent. This measure was chosen because it is generally available for all vehicles."

In vehicle simulations conducted in support of the FRM using MSC EASY5 or using the Response Surface Model (RSM) data analysis tool, EPA defined overall equivalent performance such that 0-30 mph and 0-60 mph acceleration times were kept within a performance window defined as no more than 5 percent slower or 10 percent faster than a baseline vehicle. Additional performance criteria were then cross-checked to ensure no significant degradation in vehicle utility. For example, simulation of grade-ability at 60 mph with a 5,000 lb. trailer (both in top gear and in any transmission gear) was used to cross check maintaining the utility of full size trucks. Within the FRM analysis, the 0-30 mph and 0-60 mph performance window criteria were found to be sufficient to maintain equivalence with other indicators of vehicle performance and utility, including trailer grade-ability.

In vehicle simulation modeling in ALPHA performed since the FRM, EPA investigated using additional performance criteria to define an overall performance metric. Four acceleration performance metrics were chosen: 0-60 time, ¼ mile time, 30-50 passing time, and 50-70 passing time. These metrics were chosen to give a reasonably broad set of acceleration metrics that would be sensitive enough to represent true acceleration performance, but not so sensitive that minor changes in vehicle parameters would significantly change the final metric. For each vehicle class, a baseline configuration was chosen, the vehicle package was run over the performance cycle, and the times for each performance metric were extracted. These four metrics were summed for the baseline vehicle. For each vehicle technology package based on the same vehicle class, a nominal engine size was determined based on the estimated performance effect of the technologies included in the package. The same performance cycle was run and the sum of the four metrics compared to the baseline sum. If the sum was not within three percent (tighter than the 5 percent band suggested by NAS), the size of the engine was adjusted and the performance cycle rerun until an equivalent acceleration performance was attained. When the sum was within three percent, the CO_2 emissions modeling over the standard drive cycles was performed using the engine size determined.

In general, the criteria used to define equivalent performance for the FRM analysis and for analyses using the ALPHA model since the FRM have resulted in comparable changes in engine displacement when comparable levels of vehicle technology are applied within the EPA "standard car" class for effectiveness analyses. For the Draft TAR, EPA has continued to rely on the performance criteria from the FRM analysis within its analyses of technology effectiveness, however, the addition of ¼ mile time, 30-50 passing time, and 50-70 passing time performance metrics are still under consideration for the Proposed and Final Determinations.

For the purpose of specification and costing of plug-in vehicles (BEVs and PHEVs, or collectively, PEVs), acceleration performance was maintained by a different method to account for differences in the way power is developed by electric motors and conventional engines. Originally, in the 2012 FRM analysis, PEVs of a given vehicle class (small car, large car, etc.) were assigned an electric motor power rating (kW) that would preserve the same engine-power-to-weight ratio that was observed in conventional vehicles of that class. This method assumed that the all-electric acceleration of an electrified vehicle relates to the power rating of the electric motor in the same way that the engine-powered acceleration of a conventional vehicle relates to the power rating of the engine. However, electric motors differ from combustion engines in that they deliver maximum torque at the lowest end of their speed range, while combustion engines must develop significant speed to deliver a comparable torque. This can allow an electric motor to deliver higher acceleration at low speeds than a comparable engine of the same nominal power rating, and potentially higher acceleration overall. An analysis of 2012 FRM motor power assumptions suggested that the modeled PEV motors may have been significantly more powerful than necessary for the intended acceleration performance. For this Draft TAR analysis, EPA derived an empirical equation relating PEV power-to-weight ratio to reported 0-60 acceleration time based on an informal study of MY2012-2016 BEVs and PHEVs. A target 0-60 time was selected for each PEV configuration comparable to that of conventional vehicles, and the motor power assigned based on this equation. The PEV motor sizing methodology is described in more detail in Section 5.3.4.3.7.1.

5.3.1.3 Fuels

Fuel specifications for the gasoline and diesel fuels used for demonstration of compliance with light-duty vehicle GHG and CAFE standards are contained within the Title 40, Part 86 of the U.S. Code of Federal Regulations. Tabulated values are reproduced here for reference purposes in Table 5.33 and Table 5.34 for gasoline and diesel, respectively. Analyses of the effectiveness of powertrain technologies over the regulatory drive cycles used fuel properties conforming to these specifications.

Table 5.33 Test Fuel Specifications for Gasoline without Ethanol (from 40 CFR §86.113-04)

Item	Regular	Reference Procedure[1]
Research octane, Minimum[2]	93	ASTM D2699; ASTM D2700
Octane sensitivity[2]	7.5	ASTM D2699; ASTM D2700
Distillation Range (°F):		
Evaporated initial boiling point[3]	75-95	ASTM D86
10% evaporated	120-135	
50% evaporated	200-230	
90% evaporated	300-325	
Evaporated final boiling point	415 Maximum	
Hydrocarbon composition (vol %):		
Olefins	10% Maximum	ASTM D1319
Aromatics	35% Maximum	
Saturates	Remainder	
Lead, g/gallon (g/liter), Maximum	0.050 (0.013)	ASTM D3237
Phosphorous, g/gallon (g/liter), Maximum	0.005 (0.0013)	ASTM D3231
Total sulfur, wt. %[4]	0.0015-0.008	ASTM D2622
Dry Vapor Pressure Equivalent (DVPE), psi (kPa)[5]	8.7-9.2 (60.0-63.4)	ASTM D5191

Table 5.34 Petroleum Diesel Test Fuel (from 40 CFR §86.113-94)

Property	Unit	Type 2-D	Reference Procedure[1]
(i) Cetane Number		40-50	ASTM D613
(ii) Cetane Index		40-50	ASTM D976
(iii) Distillation range:			
(A) IBP		340-400 (171.1-204.4)	
(B) 10 pct. Point		400-460 (204.4-237.8)	

(C) 50 pct. Point	°F (°C)	470-540 (243.3-282.2)	STM D86
(D) 90 pct. Point		560-630 (293.3-332.2)	
(E) EP		610-690 (321.1-365.6)	
(iv) Gravity	°API	32-37	ASTM D4052
(v) Total sulfur	ppm	7-15	ASTM D2622
(vi) Hydrocarbon composition: Aromatics, minimum (Remainder shall be paraffins, naphthenes, and olefins)	pct	27	ASTM D5186
(vii) Flashpoint, min	°F (°C)	130 (54.4)	ASTM D93
(viii) Viscosity	centistokes	2.0-3.2	ASTM D445
[1] ASTM procedures are incorporated by reference in §86.1			

EPA's analysis of effectiveness with gasoline fueled engines did not include analysis of effectiveness using Tier 3 certification gasoline (E10, 87 AKI) although protection for operation in-use on 87 AKI E10 gasoline was included in the analysis of engine technologies considered both within the original FRM and within the Draft TAR. A correction factor (or R-factor) for application to future vehicles certified using Tier 3 gasoline that will allow correction of CO_2 emissions in a manner that accounts for differences between Tier 2 and Tier 3 certification fuels is currently under regulatory development.

5.3.1.4 Vehicle Classification

The vehicle classes for which EPA has estimated effectiveness are consistent with the FRM and six vehicle classes developed for the lumped parameter model. Table 5.35 presents the mapping of lumped parameter model vehicle classes into model-specific vehicles to help the reader understand how the vehicle classes are used for modeling.

Table 5.35 EPA Vehicle Classes

EPA Vehicle Class	Lump Parameter Classification	Example	OMEGA Model Vehicle Type
Subcompact/ Small Car	Small Car	Fiesta Focus Yaris	1
Standard Car	Standard Car	Fusion Taurus Camry	2, 3, 4
Large Car	Large Car	300 Mustang	5, 6
Small MPV	Small MPV	Escape Rav4 Tacoma	7, 13
Large MPV	Large MPV	Explorer 4Runner Caravan	8, 9, 10, 14, 15, 18
Truck	Truck	F150 Tundra	11, 12, 16, 17, 19

5.3.2 Approach for Determining Technology Costs

Section 5.3.2.1 presents sources and approaches to estimating direct manufacturing costs. Section 5.3.2.1.4 presents the methods used to address indirect costs in this analysis. Section 5.3.2.1.4 presents the learning effects applied throughout this analysis. In Section 5.3.2.1 the individual technology costs are presented including: the direct manufacturing costs (DMC), their indirect costs (IC) and their total costs (TC, TC=DMC+IC).

5.3.2.1 Direct Manufacturing Costs

Estimates of direct manufacturing costs (DMC) come from many sources: detailed paper studies and analyses; published reports; supplier and OEM provided data which would generally be confidential business information (CBI); etc. The agencies consider the best source of DMC estimates to be those from tear-down studies. The 2015 NAS report503 agreed with this assessment and encouraged the agencies to make use of tear-down studies where available stating, "the use of teardown studies has improved the agencies' estimates of costs" (NAS pp. S-3) and "Updated cost estimates using teardown cost studies of recently introduced spark-ignition engine technologies, including all vehicle integration costs, should be developed to support the mid-term review," (NAS pp. S-4) and "EPA and NHTSA should conduct a teardown cost study of a modern diesel engine with the latest technologies to provide an up-to-date estimate of diesel engine costs." (NAS pp. S-5) The summary below provides our sources for many of the technologies considered in this analysis.

5.3.2.1.1 Costs from Tear-down Studies

As in the 2017-2025 FRM, there are a number of technologies in this analysis that have been costed using the rigorous tear-down method described in this section. As a general matter, the agencies believe, and the NAS agrees,[492] that the most rigorous method to derive technology cost estimates is to conduct studies involving tear-down and analysis of actual vehicle components. A "tear-down" involves breaking down a technology into its fundamental parts and manufacturing processes by completely disassembling actual vehicles and vehicle subsystems and precisely determining what is required for its production. The result of the tear-down is a "bill of materials" for each and every part of the vehicle or vehicle subsystem. This tear-down method of costing technologies is often used by manufacturers to benchmark their products against competitive products. Historically, vehicle and vehicle component tear-down has not been done on a large scale by researchers and regulators due to the expense required for such studies. Many technology cost studies in the literature are based on information collected from OEMs, suppliers, or "experts" in the industry and are thus non-reproducible and non-transparent. In contrast, EPA sponsored teardown studies are completely transparent and include a tremendous amount of data and analyses to improve accuracy. While tear-down studies are highly accurate at costing technologies for the year in which the study is intended, their accuracy, like that of all cost projections, may diminish over time as costs are extrapolated further into the future because of uncertainties in predicting commodities (and raw material) prices, labor rates, and manufacturing practices. The projected costs may be higher or lower than predicted.

Since the early development of the 2012-2016 rule, EPA has contracted with FEV, Inc. to conduct tear-down cost studies for a number of key technologies evaluated by the agencies in assessing the feasibility of future GHG and CAFE standards. The analysis methodology included procedures to scale the tear-down results to smaller and larger vehicles, and also to different technology configurations. FEV's methodology was documented in a report published as part of the MY2012-2016 rulemaking process.[493]

Additional cost studies were completed and used in support of the 2017-2025 FRM. These include vehicle tear downs of a Ford Fusion power-split hybrid and a conventional Ford Fusion (the latter served as a baseline vehicle for comparison). In addition to providing power-split HEV costs, the results for individual components in these vehicles were subsequently used to develop costs for the P2 hybrid used in the following MY2017-2025 FRM.[OO] This approach to costing P2 hybrids was undertaken because P2 HEVs were not yet in volume production at the time of hardware procurement for tear-down. Finally, an automotive lithium-polymer battery was torn down to provide supplemental battery costing information to that associated with the NiMH battery in the Fusion, because automakers were moving to Li-ion battery technologies due to the higher energy and power density of these batteries. As noted, this HEV cost work, including the extension of results to P2 HEVs, has been documented in a report prepared by FEV and was used in support of the 2017-2025 FRM. Because of the complexity and comprehensive scope of this HEV analysis, EPA commissioned a separate peer review focused exclusively on the new tear down costs developed for the HEV analysis. Reviewer comments generally supported FEV's methodology and results, while including a number of suggestions for improvement, many of which were subsequently incorporated into FEV's analysis and EPA final report. The peer review comments and responses were made available in the rulemaking docket.

Additional cost studies were completed and used in support of the Draft TAR. These include an I4 mild hybrid system (2013 Malibu with eAssist) replacing a conventional I4 engine, an I4 diesel engine replacing a conventional V6 gasoline engine, and a turbocharged I4 engine replacing a V6 gasoline engine. This latest turbocharged study replaces the original study as this technology has evolved significantly over the past few years. Peer reviews have been completed for the mild hybrid and diesel cost studies.

Over the course of this contract between EPA and FEV, FEV performed teardown-based studies on the technologies listed below. These completed studies provide a thorough evaluation of the new technologies' costs relative to their baseline (or replaced) technologies.

1) Stoichiometric gasoline direct injection (SGDI) and turbocharging with engine downsizing (T-DS) on a DOHC (dual overhead cam) I4 engine, replacing a conventional DOHC I4 engine
2) SGDI and T-DS on a SOHC (single overhead cam) on a V6 engine, replacing a conventional 3-valve/cylinder SOHC V8 engine
3) SGDI and T-DS on a DOHC I4 engine, replacing a DOHC V6 engine
4) 6-speed automatic transmission (AT), replacing a 5-speed AT
5) 6-speed wet dual clutch transmission (DCT) replacing a 6-speed AT.
6) 8-speed AT replacing a 6-speed AT
7) 8-speed DCT replacing a 6-speed DCT
8) Power-split hybrid (Ford Fusion with I4 engine) compared to a conventional vehicle (Ford Fusion with V6). The results from this tear-down were extended to address P2 hybrids. In addition, costs from individual components in this tear-down study were used by the agencies in developing cost estimates for PHEVs and EVs.

[OO] Describe what P2 hybrid means.

9) Fiat Multi-Air engine technology. (Although results from this cost study are included in the rulemaking docket, they were not used in the 2017-2025 rulemaking's technical analyses because the technology is under patent and therefore not considered in the 2017-2025 timeframe).

In addition, FEV and EPA extrapolated the engine downsizing costs for the following scenarios that were based on the above study cases:

- Downsizing a SOHC 2 valve/cylinder V8 engine to a DOHC V6
- Downsizing a DOHC V8 to a DOHC V6
- Downsizing a SOHC V6 engine to a DOHC 4 cylinder engine
- Downsizing a DOHC 4 cylinder engine to a DOHC 3 cylinder engine

Since the 2017-2025 FRM, the following teardown studies have been completed:

1) Mild hybrid with stop-start technology (Chevrolet Malibu I4 engine with eAssist), replacing a conventional I4 engine.
2) I4 diesel engine, replacing a conventional V6 gasoline engine.
3) New iteration of SGDI and T-DS on a DOHC I4 engine, replacing a DOHC V6 engine.

FEV has also updated the cost estimates for all of the teardown studies.

Additional teardown work has been done in the area of mass reduction technologies. This work is highlighted in greater detail in Section 5.2 of this report.

The agencies have relied on the findings of FEV for estimating the cost of the technologies covered by the tear-down studies. However, note that FEV based their costs on the assumption that these technologies would be mature when produced in large volumes (450,000 units or more for each component or subsystem). If manufacturers are not able to employ the technology at the volumes assumed in the FEV analysis with fully learned costs, then the costs for each of these technologies would be expected to be higher. There is also the potential for stranded capital if technologies are introduced too rapidly for some indirect costs to be fully recovered. While the agencies consider the FEV tear-down analysis results to be generally valid for the 2022-2025 timeframe for fully mature, high sales volumes, FEV performed supplemental analysis to consider potential stranded capital costs, and we have included these in our primary analyses of program costs.

5.3.2.1.2 Electrified Vehicle Battery Costs

As in the 2012 FRM, EPA has used the BatPaC model[494] to estimate battery costs for electrified vehicles. Developed by Argonne National Laboratory (ANL) for the Vehicle Technologies Program of the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy, the BatPaC model allows users to estimate the manufacturing cost of battery packs for various types of electrified powertrains given battery power and energy requirements as well as other design parameters.

In the 2015 NAS report (p. 4-25), the NAS committee endorsed the importance of the use of a bottom-up battery cost model such as BatPaC, further finding that "the battery cost estimates used by the agencies are broadly accurate" (Finding 4.4, p. 4-43). Since the publication of the

FRM, BatPaC has been further refined and updated with new costs for some cathode chemistries and cell components, improved thermal management calculations, and improved accounting for plant overhead costs. Further changes were released in late 2015 and include additional chemistries, updated material costs, improved calculation of electrode thickness limits, and improved estimation of cost and energy requirements of certain manufacturing steps and material production processes.[495] EPA has used the most recent version of BatPaC to revise the battery cost projections used in the GHG assessment of this Draft TAR analysis.

In the 2012 FRM, the agencies developed costs and effectiveness values for the mild and P2 HEV configurations, two different all-electric mileage ranges for PHEVs (20 and 40 in-use miles) and three different mileage ranges for BEVs (75, 100 and 150 in-use miles). In this Draft TAR analysis, EPA has developed cost and effectiveness values for a new 48-Volt mild hybrid, and has changed the 150-mile BEV configuration to a 200-mile configuration. Additional updates to the inputs and methodology applied to electrified vehicles are described in Section 5.3.4.

5.3.2.1.3 *Specific DMC Changes since the 2012 FRM*

EPA looked at all the latest public data and information, carefully reviewed all the NAS estimates, the latest teardown studies, and in the end determined that teardown studies remain the most robust source of cost estimates. This analysis uses updated technology costs from teardown studies conducted since the FRM including mild hybrid (high voltage) and mild hybrid (48V) which is based in large part on the mild hybrid high voltage teardown. EPA has updated costs from prior teardowns (largely the transmission teardowns) based on updated studies conducted by FEV to those prior teardowns. Remaining costs for technologies such as valve timing and lift, friction reduction, etc., have been updated to 2013 dollars since all costs in this analysis are in 2013 dollars. Lastly, EPA has updated battery and non-battery costs for electrified vehicles based on a newer version of the ANL BatPaC model. Key battery pack design parameters such as usable capacity and cell sizes have been reviewed and revised where appropriate to reflect trends in industry practice that have been observed since the FRM. Additionally, EPA has added new technologies not used in the FRM, specifically a 48-Volt mild hybrid, a more capable naturally aspirated Atkinson cycle engine with a high compression ratio, a Miller cycle engine and electrified vehicles with different ranges. For the more capable Atkinson cycle engine, costs reported by NAS have been used as technology cost inputs.

5.3.2.1.4 *Approach to Cost Reduction through Manufacturer Learning*

For some of the technologies considered in this analysis, manufacturer learning effects would be expected to play a role in the actual end costs. The “learning curve” or “experience curve” describes the reduction in unit production costs as a function of accumulated production volume. In theory, the cost behavior it describes applies to cumulative production volume measured at the level of an individual manufacturer, although it is often assumed—as both agencies have done in past regulatory analyses—to apply at the industry-wide level, particularly in industries that utilize many common technologies and component supply sources. The agencies believe there are indeed many factors that cause costs to decrease over time. Research in the costs of manufacturing has consistently shown that, as manufacturers gain experience in production, they are able to apply innovations to simplify machining and assembly operations, use lower cost materials, and reduce the number or complexity of component parts. All of these factors allow manufacturers to lower the per-unit cost of production (i.e., the manufacturing learning curve).

NAS recommended that the agencies "continue to conduct and review empirical evidence for the cost reductions that occur in the automobile industry with volume, especially for large-volume technologies that will be relied on to meet the CAFE/GHG standards." (NAS pp. 7-23) EPA has conducted such a review under contract to ICF looking at learning in mobile source industries. The goal of the effort was to provide an updated assessment on learning and its existence in manufacturing industries. An extensive literature review was conducted and the most applicable and appropriate studies were chosen with the help of a subject matter expert (SME) that is one of the leading experts in this area.[PP] EPA hoped that the study would provide clear learning rates that could be applied in various mobile source manufacturing industries rather than the more general learning rates used in the past. That study was completed in September of 2015. A peer review was initiated and completed, but the subsequent final report, which would include responses to the peer review, was not completed in time for inclusion in the docket supporting this Draft TAR.

In the contracted study, ICF performed this literature review and analysis of learning in the mobile source sector with the assistance of a Subject Matter Expert (Dr. Linda Argote of Carnegie Mellon University). The draft report, Cost Reduction through Learning in Manufacturing Industries and in the Manufacture of Mobile Sources, was subsequently peer-reviewed by three well-known experts in the field of learning (Marvin Lieberman, Ph.D., University of California, Los Angeles (UCLA) Anderson School of Management; Natarajan Balasubramanian, Ph.D., Whitman School of Management, Syracuse University; and Chad Syverson, Ph.D., University of Chicago Booth School of Business). The peer review was carried out for EPA by RTI International based on EPA Science Policy Council Peer Review Handbook, 4th Edition, and was completed in May 2016.

The study consists of two parts: a literature review and an estimate of a mobile source progress ratio. A total of 53 studies on learning were examined, with 20 of these selected for detailed review (the other 33 received a more cursory review and are not discussed in detail in the report). Five of these studies were used as the basis to estimate the progress ratio for the mobile source sector. On the basis of these studies, the SME noted: "The mean learning rate is estimated to be -0.245, with a standard error of 0.0039. Thus, the lower bound for a 95 percent confidence interval for the learning rate is -0.253; the upper bound is -0.238. These estimates translate into a mean progress ratio of 84.3 percent. The confidence interval around this number ranges from 83.9 percent to 84.8 percent, suggesting that one can be reasonably confident that the progress ratio falls in this interval. Thus, the best estimate of the progress ratio in mobile source industries is 84 percent." This is the value that EPA has used in this Draft TAR.

As a result, the learning curve recommended for use by the report has slightly lower learning rates than those EPA has used in the past. Past EPA studies have used a learning rate based on a curve that resulted in a 20 percent cost reduction for each doubling of volume; the recommended rate results in cost reductions of 15 percent. As such, EPA has updated learning rates to be consistent with the recommendation of the report. The curve used in this analysis is:

$$y_{t+1} = a x_{t+1}^{b}$$

Where:

[PP] The SME was Dr. Linda Argote of Carnegie Mellon University.

y_{t+1} = Costs required to produce a unit at time t+1
a = Costs required to produce the first unit
x_{t+1} = Cumulative number of units produced through period t+1
b = A parameter measuring the rate at which unit costs change as cumulative output increases; i.e., the learning rate

For this analysis, EPA has used this equation to estimate the learning effects and have generated the learning curves shown below. How these learning curves were actually generated using the above curve is described in a memorandum contained in the docket.[496] In general, the new learning factors were generated in a way to provide similar results to past analyses. However, because the new rate is lower, there are subtle differences especially in years further from the "base" year (i.e., the year where the learning factor is 1.0). The docket memorandum makes this clearer by providing the new factors alongside the factors used in the 2012 FRM for comparison.

Learning effects are applied to most but not all technologies because some of the expected technologies are already used rather widely in the industry and, presumably, learning impacts have already occurred. Learning effects on the steep-portion of the learning curve was applied for only a handful of technologies that are considered to be new or emerging technologies. Most technologies have been considered to be more established given their current use in the fleet and, hence, learning effects on the flat portion of the learning curve have been applied. The learning factor curve applied to each technology are summarized in Table 5.36 with the actual year-by-year factors for each corresponding curve shown in Table 5.37.

Table 5.36 Learning Effect Algorithms Applied to Technologies Used in this Analysis

Technology	Learning Factor "Curve"[a]
Aero, active	24
Aero, passive	24
Atkinson, level 1	24
Atkinson, level 2	24
Cam configuration changes	
V6 OHV to V6 DOHC	28
V6 SOHC to V6 DOHC	23
V8 OHV to V8 DOHC	28
V8 SOHC to V8 DOHC	23
V8 SOHC3V to V8 DOHC	23
Charger, in-home, EV	26
Charger, in-home, PHEV20	26
Charger, in-home, PHEV40	26
Charger, in-home, labor	1
Cylinder deactivation	24
Direct injection, stoichiometric, gasoline	23
Diesel, advanced (Tier3)	23
Diesel, lean NOx trap	23
Diesel, selective catalytic reduction	23
Downsizing, associated with turbocharging	
I4 DOHC to I3 DOHC	23
I4 DOHC to I4 DOHC	23
V6 OHV to I4 DOHC	28
V6 SOHC to I4 DOHC	23
V6 DOHC to I4 DOHC	23
V8 OHV to V6 DOHC	28
V8 SOHC to V6 DOHC	23
V8 SOHC3V to V6 DOHC	23
Engine friction reduction, level 1	1
Engine friction reduction, level 2	1
EGR, cooled	23
Electric power steering	24
EV75, battery pack	26
EV100, battery pack	26
EV200, battery pack	26
EV75, non-battery items	28
EV100, non-battery items	28
EV200, non-battery items	28
HEV, Mild, battery pack	31
HEV, Mild, non-battery items	23
HEV, Strong, battery pack	31
HEV, Strong, non-battery items	23
HEV, Plug-in, battery pack	26
HEV, Plug-in, non-battery items	23
Improved accessories, level 1	24
Improved accessories, level 2	24
Low drag brakes	1
Lower rolling resistance tires, level 1	1

Lower rolling resistance tires, level 2	32
Lube, engine changes to accommodate low friction lubes	1
Mass reduction <15%	30
Mass reduction >=15%	30
Secondary axle disconnect	24
Stop-start	25
Turbo, 18-21 bar	23
Turbo, 24 bar	23
Turbo, Miller-cycle	23
TRX11/12	23
TRX21/22	23

Note:
[a] See table below.

The actual year-by-year factors for the numbered curves shown in Table 5.37.

Table 5.37 Year-by-year Learning Curve Factors for the Learning Curves Used in this Analysis

Curve	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
22	1.37	1.33	1.29	1.25	1.21	1.18	1.15	1.13	1.11	1.08	1.06	1.04	1.02	1.00
23	1.00	0.98	0.96	0.94	0.92	0.91	0.89	0.88	0.87	0.85	0.84	0.83	0.82	0.82
24	1.09	1.06	1.03	1.00	0.98	0.96	0.94	0.92	0.91	0.89	0.88	0.87	0.85	0.84
25	2.03	1.62	1.28	1.00	0.91	0.84	0.80	0.76	0.74	0.71	0.69	0.67	0.66	0.64
26	3.05	2.44	2.11	1.89	1.74	1.61	1.51	1.43	1.36	1.30	1.25	1.20	1.16	1.12
27	1.00	0.91	0.84	0.80	0.76	0.74	0.71	0.69	0.67	0.66	0.64	0.63	0.62	0.61
28	1.13	1.09	1.06	1.03	1.00	0.98	0.96	0.94	0.92	0.91	0.89	0.88	0.87	0.85
29	1.17	1.13	1.09	1.06	1.03	1.00	0.98	0.96	0.94	0.92	0.91	0.89	0.88	0.87
30	1.29	1.24	1.20	1.17	1.13	1.09	1.06	1.03	1.00	0.98	0.96	0.94	0.92	0.91
31	3.18	2.54	2.03	1.62	1.28	1.00	0.91	0.84	0.80	0.76	0.74	0.71	0.69	0.67
32	1.74	1.61	1.51	1.43	1.36	1.30	1.25	1.20	1.16	1.12	1.09	1.06	1.04	1.01

Importantly, where the factors shown in Table 5.37 equal "1.00" represents the year for which any particular technology's cost is based. Thus, if curve 1 is applied to a technology – such as in the case of low friction lubes - it assumes no additional learning takes place over time. In the case of stop-start technology, curve 25 is applied. In this case, the cost estimate used for stop-start is considered a MY2015 cost. Therefore, its learning factor equals 1.00 in 2015 and then decreases going forward to represent lower costs due to learning effects. Its learning factors are greater than 1.00 in years before 2015 to represent "reverse" learning, i.e., higher costs than our 2015 estimate since production volumes have, presumably, not yet reached the point where our cost estimate can be considered valid. Not all of the learning curve factors follow this rule using the updated curve approach used in this Draft TAR. Also of interest is that only curves 25 (stop-start), 26 (EV & PHEV batteries) and 31 (mild and strong HEV batteries) show any steeper learning beyond the 2017-2020 timeframe, and even those curves show less than 5 percent year-over-year cost reductions beyond 2020. In other words, most curves are well into the flatter portion of the learning curve, and even those that are not are well beyond the steep learning that occurs at the early stages of learning, by the timeframe considered in this Draft TAR.

Because of the nature of full electric and plug-in electric vehicle battery pack development, the industry is arguably early in the learning-by-doing phase for the types of batteries considered. Our approach, consistent with that used in the FRM, has been to develop a direct manufacturing cost based on sales of 450,000 units. EPA has considered that to be a valid MY2025 cost (i.e., the cost is based in 2025). With that as the MY2025 cost, the costs are considered as understood today and a best fit learning curve is projected between the costs in those near-term and long-term years. This is described in more detail in the docket memorandum mentioned earlier.[497] Note that the 450,000 unit sales is considered a valid MY2025 volume for batteries because that volume is meant to represent volumes at a given production line (a battery supplier production line, not an OEM vehicle production line) and takes into consideration worldwide demand for automotive and other mobile source battery packs not just U.S. directed automotive battery packs.

Note that the effects of learning on individual technology costs can be seen in the cost tables presented in Section 5.3.4, below. For each technology, the direct manufacturing costs for the years 2017 through 2025 are shown. The changes shown in the direct manufacturing costs from year-to-year reflect the cost changes due to learning effects.

5.3.2.2 Indirect Costs

5.3.2.2.1 *Methodologies for Determining Indirect Costs*

To produce a unit of output, vehicle manufacturers incur direct and indirect costs. Direct costs include cost of materials and labor costs. Indirect costs are all the costs associated with producing the unit of output that are not direct costs – for example, they may be related to production (such as research and development [R&D]), corporate operations (such as salaries, pensions, and health care costs for corporate staff), or selling (such as transportation, dealer support, and marketing). Indirect costs are generally recovered by allocating a share of the costs to each unit of good sold. Although it is possible to account for direct costs allocated to each unit of good sold, it is more challenging to account for indirect costs allocated to a unit of goods sold. To make a cost analysis process more feasible, markup factors, which relate total indirect costs to total direct costs, have been developed. These factors are often referred to as retail price equivalent (RPE) multipliers.

Cost analysts and regulatory agencies (including both EPA and NHTSA) have frequently used these multipliers to predict the resultant impact on costs associated with manufacturers' responses to regulatory requirements. The best approach, if it were possible, to determining the impact of changes in direct manufacturing costs on a manufacturer's indirect costs would be to actually estimate the cost impact on each indirect cost element. However, doing this within the constraints of an agency's time or budget is not always feasible, or the technical, financial, and accounting information to carry out such an analysis may simply be unavailable.

RPE multipliers provide, at an aggregate level, the relative shares of revenues (Revenue = Direct Costs + Indirect Costs + Net Income) to direct manufacturing costs. Using RPE multipliers implicitly assumes that incremental changes in direct manufacturing costs produce common incremental changes in all indirect cost contributors as well as net income. However, a concern in using the RPE multiplier in cost analysis for new technologies added in response to regulatory requirements is that the indirect costs of vehicle modifications are not likely to be the same for different technologies. For example, less complex technologies could require fewer

R&D efforts or less warranty coverage than more complex technologies. In addition, some simple technological adjustments may, for example, have no effect on the number of corporate personnel and the indirect costs attributable to those personnel. The use of RPEs, with their assumption that all technologies have the same proportion of indirect costs, is likely to overestimate the costs of less complex technologies and underestimate the costs of more complex technologies.

To address this concern, modified multipliers have been developed by EPA, working with a contractor, for use in rulemakings.[498] These multipliers are referred to as indirect cost multipliers (or ICMs). In contrast to RPE multipliers, ICMs assign unique incremental changes to each indirect cost contributor as well as net income.

ICM = (direct cost + adjusted indirect cost)/(direct cost)

Developing the ICMs from the RPE multipliers requires developing adjustment factors based on the complexity of the technology and the time frame under consideration: the less complex a technology, the lower its ICM, and the longer the time frame for applying the technology, the lower the ICM. This methodology was used in the cost estimation for the recent light-duty MYs 2012-2016 and MYs 2017-2025 rulemaking and for the heavy-duty MYs 2014-2018 rulemaking. There was no serious disagreement with this approach in the public comments to any of these rulemakings. The ICMs for the light-duty context were developed in a peer-reviewed report from RTI International and were subsequently discussed in a peer-reviewed journal article.[499] Importantly, since publication of that peer-reviewed journal article, the agencies have revised the methodology to include a return on capital (i.e., profits) based on the assumption implicit in ICMs (and RPEs) that capital costs are proportional to direct costs, and businesses need to be able to earn returns on their investments.

There is some level of uncertainty surrounding both the ICM and RPE markup factors. The ICM estimates used in this Draft TAR, consistent with the FRM, group all technologies into three broad categories and treat them as if individual technologies within each of the three categories (low, medium, and high complexity) will have exactly the same ratio of indirect costs to direct costs. This simplification means it is likely that the direct cost for some technologies within a category will be higher and some lower than the estimate for the category in general. Additionally, the ICM estimates were developed using adjustment factors developed in two separate occasions: the first, a consensus process, was reported in the RTI report; the second, a modified Delphi method, was conducted separately and reported in an EPA memorandum. Both these panels were composed of EPA staff members with previous background in the automobile industry; the memberships of the two panels overlapped but were not the same. The panels evaluated each element of the industry's RPE estimates and estimated the degree to which those elements would be expected to change in proportion to changes in direct manufacturing costs. The method and the estimates in the RTI report were peer reviewed by three industry experts and subsequently by reviewers for the International Journal of Production Economics. However, the ICM estimates have not yet been validated through a direct accounting of actual indirect costs for individual technologies. RPEs themselves are also inherently difficult to estimate because the accounting statements of manufacturers do not neatly categorize all cost elements as either direct or indirect costs. Hence, each researcher developing an RPE estimate must apply a certain amount of judgment to the allocation of the costs. Since empirical estimates of ICMs are ultimately derived from the same data used to measure RPEs, this affects both measures.

However, the value of RPE has not been measured for specific technologies, or for groups of specific technologies. Thus applying a single average RPE to any given technology by definition overstates costs for very simple technologies, or understates them for advanced technologies.

5.3.2.2.2 Indirect Cost Estimates Used in this Analysis

Since their original development in February 2009, the agencies have made some changes to both the ICM factors and to the method of applying those factors relative to the factors developed by RTI and presented in their reports. These changes have been described and explained in several rulemakings over the years, most notably the 2017-2025 FRM and the more recent Heavy-duty GHG Phase 2 NPRM (80 FR 40137). In the 2015 NAS study, the committee stated: "The committee conceptually agrees with the Agencies' method of using an indirect cost multiplier instead of a retail price equivalent to estimate the costs of each technology since ICM takes into account design challenges and the activities required to implement each technology. In the absence of empirical data, however, the committee was unable to determine the accuracy of the Agencies' ICMs." (NAS Finding 7.1) EPA continues to study the issues surrounding ICMs but has not yet pursued further efforts given resource constraints and priorities in areas such as technology benchmarking and cost teardowns. For this Draft TAR analysis, recognizing there are uncertainties in the use of either ICM or RPE as indicators of indirect costs, as discussed above, EPA chose to assess indirect costs using both the ICM and RPE approaches. NHTSA is employing a similar approach of assessing costs based on both ICM and RPE factors for the CAFE analysis, as described in Section 5.4. For the ICM case, EPA has applied the ICMs as shown in Table 5.38. Near term values account for differences in the levels of R&D, tooling, and other indirect costs that will be incurred. Once the program has been fully implemented, some of the indirect costs will no longer be attributable to the standards and, as such, a lower ICM factor is applied to direct costs. For the RPE case, EPA has applied an RPE factor of 1.5x direct costs. (EPA has also applied an RPE factor of 2.0x direct costs for mass reduction costs, as discussed below).

Table 5.38 Indirect Cost Multipliers Used in this Analysis[500]

	2017-2025 FRM and this Draft TAR	
Complexity	Near term	Long term
Low	1.24	1.19
Medium	1.39	1.29
High1	1.56	1.35
High2	1.77	1.50

Here are two important aspects to the ICM method employed by EPA. First, the ICM consists of two portions: a small warranty-related term and a second, larger term to cover all other indirect costs elements. The breakout of warranty versus non-warranty portions to the ICMs are presented in Table 5.39. The latter of these terms does not decrease with learning and, instead, remains constant year-over-year despite learning effects which serve to decrease direct manufacturing costs. Learning effects are described in the next section. The second important note is that all indirect costs are forced to be positive, even for those technologies estimated to have negative direct manufacturing costs.

Table 5.39 Warranty and Non-Warranty Portions of ICMs

	Near term		Long term	
Complexity	Warranty	Non-warranty	Warranty	Non-warranty
Low	0.012	0.230	0.005	0.187
Medium	0.045	0.343	0.031	0.259
High1	0.065	0.499	0.032	0.314
High2	0.074	0.696	0.049	0.448

The complexity levels and subsequent ICMs applied throughout this analysis for each technology are shown in Table 5.40.

Table 5.40 Indirect Cost Markups (ICMs) and Near Term/Long Term Cutoffs Used in EPA's Analysis

Technology	ICM Complexity	Short term thru
Aero, active	Low2	2018
Aero, passive	Med2	2024
Atkinson, level 1	Med2	2018
Atkinson, level 2	Med2	2024
Cam configuration changes		
V6 OHV to V6 DOHC	Med2	2018
V6 SOHC to V6 DOHC	Med2	2018
V8 OHV to V8 DOHC	Med2	2018
V8 SOHC to V8 DOHC	Med2	2018
V8 SOHC3V to V8 DOHC	Med2	2018
Charger, in-home, EV	High1	2024
Charger, in-home, PHEV20	High1	2024
Charger, in-home, PHEV40	High1	2024
Charger, in-home, labor	None	2024
Cylinder deactivation	Med2	2018
Direct injection, stoichiometric, gasoline	Med2	2018
Diesel, advanced (Tier3)	Med2	2018
Diesel, lean NOx trap	Med2	2018
Diesel, selective catalytic reduction	Med2	2018
Downsizing, associated with turbocharging		
I4 DOHC to I3 DOHC	Med2	2018
I4 DOHC to I4 DOHC	Med2	2018
V6 OHV to I4 DOHC	Med2	2018
V6 SOHC to I4 DOHC	Med2	2018
V6 DOHC to I4 DOHC	Med2	2018
V8 OHV to V6 DOHC	Med2	2018
V8 SOHC to V6 DOHC	Med2	2018
V8 SOHC3V to V6 DOHC	Med2	2018
Engine friction reduction, level 1	Low2	2018
Engine friction reduction, level 2	Low2	2024
EGR, cooled	Med2	2024
Electric power steering	Low2	2018
EV75, battery pack	High2	2024
EV100, battery pack	High2	2024
EV200, battery pack	High2	2024
EV75, non-battery items	High2	2024

EV100, non-battery items	High2	2024
EV200, non-battery items	High2	2024
HEV, Mild, battery pack	High1	2024
HEV, Mild, non-battery items	Med2	2018
HEV, Strong, battery pack	High1	2024
HEV, Strong, non-battery items	High1	2018
HEV, Plug-in, battery pack	High2	2024
HEV, Plug-in, non-battery items	High1	2018
Improved accessories, level 1	Low2	2018
Improved accessories, level 2	Low2	2018
Low drag brakes	Low2	2018
Lower rolling resistance tires, level 1	Low2	2018
Lower rolling resistance tires, level 2	Low2	2018
Lube, engine changes to accommodate low friction lubes	Low2	2018
Mass reduction <15%	Low2	2024
Mass reduction >=15%	Med2	2024
Secondary axle disconnect	Low2	2018
Stop-start	Med2	2018
Turbo, 18-21 bar	Med2	2018
Turbo, 24 bar	Med2	2024
Turbo, Miller-cycle	Med2	2024
TRX11/12	Low2	2018
TRX21/22	Low2	2024

For mass reduction costs, EPA has developed a new approach to calculating indirect costs due to the unique nature of the direct manufacturing costs that EPA has developed (see Section 5.3.4.6.1). Mass reduction strategies, unlike other efficiency technologies, often involve multiple systems and components on a vehicle. A portion of the indirect costs for parts that have design and production outsourced to suppliers are incorporated into the direct manufacturing cost estimates. Components that are designed in-house and possibly produced in-house by the manufacturer, such as the body and frame structures, have higher indirect costs applied. This distinction between supplier and in-house parts is consistent with the recommendations of a study done by Argonne National Laboratory.[501] In that study, the authors suggested retail price equivalent markups of 1.5x direct costs for parts sourced from a supplier, and 2x direct costs for parts sourced internally. The end result, presumably, is an equal total cost, but the markups account for differences in where the indirect costs are incurred. Using that as a basis EPA adjusted the supplied technology ICMs (shown in Table 5.38) by the ratio 2/1.5 to determine in-house ICMs at the "engineered solution" mass reduction point (described in Sections 5.3.4.6.1.1 and 5.3.4.6.1.2) which happened to be approximately 20 percent mass reduction level for the car teardown study and the truck teardown study. Since those mass reduction levels were deemed "medium" complexity levels in the FRM, and because EPA still believes that to be a good assessment of the complexity level, EPA has worked with only the medium complexity ICMs in the context of mass reduction. As a result, the ICMs used for mass reduction are as shown in Table 5.41. For RPE based indirect costs, EPA simply used the 1.5x and 2x multipliers applied to the same DMCs used in the ICM case.

Table 5.41 Mass Reduction Markup Factors used by EPA in this Draft TAR

	Supplier Provided Mass Reduction		In-house Provided Mass Reduction	
Markup & Complexity	Near term	Long term	Near term	Long term
ICM - Medium complexity	1.39	1.29	1.85	1.72
RPE - complexity not applicable	1.5	1.5	2.0	2.0

The final element of the unique nature of the indirect cost calculations developed by EPA for mass reduction in this analysis, is to calculate the indirect costs using the above ICMs or RPEs only at the engineered solution point. Notably, EPA applied the markups to the sum of the absolute values of all mass reduction ideas throughout the entire direct manufacturing cost curve. In that way, negative direct costs that are projected at the lower mass reduction levels still have a positive impact on calculated indirect costs. Once the indirect costs were determined via this methodology at the engineered solution, EPA generated an indirect cost curve extending through $0/kg at 0 percent mass reduction and $8.75/kg/% at the engineered solution for cars and $13.23/kg/% for trucks (see Table 5.42 and Table 5.43 for the values of X). The indirect costs at all mass reduction levels between those points lie on that generated cost curve. Inherent in this approach is the assumption that the proportion of mass reduction from supplier and in-house components remains constant at all levels of mass reduction, based on the proportion at the engineered solution. Those curves are shown in Table 5.42 for cars and in Table 5.43 for trucks.

Table 5.42 Mass Reduction Indirect Cost Curves used by EPA for Cars Using ICMs

		$/kg DMC*	ICM	$/kg IC at Engineered Solution	$/kg IC at Engineered Solution	$/kg/% IC curve**
Near term	Supplied tech DMC	$1.75	0.39	$0.678	$0.678+0.986=1.66	$8.75x
	In-house tech DMC	$1.16	0.85	$0.986		
Long term	Supplied tech DMC	$1.75	0.29	$0.507	$0.507+0.835=1.34	$7.06x
	In-house tech DMC	$1.16	0.72	$0.835		

Notes:
* Calculated as the absolute value of all direct manufacturing costs needed to achieve the engineered solution.
** Where x is the percent mass reduction.

Table 5.43 Mass Reduction Indirect Cost Curves used by EPA for Trucks Using ICMs

		$/kg DMC*	ICM	$/kg IC at Engineered Solution	$/kg IC at Engineered Solution	$/kg/% IC curve**
Near term	Supplied tech DMC	$2.59	0.39	$1.00	$1.00+1.78=2.78	$13.23x
	In-house tech DMC	$2.09	0.85	$1.78		
Long term	Supplied tech DMC	$2.59	0.29	$0.75	$0.75+1.50=2.25	$10.73x
	In-house tech DMC	$2.09	0.72	$1.50		

Notes:

* Calculated as the absolute value of all direct manufacturing costs needed to achieve the engineered solution.
** Where x is the percent mass reduction.

Table 5.44 Mass Reduction Indirect Cost Curves used by EPA for Cars Using RPEs

		$/kg DMC*	RPE	$/kg IC at Engineered Solution	$/kg IC at Engineered Solution	$/kg/% IC curve**
Near & Long term	Supplied tech DMC	$1.75	0.5	$0.875	$0.875+1.16=2.04	$10.71x
	In-house tech DMC	$1.16	1.0	$1.16		

Notes:
* Calculated as the absolute value of all direct manufacturing costs needed to achieve the engineered solution.
** Where x is the percent mass reduction.

Table 5.45 Mass Reduction Indirect Cost Curves used by EPA for Trucks Using RPEs

		$/kg DMC*	ICM	$/kg IC at Engineered Solution	$/kg IC at Engineered Solution	$/kg/% IC curve**
Near & Long term	Supplied tech DMC	$2.59	0.5	$1.30	$1.30+2.09=3.39	$16.12x
	In-house tech DMC	$2.09	1.0	$2.09		

Notes:
* Calculated as the absolute value of all direct manufacturing costs needed to achieve the engineered solution.
** Where x is the percent mass reduction.

5.3.2.3 Maintenance and Repair Costs

5.3.2.3.1 Maintenance Costs

To estimate maintenance costs that could reasonably be attributed to the 2017-2025 standards, the agencies looked—in the 2017-2025 FRM—at vehicle models for which there exists a version with a fuel efficiency and GHG emissions improving technology and a version with the corresponding baseline technology. The difference between maintenance costs for the two models represent a cost which the agencies attributed to the standards. For example, the Ford Escape Hybrid versus the Ford Escape V6 was considered when estimating the types of maintenance cost differences that might be present for a hybrid vehicle versus a non-hybrid, and a Ford F150 with EcoBoost versus the Ford F150 5.0L was considered when estimating the types of maintenance cost differences that might be present for a turbocharged and downsized versus a naturally aspirated engine. In the case of low rolling resistance tires, specific parts were considered rather than specific vehicle models.

By comparing the manufacturer recommended maintenance schedule of the items compared, the differences in maintenance intervals for the two was estimated. With estimates of the costs per maintenance event, a picture of the maintenance cost differences associated with the “new” technology was developed.

EPA continues to believe that the maintenance estimates used in the FRM are still reasonable and have therefore used them again in this analysis. EPA distinguished maintenance from repair costs as follows: maintenance costs are those costs that are required to keep a vehicle properly maintained and, as such, are usually recommended by auto makers to be conducted on a regular, periodic schedule. Examples of maintenance costs are oil and air filter changes, tire replacements, etc. Repair costs are those costs that are unexpected and, as such, occur randomly and uniquely for every driver, if at all. Examples of repair costs would be parts replacement following an accident or a mechanical failure, etc.

In Chapter 3.6 of the final joint TSD supporting the 2012 FRM, the agencies presented a lengthy discussion of maintenance costs and the impacts projected as part of that rule.[502] Table 5.46 shows the results of that analysis, the maintenance impacts used in the 2012 FRM and again in this analysis, although the costs here have been updated to 2013$. Note that the technologies shown in Table 5.46 are those for which EPA believes that maintenance costs would change; it is clearly not a complete list of technologies expected to meet the MY2025 standards.

Table 5.46 Maintenance Event Costs & Intervals (2013$)

New Technology	Reference Technology	Cost per Maintenance Event	Maintenance Interval (miles)
Low rolling resistance tires level 1	Standard tires	$6.71	40,000
Low rolling resistance tires level 2	Standard tires	$51.55	40,000
Diesel fuel filter replacement	Gasoline vehicle	$51.93	20,000
EV oil change	Gasoline vehicle	-$40.78	7,500
EV air filter replacement	Gasoline vehicle	-$30.16	30,000
EV engine coolant replacement	Gasoline vehicle	-$62.21	100,000
EV spark plug replacement	Gasoline vehicle	-$87.52	105,000
EV/PHEV battery coolant replacement	Gasoline vehicle	$123.37	150,000
EV/PHEV battery health check	Gasoline vehicle	$40.78	15,000

Note that many of the maintenance event costs for EVs are negative. The negative values represent savings since EVs do not incur these costs while their gasoline counterparts do. Note also that the 2010 FRM is expected to result in widespread use of low rolling resistance tires level 1 (LRRT1) on the order of 85 percent penetration. Therefore, as 2012 FRM results in increasing use of low rolling resistance tire level 2 (LRRT2), there is a corresponding decrease in the use of LRRT1. As such, as LRRT2 maintenance costs increase with increasing market penetration, LRRT1 maintenance costs decrease. Importantly, the maintenance costs associated with lower rolling resistance tires is the incremental cost of the tires at replacement; it is not associated in any way with a decrease in durability of these tires.

5.3.2.3.2 Repair Costs

Both EPA's and NHTSA's FRM central analyses accounted for the costs of repairs covered by manufacturers' warranties, and a sensitivity analysis estimated costs for post-warranty repairs**.** The indirect cost multipliers (ICMs) applied in the agencies' analyses include a component representing manufacturers' warranty costs. For the cost of repairs not covered by OEMs' warranties, the agencies evaluated the potential to apply an approach similar to that described above for maintenance costs. As for specific scheduled maintenance items, the ALLDATA subscription database applied above provides estimates of labor and part costs for specific repairs to specific vehicle models. However, although ALLDATA also provides service intervals for scheduled maintenance items, it does not provide estimates of the frequency at which specific failures may be expected to occur over a vehicle's useful life. The agencies have not yet been able to develop an alternative method to estimate the frequencies of different types of repairs, and are therefore unable to apply these ALLDATA estimates in order to quantify the cost of repairs throughout vehicles' useful lives. Moreover, the frequency of repair of technologies that do not yet exist in the fleet, or are only emerging today provides insufficient representation of what they will be in the future with wider penetration of those technologies. As a result, the agencies assume per-vehicle repair costs during the post-warranty period are the same as the OEM warranty period. To ensure repair costs for newer technologies are considered, those costs are proportional to incremental direct costs. The frequency of repair is scaled by vehicle survival rates.

5.3.2.4 Costs Updated to 2013 Dollars

EPA is using technology costs from many different sources. These sources, having been published in different years, present costs in different year dollars (i.e., 2009 dollars or 2012 dollars). For this analysis, the agencies sought to have all costs in terms of 2013 dollars to be consistent with the dollars used by EIA in its Annual Energy Outlook 2015. While the factors used to convert from 2009 dollars (or other) to 2013 dollars are small, the agencies prefer to be overly diligent in this regard to ensure consistency across our analyses. The agencies have used the GDP Implicit Price Deflator for Gross Domestic Product as the converter, with the actual factors used as shown in Table 5.47.

Table 5.47 Implicit Price Deflators and Conversion Factors for Conversion to 2013$

Calendar Year →	2006	2007	2008	2009	2010	2011	2012	2013
Implicit Price Deflators for Gross Domestic Product	94.814	97.337	99.246	100	101.221	103.311	105.166	106.733
Factor applied to convert to 2013$	1.126	1.097	1.075	1.067	1.054	1.033	1.015	1.000

Source: Bureau of Economic Analysis, Table 1.1.9 Implicit Price Deflators for Gross Domestic Product; last revised on June 24, 2015; accessed on 7/8/2015 at www.bea.gov.

5.3.3 Approach for Determining Technology Effectiveness

EPA reevaluated the effectiveness values for all technologies discussed in 2017-2025 LD final rule for this Draft TAR, as well as prominent technologies that have emerged since then. The process used to determine the effectiveness of each technology for this Draft TAR is similar to the one used for the FRM. Along with the vehicle benchmarking and full vehicle simulation process, EPA reviewed available data including the 2015 LD National Academy of Sciences report[503], confidential manufacturer estimates, OE and supplier meetings, technical conferences, literature reviews, and press announcements regarding technology effectiveness. In most cases, multiple sources of information were considered in the process of determining the effectiveness values used in this assessment.

Full vehicle simulation modeling has been used in both of the previous light-duty greenhouse gas rules to establish the effectiveness of technologies, and is regularly applied by vehicle manufacturers, suppliers, and academia to evaluate and choose alternative technologies to improve vehicle efficiency. In the 2015 NAS report,[503] the committee recognized the important contribution of full vehicle simulation and lumped parameter modeling in these previous rulemakings, and recommended continued use of these methods as the best way of assessing technologies and the combination of technologies. While the full vehicle simulation modeling results from Ricardo Engineering used in the 2017-2025MY FRM have been found to be robust and accurate, some of the underlying analyses performed by Ricardo were proprietary and could not be fully disclosed to the public.

For this Draft TAR, EPA is employing its own full vehicle simulation model; Advanced Light-duty Powertrain and Hybrid Analysis tool (ALPHA). The ALPHA model has been developed and refined over several years and used in multiple rulemakings to evaluate the effectiveness of vehicle technology packages. Using ALPHA improves the transparency of the process and provides additional flexibility to allow consideration of the most recent technological developments and vehicle implementations of technologies. Input data for the ALPHA model has been created largely through benchmarking activities. Benchmarking is a commonly used technique that is intended to create a detailed characterization of a vehicle's operation and performance. For the purposes of developing ALPHA, and for establishing overall technology effectiveness, EPA performed many benchmarking activities including measuring vehicle performance over the standard emission cycles and measuring system and component performance on various test stands.

5.3.3.1 Vehicle Benchmarking

As part of its mandated evaluation of the appropriateness of the MY2022-2025 standards, EPA is re-assessing any potential changes to the cost and the effectiveness of advanced technologies available to manufacturers. See section 86.1818-12 (h) (1)(i) and (ii). Benchmarking is a process by which detailed vehicle, system, and component performance is characterized. Benchmarking is commonly used by vehicle manufacturers, automotive suppliers, national laboratories, and universities in order to gain a better understanding of how vehicles are engineered and to create large datasets that can be applied in modeling and other analyses. In its effort to assess light-duty vehicles in preparation for the MTE, EPA has benchmarked over twenty vehicles, with the results summarized in 15 peer-reviewed SAE papers.[504] [505] As the result of these activities, EPA has calibrated the ALPHA full vehicle simulation model and applied the results of this model to establish and confirm technology effectiveness. In addition, EPA has also been able to capture the performance of current vehicles, which is an important goal of the MTE. Over the coming years, the agency intends to continue to benchmark additional vehicles to inform the Proposed and Final Determination.

The ALPHA model has been used to confirm and update, where necessary, efficiency data from the previous Ricardo study, such as from advanced downsized turbo and naturally aspirated engines. It is also being used to quantify effectiveness from advanced technologies which the agencies did not project to be part of a compliance pathway during the FRM, such as continuously variable transmissions (CVTs), multi-mode normally aspirated engines, and clean diesel engines. The ALPHA model accounts for synergistic effects between technologies and has been used by EPA to calibrate the Lumped Parameter Model to incorporate the latest technology package effectiveness data into the OMEGA compliance model.

To simulate drive cycle performance, the ALPHA model requires various vehicle input parameters, including vehicle inertia and road loads, and component efficiencies and operations. Vehicle benchmarking is the detailed process for obtaining these parameters.

5.3.3.1.1 *Detailed Vehicle Benchmarking Process*

The following discussion describes the vehicle benchmarking elements used as required for the vehicles tested by EPA for this Draft TAR. The vehicle benchmarked in this example is a 2013 Chevy Malibu 1LS as detailed in Table 5.48. This vehicle was chosen as representative of a midsize car with a typical conventional powertrain with a naturally aspirated engine and a 6 speed automatic transmission. The first task of the vehicle benchmarking process involved collecting data from on-road and dynamometer testing (Figure 5.81) before removing the engine and transmission for separate component testing. Major components such as the engine and transmission of a vehicle must be isolated and evaluated separately to create accurate performance maps to be included in the ALPHA model.

Table 5.48 Benchmark Vehicle Description

Model	2013 Chevy Malibu 1LS
Engine	2.5L inline-4, GDI, naturally aspirated
Powertrain	Conventional FWD 6-speed automatic, GM6T40 transmission
Gear Ratios	4.584, 2.965, 1.912, 1.446, 1.000, 0.746 with 2.89 final drive
Tire Size	215/60/R16
EPA Label Fuel Economy	22 City, 34 Highway, 26 Combined MPG
Emissions Equivalent Test Weight (ETW)	4,000 lbs (1814 kg)
Emissions Target Road Load A	38.08 lbs (169.4 N)
Emissions Target Road Load B	0.2259 lbs/mph (2.248 N/m/s)
Emissions Target Road Load C	0.01944 lbs/mph^2 (0.4327 N/(m/s)^2)
Fuel Economy ETW	3,625 lbs (1644 kg)
Fuel Economy Target Road Load A	28.62 lbs (127.3 N)
Fuel Economy Target Road Load B	0.1872 lbs/mph (1.863 N/m/s)
Fuel Economy Target Road Load C	0.01828 lbs/mph^2 (0.4069 N/(m/s)^2)

Figure 5.81 Chevy Malibu Undergoing Dynamometer Testing

5.3.3.1.1.1 Engine Testing

The engine was removed from the vehicle and installed in an engine dynamometer test cell, as shown in Figure 5.82. The complete vehicle exhaust and emission control systems were included in the test setup. All necessary signals including the transmission input and output shaft speed signals were supplied by the test stand to prevent engine controller fault codes. The engine was fully instrumented to collect detailed performance information (e.g., exhaust/coolant temperatures, cam angles, throttle position, mass airflow).

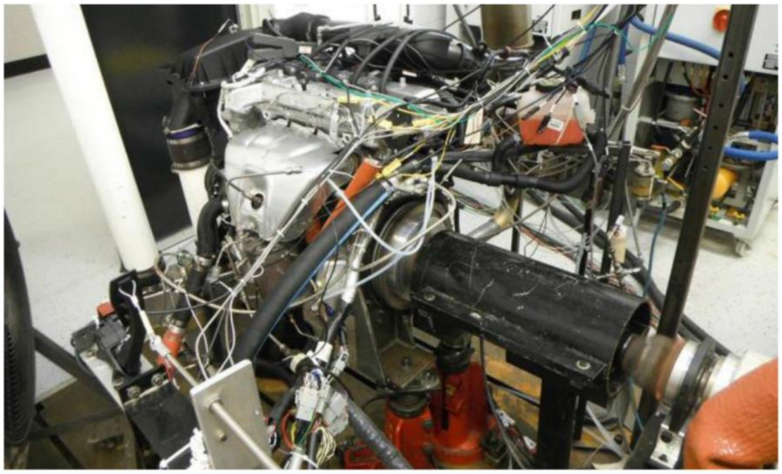


Figure 5.82 Engine Test Cell Setup

The engine fuel consumption was measured at the steady state torque and speed operating points as shown in Figure 5.83.

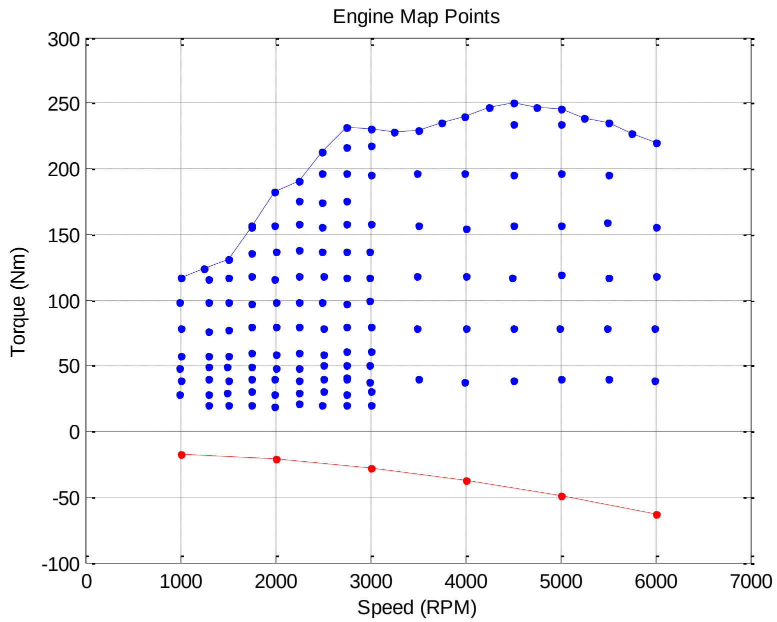


Figure 5.83 Engine Map Points

5.3.3.1.1.2 Transmission Testing

The 6-speed automatic transmission was removed from the vehicle and installed on a test stand as shown in Figure 5.84. The transmission control solenoid commands were reverse engineered and the transmission was manually controlled during testing. Transmission line pressure was externally regulated to match the pressures measured during chassis dynamometer testing. Torque and speed were measured at the input of the transmission and both outputs. The input to the transmission was driven by an electric motor.

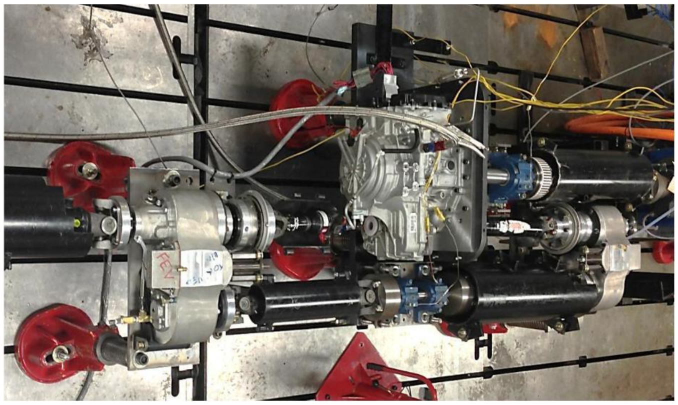


Figure 5.84 GM6T40 Transmission during Testing

The transmission losses were measured at input torques ranging from 25 to 250 Nm and input speeds ranging from 500 to 5000 RPM. For efficiency testing the torque converter clutch was fully locked by manually overriding the clutch control solenoid. Tests were performed at two transmission oil temperatures, 37 C and 93 C. Total efficiency for each gear during operation at 93 C, including pump and spin losses, is shown in Figure 5.85.

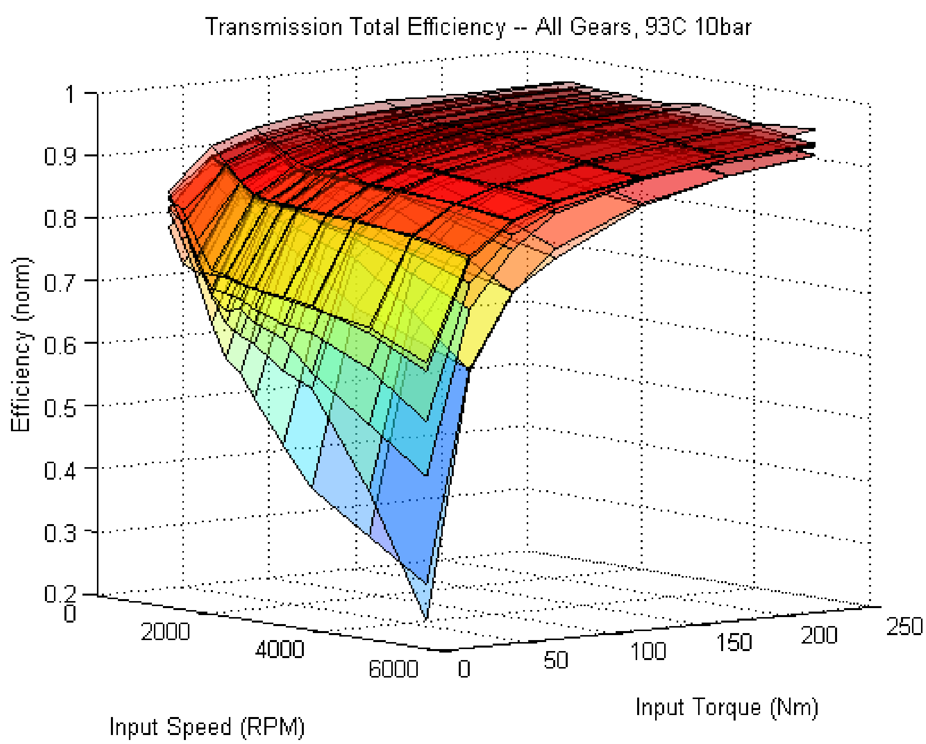


Figure 5.85 Transmission Efficiency Data at 93 C and 10 Bar Line Pressure

The torque converter was tested unlocked in 6th gear to determine speed ratio (SR), K factor[QQ] and torque ratio curves. The input speed to the transmission was held at 2000 RPM while decreasing the output speed to traverse the SR curve from 1.0 to 0.35 (limited due to line pressure and transmission slip). The data below SR 0.35 was extrapolated using the higher SR data. The torque converter data is shown in Figure 5.86, with the K factor curve normalized by dividing by the K factor at SR 0 (torque converter stall). Normalizing the K factor curve allows for scaling the curve up or down by multiplying by a new stall K value.

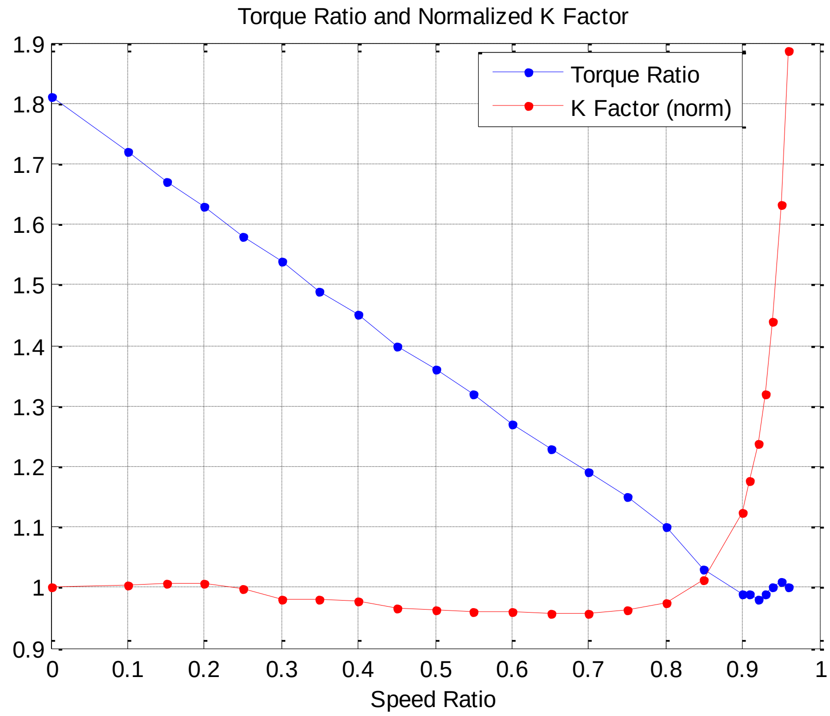


Figure 5.86 Torque Converter Torque Ratio and Normalized K Factor Versus Speed Ratio

Transmission spin losses were measured in each gear with a locked torque converter and no load applied to the output shaft while varying the input speed from 500 RPM to 3000 to 5000 RPM depending on the chosen gear. Spin loss testing was performed at 5 bar and 10 bar line pressures and 37 C (cold) and 93 C (operating) oil temperatures. Figure 5.87 shows the spin loss data at 93 C for all gears and both line pressures.

[QQ] K-factor is approximately equal to rpm/sqrt(torque).

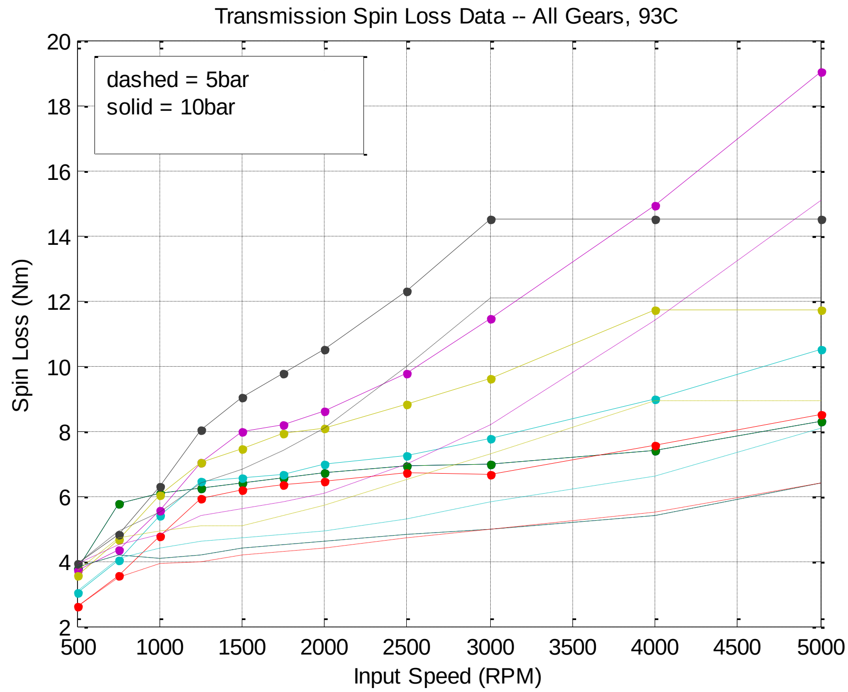


Figure 5.87 Transmission Spin Losses at 93C

5.3.3.1.2 *Development of Model Inputs from Benchmarking Data*

After compiling the raw data, it was necessary to adapt the data to a form suitable for use by the ALPHA model, including filling any data gaps and interpolating or extrapolating as required.

5.3.3.1.2.1 *Engine Data*

For use with the ALPHA model, the engine's fuel consumption map was created by converting the set of points to a rectangular surface. In addition, an estimate of the engine inertia was required since it plays a significant role in the calculation of vehicle performance and fuel economy.[506] The resulting engine data was reviewed with manufacturers prior to use in the ALPHA model.

5.3.3.1.2.2 *Engine Map*

Figure 5.88 shows one of the engine maps generated from the test stand data in terms of brake-specific fuel consumption (BSFC).

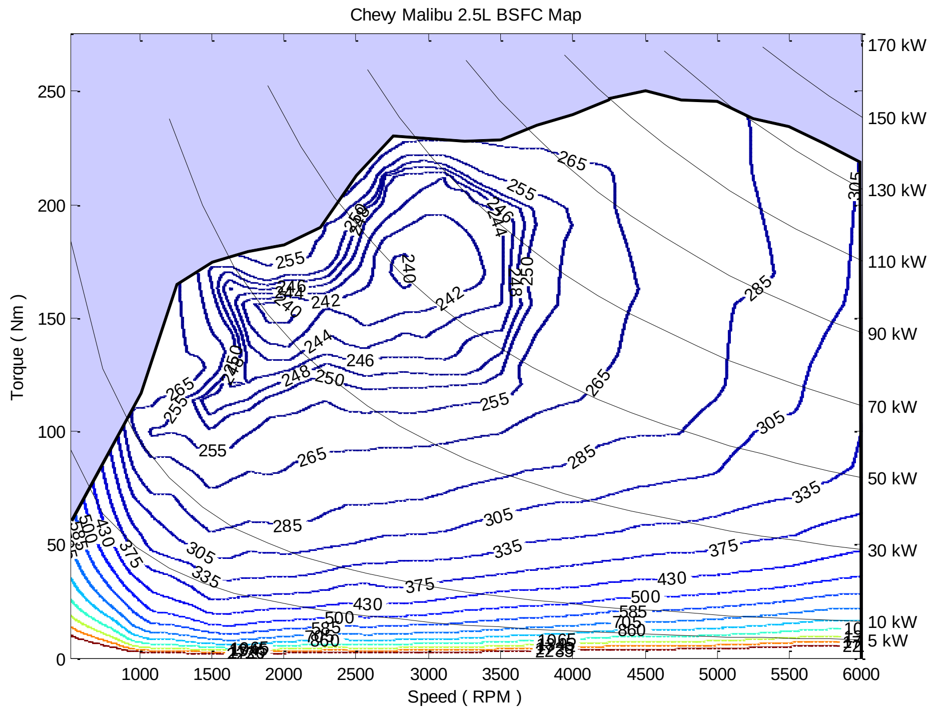


Figure 5.88 Chevy Malibu 2.5L BSFC Map

5.3.3.1.2.3 Inertia

Engine inertia plays a significant role in vehicle performance and fuel economy, particularly in the lower gears due to the high effective inertia (proportional to the square of the gear ratio) and higher acceleration rates.

To estimate the combined inertia of the engine, its attached components, and the torque converter impeller, a simple test was performed in-vehicle: the engine was accelerated with the transmission in park to the engine's maximum governed speed, then the ignition was keyed off, and the engine speed and torque were observed until the engine stopped. Engine speed and reported engine torque data (shown as negative during ignition off) were collected. The data was then run through a simple simulation and the inertia varied until the model deceleration rate reasonably matched the observed deceleration rate down to 500 RPM. Figure 5.89 shows the model result using a 0.2 kg-m^2 total inertia with the engine drag torque.

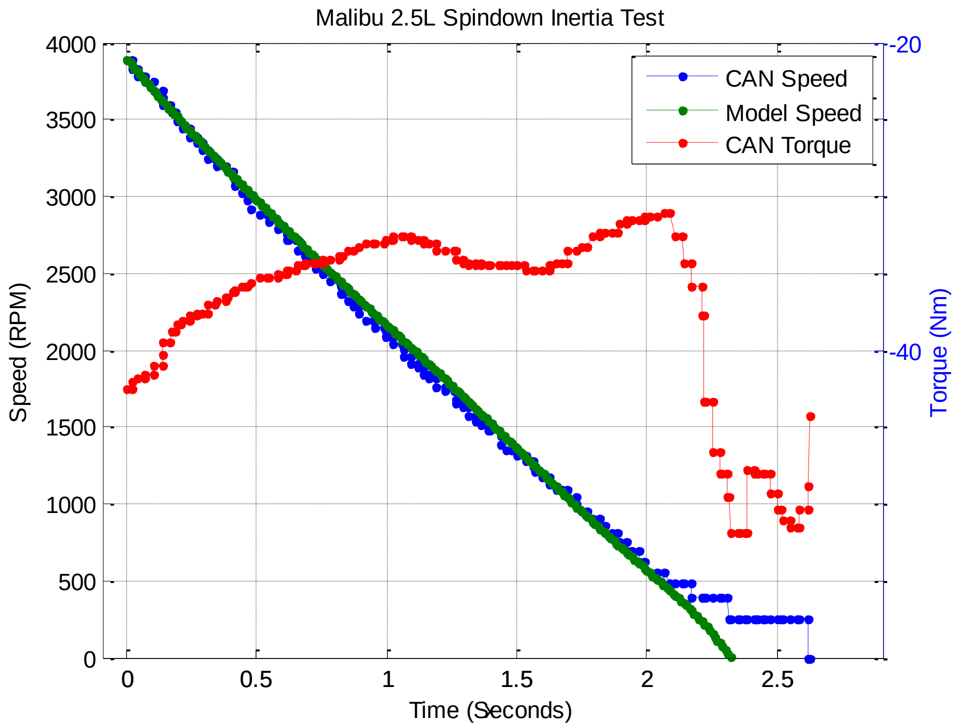


Figure 5.89 Engine Spin down Inertia Test

A wet torque converter from the 2013 Malibu was weighed and measured to estimate the inertia. The weight of 12.568 kg and total diameter of 0.273 m gives an estimated 0.0585 kg-m^2 total inertia. For the purposes of modeling this inertia was then proportioned 2/3 for the impeller side and 1/3 for the turbine side based on the inertia split from other known torque converters.

Subtracting the estimated torque converter inertia results in an engine (including all attached components) inertia of approximately 0.161 kg-m^2 (0.2 – 2/3*0.0585).

The exact proportioning of the inertia makes no difference to the outcome of the model (since the total inertia is always the same) but can guide future work or estimates of component inertias.

5.3.3.1.2.4 Transmission Data

For use with the model, the total transmission efficiency data needed to be separated into gear efficiency and pump/spin torque losses. Torque converter back-drive torque ratio and K factor also needed to be calculated.

5.3.3.1.2.5 Gear Efficiency and Spin Losses

To separate the gear efficiency from the total efficiency (which includes the pump/spin losses), the total efficiency data for each gear was converted to torque loss data and the spin loss torques were subtracted. The resulting gear torque loss data was then converted to an efficiency lookup tables. Some data points had to be extrapolated to cover the full speed and/or torque range. For example, first gear was only tested to 150 Nm but the full table required data up to 250 Nm. Figure 5.90 shows the estimated gear efficiencies for all gears. This process was followed for both the 37 C and 93 C data.

Transmission pump losses were factored out of the spin losses (as a rough approximation, since no pump loss data was available), using the lowest common spin loss to represent the pump loss.

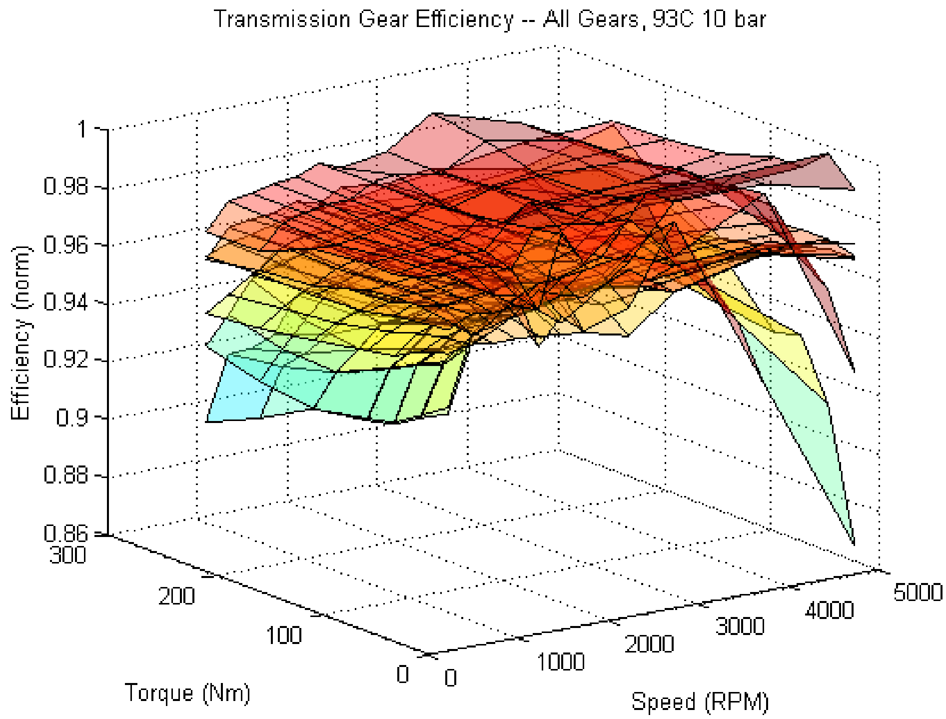


Figure 5.90 Gear Efficiency Data At 93 C and 10 Bar Line Pressure

5.3.3.1.2.6 Torque Converter

To complete the model inputs for the torque converter, the torque ratio and K factor need to be calculated for the full range of speed ratios.

The torque converter back-drive torque ratio is assumed to be 0.98 for all speed ratios. The back-drive K factor is calculated from the drive K factor mirrored relative to speed ratio (SR) 1 and shifted upwards by 70 percent. The K factor at SR 1 is calculated, for modeling purposes, as 7.5 times the highest drive K factor. In practice the K factor at SR 1 is either poorly defined or near infinite so the model requires a large value but not so large as to make the solver unstable. Figure 5.91 shows the given (SR < 0.95) and calculated torque converter data.

These additional data points have little effect on the modeled fuel economy but are required for model operation and smooth transitions from positive to negative torques.

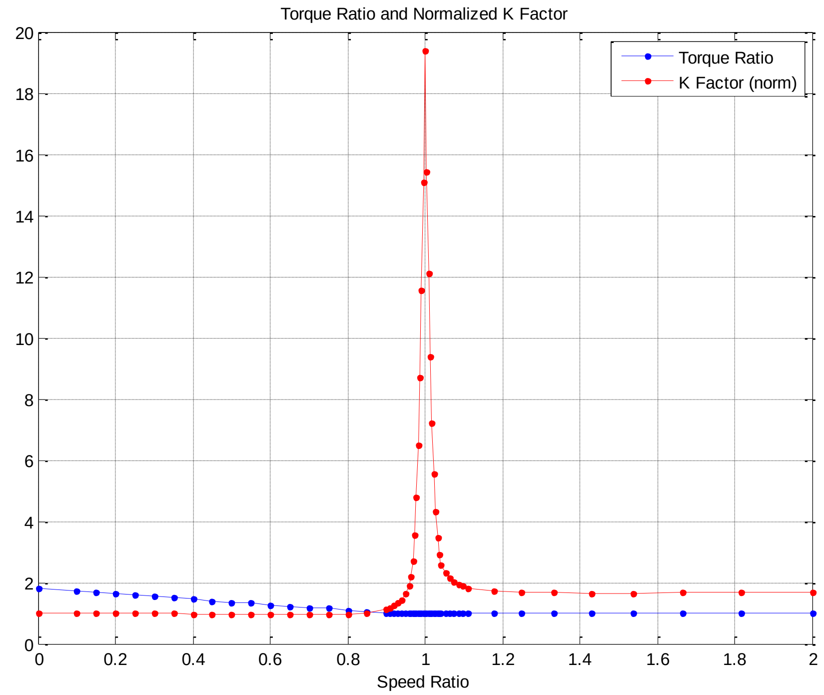


Figure 5.91 Torque Converter Drive and Back-Drive Torque Ratio and Normalized K Factor versus Speed Ratio

5.3.3.1.3 Vehicle Benchmarking Summary

Section 5.3.3.1 outlined the vehicle benchmarking process for a typical vehicle. While complex, this process yields the necessary input parameters for physics based full vehicle simulation models such as ALPHA. The following list represents the main model input parameters generated from the benchmarking process:

- Engine Maps:
  - Fuel Consumption
  - BSFC
  - Friction/Inertia
  - Performance
- Transmission Maps
  - Efficiency
  - Torque Converter
  - Shifting Strategy
- Vehicle:
  - Road Loads
  - Mechanical Loads
  - Electrical Loads

This information plus the remaining known vehicle characteristics (mass, etc.) provide the model with all of the necessary information needed for simulation. During the initial development of the ALPHA model, this complete data set from several vehicles was used to validate all of the internal calculations of the model. Once the model was validated, a wide variety of engines, transmissions, and other vehicle components were introduced to model current and future vehicles. This process is described in Section 5.3.3.2.

5.3.3.2 ALPHA Vehicle Simulation Model

The Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) tool was created by EPA to evaluate the Greenhouse Gas (GHG) emissions of Light-Duty (LD) vehicles. In the two prior rules, EPA relied on Ricardo to conduct full vehicle simulations. In order to have additional flexibilities and transparency, EPA developed an in-house full vehicle simulation model that could freely be released to the public. Model development, along with the data collection and benchmarking that comes along with model calibration, is an extremely effective means of developing expertise and deeper understanding on technologies. Better understanding of technologies makes for more robust regulatory analysis. Having a model available in-house also allows EPA to make rapid modifications as new data is collected, which cannot be done easily with contractors.

For the Draft TAR, EPA has achieved significantly higher levels of transparency for its modeling than was anticipated when beginning the work several years ago. Throughout this section of the Draft TAR, EPA has provided details on the major technology assumptions built into ALPHA. EPA has also provided extensive technical details in the docket for the Draft TAR describing the process used to build the fuel consumption maps for six of the engines mentioned in the Draft TAR, as well as data maps for two transmissions.[507] In the time leading up to the publication of the Draft TAR, EPA has published over 15 peer-reviewed papers describing results of key testing, validation and analyses.

In-house development of the models continues to be more accurate, efficient, transparent, and cost-effective than relying on contractors. EPA began developing both light-and heavy-duty vehicle simulations simultaneously as these vehicles share many of the same basic components. The light-duty vehicle model (ALPHA), and the heavy-duty model (GEM), share the same basic architecture.

EPA has validated the ALPHA model using several sources including vehicle benchmarking,[508] stakeholder data, and industry literature. While the ALPHA model is continuing to be refined and calibrated, the version in use as of April 26, 2016 was externally peer reviewed.[509] To further enhance transparency, EPA has included the results of this external peer review on its website along with a copy of this specific version of the ALPHA model that was reviewed (peer review input data and run-able MatLab Simulink source code).

5.3.3.2.1 *<u>General ALPHA Description.</u>*

ALPHA is a physics-based, forward-looking, full vehicle computer simulation capable of analyzing various vehicle types with different powertrain technologies, showing realistic vehicle behavior. The software tool is a MATLAB/Simulink based desktop application.

Within ALPHA, an individual vehicle is defined by specifying the appropriate vehicle road loading (inertia weight and coast-down coefficients) and specifications of the powertrain components. Powertrain components (such as engines or transmissions) are individually parameterized and can be exchanged within the model.

Vehicle control strategies are also modeled, including engine accessory loading, decel fuel shutoff, hybrid behavior, torque converter lockup, and transmission shift strategy. Transmission shifting is parameterized and controlled by ALPHAshift,[510] a shifting strategy algorithm that ensures an appropriate shifting strategy when engine size or vehicle loading changes. The control strategies used in ALPHA are modeled after strategies recorded during actual vehicle testing.

Vehicle packages defined within ALPHA can be run over any pre-determined vehicle cycle. To determine fuel consumption values used to calculate LD GHG rule CO_2 values, an FTP and HWFET cycle are simulated, separated by a HWFET prep cycle as normally run during certification testing. ALPHA does not include a temperature model, so the FTP is simulated within the model assuming warm component efficiencies for all bags. Additional fuel consumption due to the FTP cold start is calculated in post-processing by applying a fuel consumption penalty to bags 1 and 2, depending on the assumed warmup strategy. Any vehicle drive cycle can be defined and fuel economy simulated in ALPHA. For example, the results from the US06, NEDC, and WLTP cycles (among others) are used to tune vehicle control strategy parameters to match simulation results to measured vehicle test results across a variety of conditions. In addition, performance cycles have been defined, which are used to determine acceleration performance metrics.

5.3.3.2.2 Detailed ALPHA Model Description

The ALPHA model architecture is comprised of four systems: Ambient, Driver, Powertrain, and Vehicle as seen in Figure 5.92. With the exception of Ambient and Driver, each system consists of one or more subcomponents. The function of each system and its respective component models are discussed in this chapter. The structure and operation described in this section incorporate numerous constructive comments from both public comments and peer reviews. The model has been upgraded to integrate new technologies, improve the fidelity of the simulation results and better match the operation of the benchmarked vehicles. This all supports our primary goal of accurately reflecting changes in technology for both the current and future light duty fleet. As part of this effort, substantial effort has been put forth to accurately track and audit power flows through the model to ensure conservation of energy, and provide better data on technology effectiveness.

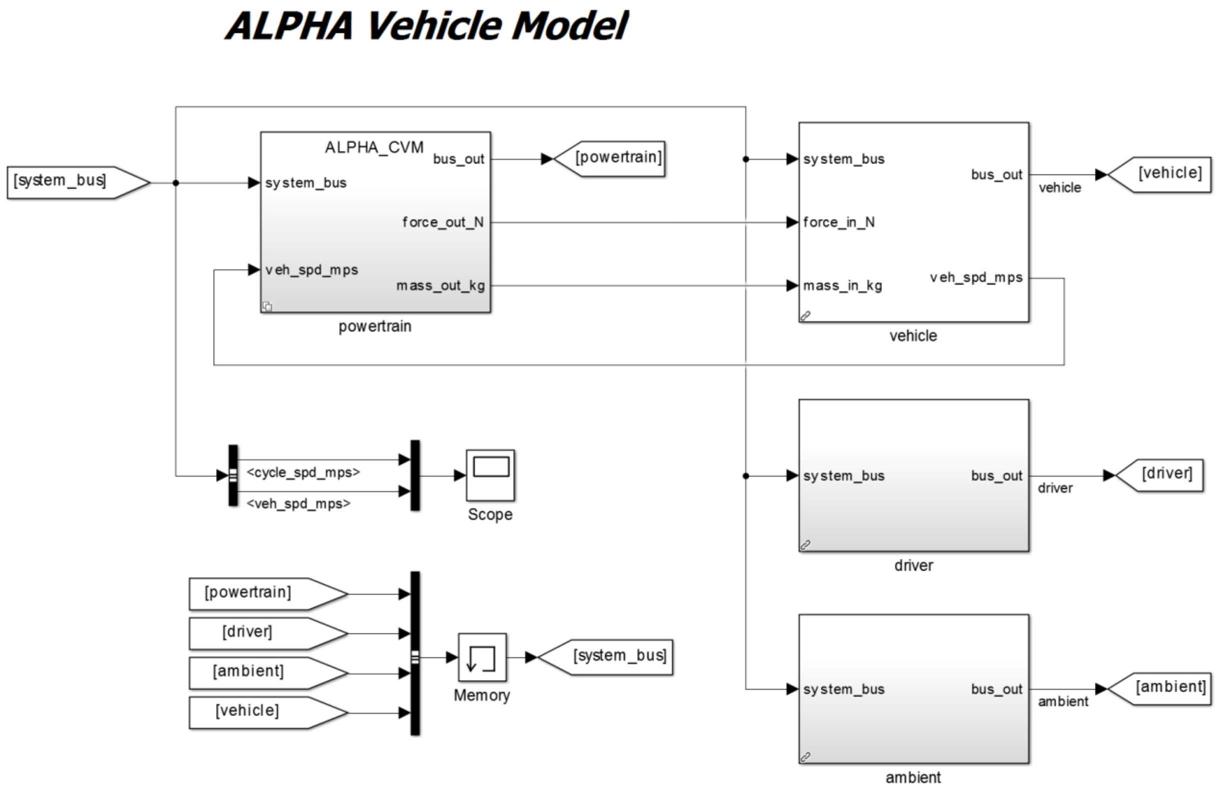


Figure 5.92 ALPHA Model Top Level View

One of the novel features of ALPHA is the inclusion of dynamic lookup tables. These tables allow additional customization of models for specific vehicles. This is enabled by a table description within the parameters for a component. This allows tables in the model such as transmission losses to be parameterized in a way that best matches the available data for that particular component.

5.3.3.2.2.1 Ambient System

This system defines ambient conditions such as pressure, temperature, and road gradient, where vehicle operations are simulated. ALPHA has been calibrated to generate fuel economy results corresponding to chassis dynamometer certification tests; therefore conditions within the simulation have been maintained to align with current test procedures.

5.3.3.2.2.2 Driver System

The driver model in ALPHA is a purely proportional-integral control driver that features a small look ahead to anticipate upcoming accelerations in the drive cycle. This is especially useful at launch where the vehicle response may be delayed due to the large effective inertia in lower gears. The driver in ALPHA is designed to follow a vehicle speed versus time driving cycle such as the UDDS or HWFET. The driver is tuned to mimic activities of a real driver during a chassis test, including starting the engine, putting the transmission into gear and then operating both the accelerator and brake pedals.

5.3.3.2.2.3 Powertrain System

The engine, transmission, electrical systems and accessories discussed in the following section are combined to form vehicle powertrain systems. The conventional powertrain system shown in Figure 5.13 contains sub-models representing each of the components. Additional powertrains were constructed to simulate power split and P2 hybrid as well as full electric drivetrains.

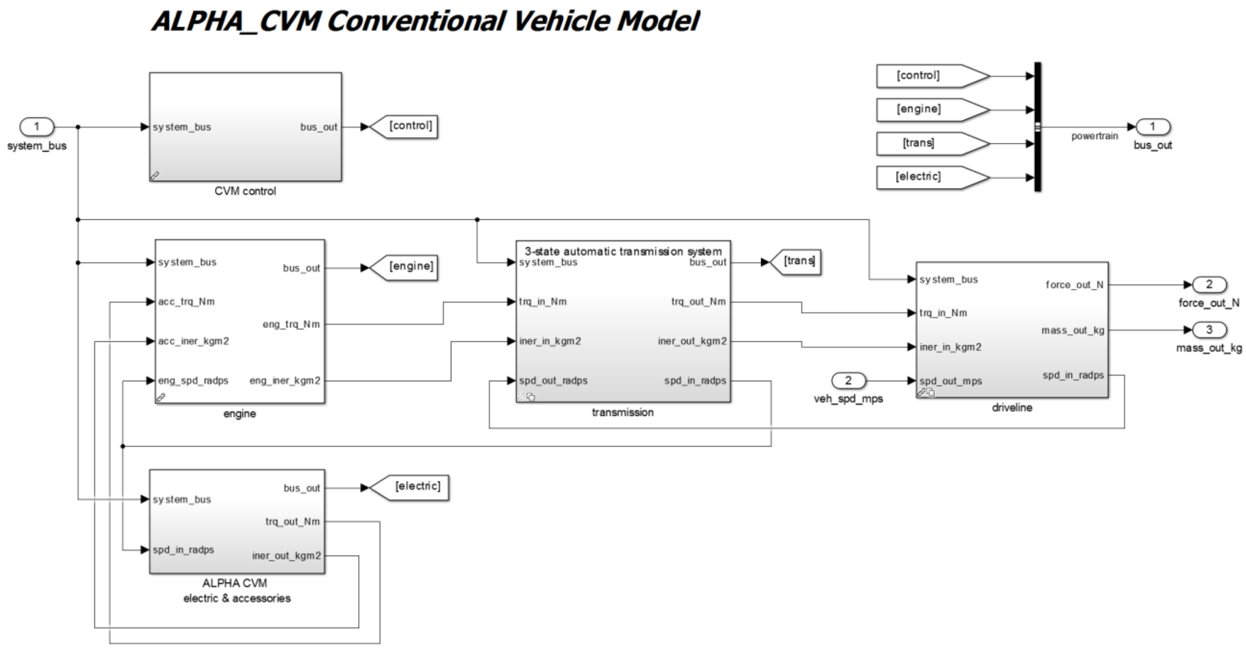


Figure 5.93 ALPHA Conventional Vehicle Powertrain Components

5.3.3.2.2.3.1 Engine Subsystem

The engine model is built around a steady-state fuel map covering all engine speed and torque conditions with torque curves restricting operation between wide open throttle (full load) and closed throttle (no load). The engine fuel maps for various engines are provided by benchmark data, generated via tools like GT-Power, or adapted from other data sources. The engine fuel map contains fuel mass flow rates vs engine crankshaft speed and brake torque. In-cylinder combustion processes are not modelled.

The steady-state fuel map used in ALPHA is adapted from the available test data or model output by creating an interpolant grid covering the area between idle speed and redline speed, and between the wide open throttle and closed throttle curves. In some circumstances, portions of the map (for example, those near redline speed or near the closed throttle curve) are extrapolated from the original data. In general, these area represent engine operation which is either outside of that used in two-cycle operation (near redline speed) or which uses little fuel in general (near the closed throttle curve).

During the simulation, the engine speed at a given point in the drive cycle is calculated from the physics of the downstream speeds. The quantity of torque required is calculated from the driver model accelerator demand, an idle speed controller, and requests from the transmission during shifts. The torque request is then limited by a torque response model which has been tuned to match the torque response of naturally aspirated and turbocharged gasoline and diesel engines. The resulting engine torque and speed are used to interpolate a fuel rate from the fuel map.

Additional sources of fuel consumption documented in benchmarking activities have been included in the model as well. On gasoline engines, the torque management that occurs during shifting is implemented such that the reduction in torque does not cause a corresponding reduction in the fuel rate. This approximates the effect of the observed spark retard to lessen the lurch associated with decelerating engine inertia during upshifts. Another source of additional fueling occurs after engines transition out of decel fuel cutoff. Additional fuel is applied for a few seconds for emissions control. Finally, there are additional fuel penalties applied within the simulation associated with rapid changes in engine power.

5.3.3.2.2.3.2 Electric Subsystem

The electric subsystem consists of 3 major components, battery, starter, and alternator.

The battery model for ALPHA was created after a literature review of battery models, particularly for hybrid vehicle applications. The same battery model structure[511,512] is used for both conventional and hybrid vehicles, with different calibrations used to simulate different chemistries such as lead-acid or lithium ion. The model features an open circuit voltage that varies with state of charge, a series resistance, and dual RC time constant filters to provide realistic voltage response. Calibrations were generated from published literature or benchmark testing for the open circuit voltage and transient behavior. The simulated battery also features a thermal model, with the output current limited at extremes in temperature or state of charge.

The engine starter is modeled as a simplified electric motor. It has a fixed efficiency and is commanded via a Boolean activation signal. The operation of the starter is characterized by a desired cranking speed and a torque capacity. These values are generally calculated to match the engine specifications. When an engine start is requested a proportional integral controller is used to determine the torque applied to accelerate the engine to the desired cranking speed, limited by the torque capacity. The mechanical power required and efficiency then determine the resulting electrical power consumed.

The engine alternator is modeled as a simplified electric generator with fixed efficiency. The electrical output current is determined by a charging controller. The efficiency and electrical power output can then be used to compute the mechanical load applied to the engine. The charging controller can operate in two different modes. In a basic mode it always tries to charge the battery to a fixed voltage target. It also features an adaptive charging / alternator regen mode that varies the voltage target and thus current output to driving conditions. Lower electrical output is provided during cruising, enough to maintain a minimal state of charge. During decelerations and transmission upshifts electrical output and thus mechanical load are increased to capture energy that would otherwise be dissipated via the brakes or transmission. The adaptive charging / alternator regen strategy exhibits increased variability of battery state of charge over various driving cycles. Therefore it is necessary to precondition the model with a prep cycle just as would be done on a test such as the HWFET to get accurate results.

5.3.3.2.2.3.3 Accessories Subsystem

The accessories subsystem in ALPHA is responsible for applying electrical and mechanical loads to mimic those observed during testing. The system is capable of applying 4 different loads: power steering, air conditioning, fan and a generic load to cover the remaining losses observed. Each load can apply mechanical loads to the engine crankshaft and/or electrical loads to the battery. Each load can be independently correlated to model signals via dynamic lookup tables, and is calibrated to match test data. Baseline vehicles with mechanical power steering often have mechanical losses that vary with engine speed, while future vehicles featuring electric power steering have electrical losses that vary with vehicle speed.

5.3.3.2.2.3.4 Transmission Subsystem

The transmission subsystem features different variants representing the major types of transmissions that are currently in use in LD vehicles. The different transmission models are built from similar components, but each features a unique control algorithm matching behaviors observed during vehicle benchmarking.

One of the features in ALPHA, which is required for the model to conserve energy, is multiple speed integrators. One is located at each of the points in the driveline where rotational inertias may become decoupled such as the transmission gearbox. These integrators use the torque and upstream inertia to compute the resulting acceleration and thus speed for the upstream components. For couplings that may become locked up, such as completing a transmission shift, the torques and rotational inertia are then passed down toward the next integrator in the model.

5.3.3.2.2.3.4.1 Transmission Gear Selection

All of the gear transmission models use a dynamic shift algorithm, ALPHAshift,[513] to determine the operating gear over the cycle. This employs a rule based approach utilizing the engine torque curve and fuel map to select gears that optimize efficient engine operation and provide a torque reserve as a traditional transmission calibration would. The ALPHAshift algorithm attempts to select the minimum fuel consumption gear after applying constraints on engine speed and torque reserve. It also allows downshifts due to high driver demand.[RR]

The ALPHAshift algorithm contains calibration parameters that can be tuned to match benchmarked shift behavior data from a particular engine and transmission. A generic calibration tuning strategy has been developed from these specific benchmarked calibrations, and is useful for simulating the shifting behavior of engine and transmission combinations that are from different vehicles or represent future technologies.

The CVT transmission model uses a similar ALPHAshiftCVT[514] algorithm for determining gear ratio selection. It attempts to maintain operation on an engine speed vs requested power line that minimizes fuel consumed. This method also has constraints for minimum engine speed and the rate at which the gear ratio can be changed.

[RR] Also known as a power downshift or kickdown.

5.3.3.2.2.3.4.2 Clutch Model

The clutch model in ALPHA can be modulated during launch and requires a fixed time to engage. Torque is conserved across the clutch during engagement and the inertial effects of accelerating and decelerating the upstream inertias are captured. This additional fidelity necessitates a more complicated control algorithm to manage clutch slip during launch which is included in the control strategy for the appropriate transmissions.

Two clutches are bundled together to create the dual clutch module for the dual clutch transmission. The dual clutch features a single integrator for calculating engine speed during shifts.

5.3.3.2.2.3.4.3 Gearbox Model

The gearbox model for ALPHA has been developed with the goal of simulating realistic operation during shifts for all types of transmissions. The gearbox contains gear ratios and properly scales torque and rotational inertia through the ratio change. Power loss within the gearbox are applied via dynamic lookup tables which determine torque loss and/or gearbox efficiency. These loss tables are typically constructed using signals such as input torque, input speed, commanded gear and/or line pressure.

Realistic shifting behavior is achieved with appropriate delays provided by a synchronizer clutch model. The layout of the gearbox model is most similar to a manual transmission, but the application for a planetary gearbox is a reasonable approximation once the neutral delay between gears is omitted.

The gearbox rotational inertias are split between a common input inertia, common output inertia and a gear specific inertia. The common inertias represent rotational inertia always coupled to the input or output shafts. The gear specific inertias, which are only used for planetary automatic transmissions, are added or removed as gears are engaged or disengaged and incur additional losses as the rotational inertia is spun up.

5.3.3.2.2.3.4.4 Torque Converter Model

The torque converter model in ALPHA simulates a lockup-type torque converter. The torque multiplication and resulting engine load are calculated via torque ratio and K-factor curves that vary as a function of speed ratio across the torque converter. Base torque ratio and the K-factor curves are often scaled in situations where detailed torque converter information is unavailable.

The lockup behavior of the torque converter is accomplished by integrating a clutch model similar to the one discussed above. The torque converter model also contains a pump loss torque that is implemented via a dynamic lookup table to simulate the power required to operate the pump on an automatic transmission.

5.3.3.2.2.3.4.5 Automatic Transmission & Controls

The automatic transmission (AT) is composed of the torque converter and gearbox systems discussed above. The AT is allowed to shift under load. During upshifts and torque converter lockup the engine output torque is slightly reduced to minimize the resultant torque pulse encountered by decelerating the engine inertia.

The torque converter lockup clutch command is determined based on transmission gear and gearbox input speed. The thresholds that trigger lock and unlock of the torque converter are calibrated to match benchmark data.

5.3.3.2.2.3.4.6 DCT Transmission & Control

The ALPHA DCT model is constructed from two separate gearbox components and a dual clutch module as described above. The dual clutch module features a dynamic lookup torque loss table that can be used to represent all the gearbox losses in one location if loss information for the separate gearboxes is not available. After a gear change to a new preselected gear is requested, the dual clutch module will transition and begin applying torque through the new gear.

The DCT transmission controller also includes a low speed clutch engagement routine to feather the clutch for low speed operation or launch. Similar to the automatic transmission engine output torque is reduced during upshifts to minimize the torque pulse at the wheels.

5.3.3.2.2.3.4.7 CVT Transmission & Control

The CVT transmission in ALPHA consists of the torque converter and gearbox modules. When operating as a CVT the gearbox maintains a state of partial engagement allowing the gear ratio to be constantly changed.

5.3.3.2.2.3.4.8 Driveline

The driveline system contains all of the components that convert the torque at the transmission output to force at the wheels. This includes drive shafts as well as driven axles, consisting of a differential, brakes and tires. ALPHA is capable of simulating multiple axles, but it is often simpler to convert a driveline to a single axle equivalent.

The driveshaft is a simple component for transferring torque while adding additional rotational inertia. It is only used for rear wheel drive vehicles.

The final drive is modeled as a gear ratio change with an associated torque loss and/or efficiency. These losses are applied via a dynamic lookup table. For front wheel drive transmissions, the final drive losses are often difficult to separate. In these situations all losses are applied in the gearbox.

The brake system on each axle applies a torque to the axle proportional to the brake pedal position from the driver model. The brake torque capacity is scaled to match the stopping requirements of the vehicle.

The tire component model transfers the torques and rotational inertias from upstream components to a force and equivalent mass that is passed to the vehicle model. This conversion uses the loaded tire radius and adds the tire's rotational inertia. A force associated with the tire rolling resistance is not simulated because these losses are included in the road load ABC coefficients applied within the vehicle subsystem.

5.3.3.2.2.3.5 Vehicle System

The vehicle system consists of the chassis, its mass and forces associated with aerodynamic drag, rolling resistance, and changes in road grade. The vehicle system also contains the vehicle speed integrator that computes acceleration from the input force and equivalent mass which is integrated to generate vehicle speed and distance traveled. The road load force is calculated from the ABC coefficients determined through coast down testing, or modified to simulate future improvements.

5.3.3.2.3 *Energy Auditing*

One of the quality control components within the ALPHA model is an auditing of all the energy flows. This auditing enables verification that the physics represented in the model is done correctly, generally resulting in a simulation energy error less than a few hundredths of a percent. The audit data can also be compared between simulations to verify that individual component losses are reasonable when compared to baseline packages or products that may feature similar technologies. An example energy audit report for a package similar to a current production sedan is shown in the figure below. It should be noted that the lack of final drive losses in this case is attributed to the vehicle being front wheel drive, and the thus the final drive losses are included in the gearbox.

```
         ---- Energy Audit Report ----
Total Energy Consumed                = 205975.66 kJ
    Fuel Energy                      = 205971.83 kJ
    Stored Energy                    =      3.83 kJ
         Battery Internal Losses =      0.91 kJ         0.00%
    Kinetic Energy                   =      0.00 kJ
    Potential Energy                 =      0.00 kJ

Usable System Energy Provided        = 63307.72 kJ
    Engine Energy                    = 63304.80 kJ
         Engine Efficiency           =    30.73 %
    Stored Energy                    =      2.92 kJ
    Kinetic Energy                   =      0.00 kJ
    Potential Energy                 =      0.00 kJ

Energy Consumed by ABC roadload      = 37465.54 kJ      59.17%
Energy Consumed by gradient          =      0.00 kJ      0.00%
Energy Consumed by brakes            = 11429.43 kJ      18.05%
Energy Consumed by Accessories       =  3505.29 kJ       5.54%
    Starter                          =      0.45 kJ      0.00%
    Alternator                       =  1225.99 kJ       1.94%
    Battery Stored Charge            =      0.00 kJ      0.00%
    Engine Fan                       =      0.00 kJ      0.00%
         Electrical                  =      0.00 kJ      0.00%
         Mechanical                  =      0.00 kJ      0.00%
    Power Steering                   =      0.00 kJ      0.00%
         Electrical                  =      0.00 kJ      0.00%
         Mechanical                  =      0.00 kJ      0.00%
    Air Conditioning                 =      0.00 kJ      0.00%
         Electrical                  =      0.00 kJ      0.00%
         Mechanical                  =      0.00 kJ      0.00%
    Generic Loss                     =  2278.85 kJ       3.60%
         Electrical                  =  2278.85 kJ       3.60%
         Mechanical                  =      0.00 kJ      0.00%
    Total Electrical Accessories =  2278.85 kJ       3.60%
    Total Mechanical Accessories =      0.00 kJ      0.00%
Energy Consumed by Driveline         = 10913.96 kJ      17.24%
     Launch Device                   =  1796.61 kJ       2.84%
     Gearbox                         =  8150.72 kJ      12.87%
         Pump Loss                   =  3243.10 kJ       5.12%
         Spin Loss                   =  2837.18 kJ       4.48%
         Gear/Inertia Loss           =  2070.44 kJ       3.27%
     Final Drive                     =      0.00 kJ      0.00%
     Tire Slip                       =    966.63 kJ      1.53%
Net System Kinetic Energy Change =      0.44 kJ      0.00%
                                       ------------
Total Loss Energy                    = 63314.66 kJ
Simulation Error                     =     -6.94 kJ
Energy Conservation                  =  100.011 %
```

Figure 5.94 Sample ALPHA Energy Audit Report

5.3.3.2.4 ALPHA Simulation Runs

ALPHA was used to perform a series of simulation runs, where various technology packages were compared to a baseline vehicle. The baseline vehicle was chosen to have component efficiencies and vehicle loads consistent with the baseline vehicles used in the modeling runs in the FRM. Four acceleration performance metrics were calculated for the baseline vehicle: 0-60 time, ¼ mile time, 30-50 passing time, and 50-70 passing time. These metrics were chosen to give a reasonably broad set of acceleration metrics that would be sensitive enough to represent true acceleration performance, but not so sensitive that minor changes in vehicle parameters would significantly change the final metric.

For each subsequent comparative run, a vehicle package was defined within ALPHA by specifying powertrain components and road load specifications. ALPHA's road load force at a specific vehicle velocity (v) is determined by using the following formula: F = Cv2 + Bv + A where the coastdown coefficients (A, B, and C) are derived from a least squares fit of data from track coast-down tests.

In ALPHA modeling, it is assumed that the A coefficient is a factor for the road load force that is mostly associated with tire rolling resistance, the B coefficient is a small factor, which represents higher order rolling resistance and gearing loss factors, and the C coefficient is a factor which mostly represents aerodynamic air drag. Thus, changes in aerodynamic losses are modeled by changing the C coefficient, and changes in rolling resistance losses are modeled by changing the A coefficient. Changes in mass reduction are modeled by reducing the test weight, and by reducing the A coefficient (as rolling resistance is a function of vehicle weight).

The nominal engine size for the package was determined based on the estimated performance effect of the technologies included in the package. The same performance metrics calculated for the baseline vehicle were calculated for each package, and the sum compared to the baseline sum. If the sum was not within three percent, the torque output (and thus size) of the engine was adjusted and the performance cycle rerun until an equivalent acceleration performance was attained.

Once the appropriate engine size was determined, the base engine map was adjusted by first scaling the torque output of the original map by the appropriate factor, and then adjusting the BSFC so as not to overestimate the efficiency gain from using a smaller engine. As engine size is reduced, the cylinder surface area to volume ratio increases, which increases the relative heat losses and decreases efficiency. An adjustment factor corresponding to approximately 1 percent increase in BFSC for every 10 percent decrease in engine displacement was used to adjust the engine maps. This factor is consistent with the well-known rule of thumb governing efficiency losses due to wall heat losses[515], and with the process used by Ricardo, Inc. in the FRM, to scale the BSFC maps.

Once the engine was appropriately scaled, the final vehicle package was run through an FTP and HWFET cycle simulation as described above to determine fuel consumption values.

5.3.3.2.5 Post-processing

ALPHA simulation runs are performed assuming warm component efficiencies. Additional fuel consumption due to the FTP cold start is calculated in post-processing by applying a fuel consumption penalty to bags 1 and 2. These fuel consumption penalty factors represent additional fuel used to heat the catalyst, and additional energy lost to higher viscosity lubricating oil in the engine and transmission. The fuel consumption penalties for "present" and "past" vehicles are set at 15 percent (present) to 17 percent (past) for bag 1 and 2.5 percent for bag 2. The penalty factors are applied during post-processing so that the fuel consumption for the appropriate bag is increase by the indicated amount. These factors were determined by comparing the "cold" FTP bags 1 and 2 to the "warm" bags 3 and 4 for a range of vehicles.

Since the three-bag FTP is a standard test, the difference in fuel consumption between bags 1 and 3 of the FTP could be calculated for the entire fleet (available in the Test Car List data files[516]), as seen in the graph below. However, the data sources for bag 4 are more limited. EPA based the 2.5 percent penalty factor on test data available from conventional vehicle testing from Argonne National Labs[517] and from internal testing, where differences between bags 2 and 4 averaged about 2.5 percent.

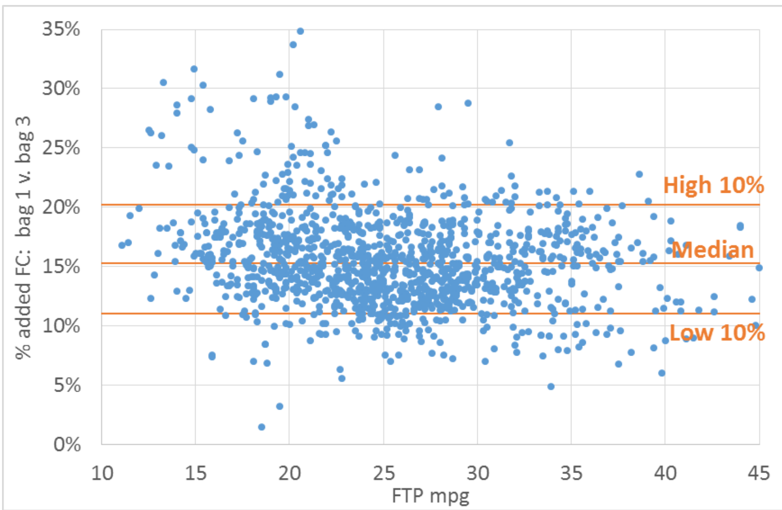


Figure 5.95 Example: Difference in 2016, Between Bags 1 and 3 of the FTP, from the Test Car List.

For simulation of advanced vehicle packages which included thermal management of the engine or transmission, the penalty factors were reduced (to a minimum of 11 percent for bag 1 and 0 percent for bag 2) to account for the reduction in losses associated with faster component warmup.

5.3.3.2.6 Vehicle Component Vintage

Vehicle components (engines and transmissions) are assigned a vintage of "past," "present," or "future." The vintage of the component determines the assumed technology package associated with the component, and thus the default value of some associated parameters.

One parameter affected by vintage is electric accessory loading. The "past" value for electrical loads includes a base electrical load of 154 W, additional power draw based on engine speed (approximately 700 W at 2500 rpm and 1050 W at 6000 rpm), and an alternator efficiency of 55 percent. These values are based on the modeling Ricardo did for the FRM, and assumes mechanical power steering. The "present" value for electrical load includes a base electrical load of 490 W, no additional variable accessory power draw, and an alternator efficiency of 65 percent. This is based on loads measured in various tested vehicles, in particular the Chevrolet Malibu.[518] The "future" electrical load maintains the same 490 W base electrical load, but with a high-efficiency (70 percent efficient) alternator. EPA is reviewing the values used for accessory loading, and may update them based on the results of the review.

Another parameter is the cold start penalty applied during post-processing. It is assumed that a bag 1 cold start penalty of 17 percent is associated with past engines, and a bag 1 cold start penalty of 15 percent is associated with present engines, as described in the section above. Future engines receive a bag 1 cold start penalty of 11 percent, representing the effect of thermal management of the engine included in the engine friction reduction package. Likewise, for past and present transmissions, a bag 2 cold start penalty of 2.5 percent, while for future transmissions the high-efficiency gearbox fast warmup technology is assumed, and a bag 2 cold start penalty of 0 percent is applied.

Future vintage transmissions are also assumed to be associated with early torque converter lockup.

Although the assigned vintage determines default values for accessory loads and cold start penalty, these defaults can be overridden in the model to examine the effects of specific technologies separately.

5.3.3.2.7 Additional Verification

As an additional verification of ALPHA model simulations, technology package combinations are further compiled and executed using a hardware-in-the-loop (HIL) system. This process enables powertrain, vehicle, and driver behavior to be observed in real time for both on-cycle and off-cycle situations. Any undesirable behavior is analyzed and used to fine tune the modeling process. These compiled HIL models are also utilized in the vehicle benchmarking process when testing vehicle subsystems such as engines, transmissions, battery modules, and other components. Figure 5.96 shows an example ALPHA model simulation observation display.

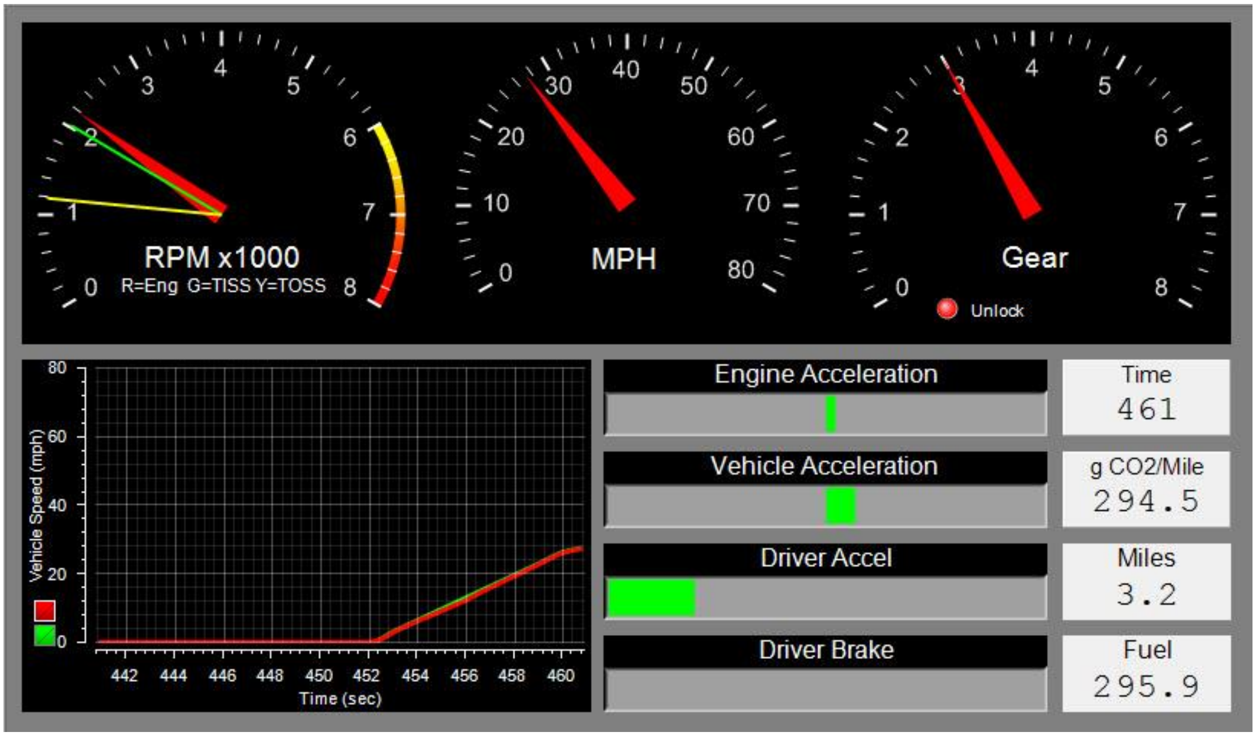


Figure 5.96 Example ALPHA Model UDDS Simulation Observation Display

As part of EPA's on-going quality process, several comparative analyses were completed as part of the ongoing MTE work. ALPHA results have been compared Ricardo EASY5 results from the original MY2017-2025 Light-Duty FRM, as well as with results from Autonomie.[519] When viewing the models as a calculators, then providing the same inputs to the calculators should provide the same outputs. Results of both comparisons showed only minor differences between simulation results due to specific model behaviors or implementations, convincing EPA that these models are very close in terms of computational results when run using the same input data and assumptions.

5.3.3.3 Determining Technology Effectiveness for MY2022-2025

EPA collected information on the effectiveness of current CO_2 emission reducing technologies from a wide range of sources. The primary sources of information were the 2017-2025 FRM, EPA's ALPHA model, EPA's vehicle benchmarking studies, the 2015 NAS Report, OEM and Supplier meetings, and industry literature. In addition, EPA considered confidential data submitted by vehicle manufacturers, along with confidential information shared by automotive industry component suppliers in meetings with EPA, CARB, and NHTSA staff. These confidential data sources were used primarily as a validation of the estimates since EPA prefers to rely on public data rather than confidential data wherever possible.

EPA recognizes that technologies will be further developed and introduced for MY2022-2025 and that innovation by automobile manufacturers and suppliers will continue to occur. While it is impossible for the agency to predict all of the technologies that will come to fruition, likely trends can be identified in the development of automotive systems that impact GHG emissions over the next decade. EPA uses methods similar to those used by industry to identify and evaluate emerging automotive technology trends. The use of computer aided engineering (CAE) tools for technology evaluation has been a key source of technology effectiveness data for MY2022-2025 vehicle technology packages. A number of other sources of data are also used to either validate CAE results or as independent sources of effectiveness data. Sources of data include:

1) Engineering analysis of logical developments based on current or near-term technology
2) Review of peer-reviewed journal papers, U.S. Department of Energy Reports, and other public sources of peer-reviewed data
3) Purchase and review of proprietary reports by major automotive industry analytical firms (e.g., R.L. Polk, IHS Automotive)
4) Meetings with automobile manufacturers
5) Meetings with Tier 1 automotive suppliers
6) Contracts with major automotive engineering design, analysis, and services firms (e.g., FEV, Munro and Associates, Southwest Research Institute, Ricardo PLC) to purchase data or engineering services
7) "Proof of concept" research either conducted directly by EPA at EPA-NVFEL or under contract with engineering services firms
8) CAE tools, including:
    a) Engine modeling (e.g., Ricardo WAVE, Gamma Technologies GT-POWER)
    b) Vehicle modeling (e.g., EPA LPM, EPA ALPHA, Ricardo RSM, MSC EASY5)
    c) HIL simulation of drive cycles
    d) Computational fluid dynamics (CFD) for initial component development
9) Chassis dynamometer testing
10) Engine dynamometer testing
11) Transmission dynamometer testing

Data from all sources listed above is used to develop and validate vehicle effectiveness within the EPA ALPHA model and EPA LPM. Modeling of technology package effectiveness within the ALPHA model and LPM is the source of all technology package effectiveness data contained within the OMEGA cost-effectiveness analyses. With respect to engine and powertrain technologies, the general progression of data into the OMEGA analyses for this Draft TAR has been:

1) Develop physics-based models of the technology with extensive validation of a base configuration to actual hardware (e.g., validation of an engine model to actual engine performance, combustion measurements and knock characteristics)
2) Use the validated physics-based model to evaluate hardware changes and to develop calibrations necessary to account for such hardware changes
3) Use the ALPHA model to determine the CO_2 effectiveness of the powertrain package for different vehicle configurations
4) Compare the energy balance of ALPHA model results with vehicle benchmark results as an additional plausibility analysis.
5) Use ALPHA modeling results to provide a calibration for technology package effectiveness within the LPM

6) Validate ALPHA modeling results using a variety of data sources (chassis dynamometer testing of production or developmental vehicles, HIL testing of developmental engine configurations, comparison with automobile manufacturer and Tier 1 supplier data, comparison with peer-reviewed/published data sources)
7) Update LPM calibration with validated ALPHA model technology package effectiveness
8) Use technology package effectiveness from the LPM within the OMEGA cost-effectiveness analysis for this Draft TAR

The EPA analysis of naturally aspirated Atkinson cycle engines provides an example of an analytical framework that integrates CAE together with other methods used by EPA to evaluate future vehicle technologies. The 2.0L Mazda SKYACTIV-G engine was introduced in 2012 in the U.S. This engine represents state-of-the art brake thermal efficiency and is the first non-HEV application of an Atkinson cycle engine in a U.S. light-duty vehicle application. EPA conducted chassis dynamometer testing of Mazda vehicles with the SKYACTIV-G engine and also purchased versions of this engine marketed in the U.S. (13:1 geometric compression ratio) and EU (14:1 geometric compression ratio) for detailed engine dynamometer mapping and HIL testing. After both chassis dynamometer testing and initial engine dynamometer testing, an engineering analysis was conducted to prioritize near-term technologies that could potentially yield further brake thermal efficiency improvements, broaden areas of high thermal efficiency and/or better align high brake thermal efficiency operation with both the regulatory drive cycles and with urban driving with the goal of meeting the 2022-2025 GHG standards in a “standard car” configuration (approximately D-segment size-class).

The technologies chosen for further analysis included:

- Improving alignment of high brake thermal efficiency operation with urban driving via road load reduction, switching to an advanced 8-speed automatic transmission, and using fixed 4/2 cylinder deactivation
- Improving brake thermal efficiency by increasing expansion the ratio from 13:1 to 14:1 along with the addition of low-pressure-loop EGR for additional knock mitigation on standard pump fuel and additional pumping loss improvements

An initial proof of concept evaluation of increased expansion ratio, low-pressure-loop cooled EGR and cylinder deactivation was conducted using GT-POWER engine modeling.[520] Engine dynamometer testing with HIL simulation of regulatory drive cycles was used for initial proof of concept evaluation of switching to use of an advanced 8-speed automatic transmission and using road-load reduction and application of the 2.0L SKYACTIV-G to larger D-segment vehicles.[521] Combinations of these technologies were also compared to similar vehicle configurations using turbocharged, downsized GDI engines using the ALPHA vehicle model.[522] An important part of EPA’s use of CAE has been to validate CAE results using other data sources. For example, ALPHA modeling and HIL testing were validated using chassis dynamometer test data and GT-POWER modeling was validated using engine dynamometer test data.

5.3.3.4 Lumped Parameter Model

It is widely acknowledged that full-scale physics-based vehicle simulation modeling is the most thorough approach for estimating future benefits of a package of new technologies. This is especially important for quantifying the efficiency of technologies and groupings (or packages) of technologies that do not currently exist in the fleet or as prototypes. However, developing and executing every possible combinations of technologies directly in a fleet compliance model using full scale vehicle simulation would not be practical to implement.

As part of rulemakings, EPA analyzes a wide array of potential technology options rather than attempt to pre-select the “best” solutions. For example, analysis for the MYs 2017-2025 Light Duty Vehicle GHG rule, EPA built over 800,000 packages for use in its OMEGA compliance model, which spanned 19 vehicle classes and over 1,200 baseline vehicle models. The Draft TAR analysis has expanded the number of baseline vehicle models to approximately 2,200. The lumped parameter approach was again chosen as the most practical surrogate to estimate the effectiveness of the technology package combinations for the Draft TAR analysis.

As in the FRM, the basis for calibrating and validating the lumped parameter model for this assessment is the effectiveness data generated by the benchmarking and full vehicle simulation modeling activities described earlier in this section. The lumped parameter model also allows benchmarked and/or simulated vehicle packages to be separated into individual components to properly account for the technologies already in the vehicle fleet to avoid any double counting of these technologies. General Motors (Patton et al)[523] presented a vehicle energy balance analysis to highlight the synergies that arise with the combination of multiple vehicle technologies. This report demonstrated an alternative methodology (to vehicle simulation) to estimate these synergies, by means of a “lumped parameter” approach. This approach served as the basis for EPA’s lumped parameter model. The Lumped Parameter approach has recently been endorsed by the National Academy of Science: "In particular, the committee notes that the use of full vehicle simulation modeling in combination with lumped parameter modeling has improved the agencies’ estimation of fuel economy impacts."[524]

As described in Section 5.3.3.2.3, the ALPHA simulation results used to calibrate the lumped parameter model are checked against conservation of energy requirements as part of the quality assurance process. Similarly, the basis for EPA’s lumped parameter analysis is a first-principles energy balance that estimates the manner in which the chemical energy of the fuel is converted into various forms of thermal and mechanical energy on the vehicle. The analysis accounts for the dissipation of energy into the different categories of energy losses, including each of the following:

- Second law losses (thermodynamic losses inherent in the combustion of fuel)
- Heat lost from the combustion process to the exhaust and coolant
- Pumping losses, i.e., work performed by the engine during the intake and exhaust strokes
- Friction losses in the engine
- Transmission losses, associated with friction and other parasitic losses of the gearbox, torque converter (when applicable) and driveline
- Accessory losses, related directly to the parasitics associated with the engine accessories

- Vehicle road load (tire and aerodynamic) losses
- Inertial losses (energy dissipated as heat in the brakes)

It is assumed that each baseline vehicle has a fixed percentage of fuel lost to each category. Each technology is grouped into the major types of engine loss categories it reduces. In this way, interactions between multiple technologies that are applied to the vehicle may be determined. When a technology is applied, the lumped parameter model estimates its effects by modifying the appropriate loss categories by a given percentage. Then, each subsequent technology that reduces the losses in an already improved category has less of a potential impact than it would if applied on its own.

Using a lumped parameter approach for calculating package effectiveness provides necessary grounding to physical principles. Due to the mathematical structure of the model, it naturally limits the maximum effectiveness achievable for a family of similar technologies. This can prove useful when computer-simulated packages are compared to a "theoretical limit" as a plausibility check. Additionally, the reduction of certain energy loss categories directly impacts the effects on others. For example, as mass is reduced the benefits of brake energy recovery decreases because there is not as much inertia energy to recapture.

The LP model has been updated from the MYs 2017-2025 final rule for this Draft TAR. Changes were made to include new technologies for 2017 and beyond and to improve fidelity for baseline attributes and technologies. In addition, the LP model has been calibrated to follow the results of the ALPHA full vehicle simulation model to facilitate the vehicle package building process used in the OMEGA model.

5.3.3.4.1 Lumped Parameter Model Usage in OMEGA

The Lumped Parameter Model (LPM) is used in the OMEGA model to incrementally improve the effectiveness of vehicle models in the baseline fleet. As a first step, approximately fifty technology packages are created with increasing effectiveness for each vehicle type. Several example packages are shown in Table 5.49.

Table 5.49 Example OMEGA Vehicle Technology Packages (values are for example only)

Package #	Technology Package	Technology Package Effectiveness
0	4-Speed Auto	0%
1	6-Speed Auto	4%
2	8-Speed Auto + DCP	10%
10	8-Speed + DCP + TURB24	20%
20	8-Speed + DCP + Aero2 + TURB24 + 10%MR	28%

Step two selects the next vehicle in the baseline fleet and applies all fifty technology packages in sequence using the LPM to calculate a new effectiveness value at each step. As the technologies in the baseline vehicles have been tabulated based on publically available data, the incremental effectiveness improvement will not include these baseline vehicle technologies to avoid double counting. Table 5.50 contains an example baseline vehicle. Table 5.51 illustrates the package application process.

Table 5.50 Example Baseline Vehicle (values are for example only)

Baseline Vehicle Technologies	Baseline Vehicle Effectiveness
6-Speed Auto + DCP	6%

Table 5.51 Example Package Application Process (values are for example only)

Package #	Technology Package	Technology Package Effectiveness	Resulting Vehicle Incremental Effectiveness
0	4-Speed Auto	0%	0%
1	6-Speed Auto	4%	0%
2	8-Speed Auto + DCP	10%	3%
10	8-Speed + DCP + TURB24	20%	11%
20	8-Speed + DCP + Aero2 + TURB24 + 10%MR	28%	17%

As shown, the incremental effectiveness is not simply additive as the LPM takes into account synergies and dis-synergies between the existing and applied technologies. This process also enables the OMEGA model to assign baseline vehicles a cost to represent their existing technologies and calculate an incremental cost to match with the incremental effectiveness as each technology package is applied. The completed technology package effectiveness values from the LPM are compared to the corresponding ALPHA model results as shown in Table 5.52 as a final check before they are used in the OMEGA model. This calibration process is an important step to ensure that full vehicle simulation results from the ALPHA model are used as the primary effectiveness inputs to the OMEGA model.

Table 5.52 Example LPM Calibration Check

Technology Package	Mass	Aero	Roll	ALPHA Effectiveness from Reference Package	LPM Effectiveness from Reference Package	Delta Effectiveness from Reference Package	LPM Effectiveness from Null Package
Standard Car+LUB +EFR1+DCP+SGDI+6AT +HEG1+EPS+IACC1	0%	0%	0%	0.0%	0.0%	0.0%	16.5%
Standard Car+LUB +EFR1+DCP+SGDI+8AT +HEG1+EPS+IACC1	0%	0%	0%	7.1%	6.9%	-0.2%	22.3%
Standard Car+LUB +EFR2+ATK2+DCP +SGDI+6AT+HEG1+EPS +IACC1	0%	0%	0%	4.9%	4.8%	-0.1%	20.5%
Standard Car+LUB +EFR2+ATK2+DCP +SGDI+8AT+HEG1+EPS +IACC1	0%	0%	0%	11.2%	11.2%	0.0%	25.9%
Standard Car+LUB +EFR2+ATK2+CEGR +DEAC+DCP+SGDI+8AT +HEG2+EPS+IACC2	0%	0%	0%	26.9%	26.8%	-0.1%	38.9%
Standard Car+LUB +EFR2+TURB24+CEGR +DEAC+DCP+SGDI+8AT +HEG2+EPS+IACC2	0%	0%	0%	26.3%	26.2%	-0.1%	38.4%
Standard Car+LUB +EFR2+ATK2+CEGR +DEAC+DCP+SGDI+8AT +HEG2+EPS+IACC2	10%	0%	0%	30.5%	30.5%	0.0%	42.0%
Standard Car+LUB +EFR2+ATK2+CEGR +DEAC+DCP+SGDI+8AT +HEG2+EPS+IACC2	0%	20%	0%	30.4%	30.3%	-0.1%	41.8%
Standard Car+LUB +EFR2+ATK2+CEGR +DEAC+DCP+SGDI+8AT +HEG2+EPS+IACC2	0%	0%	20%	30.3%	30.3%	0.0%	41.8%
Standard Car+LUB +EFR2+ATK2+CEGR +DEAC+DCP+SGDI+8AT +HEG2+EPS+IACC2	10%	20%	20%	37.8%	37.5%	-0.3%	47.8%
Standard Car+LUB +EFR2+TURB24+CEGR +DEAC+DCP+SGDI+8AT +HEG2+EPS+IACC2	10%	20%	20%	37.3%	37.1%	-0.2%	47.4%

The complete list of baseline fleet vehicles each incremented approximately fifty times results in approximately 100,000 improved vehicles as input to the OMEGA model.

The effectiveness reductions and costs that are associated with applying a technology will depend on the starting point technologies from which the cost and effectiveness improvements are measured. For example, two vehicle models that start with different packages of technologies will likely have different costs and effectiveness, even if both models finally arrive at the same package combination of technologies. The agencies' recognition of the importance of clearly specifying the point of comparison for cost and effectiveness estimates is consistent with the NAS committee's finding "that understanding the base or null vehicle, the order of technology application, and the interactions among technologies is critical for assessing the costs and effectiveness for meeting the standards."

As long as the point of comparison is maintained consistently throughout the analysis for both the baseline and future fleets, the decision of where to place an origin along the scale of cost and effectiveness is inconsequential. For EPA's technology assessment, the origin is defined to coincide with a "null technology package," which represents a technology floor such that all technology packages considered in this assessment will have equal or greater effectiveness, consistent with the FRM approach. While other choices would have been equally valid, this definition of a "null package" has the practical benefits of avoiding technology packages with negative effectiveness values, while also allowing for a direct comparison of effectiveness assumptions with the FRM.

5.3.4 Data and Assumptions Used in GHG Assessment

5.3.4.1 Engines: Data and Assumptions for this Assessment

The majority of engine technologies used in this assessment are detailed in Section 5.2 of this Draft TAR. This section details engine technology information specific to the EPA GHG analysis.

In an effort to characterize the efficiency and performance of late model vehicle powertrains, and to update our engine data from that used in the FRM, EPA tested several engines at the National Vehicle and Fuel Emission Laboratory and contractor facilities. Depending on the information required, the engines were tested with their factory and/or developmental engine management systems that allowed EPA engineering staff to calibrate engine control parameters. Figure 5.97 illustrates a typical engine test.

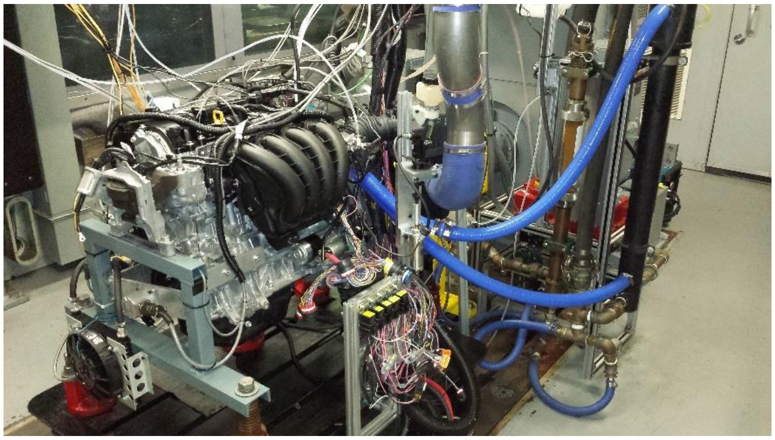


Figure 5.97 2.0L I4 Mazda SKYACTIV-G engine Undergoing Engine Dynamometer Testing at the EPA-NVFEL Facility.

In some cases, future engine configurations can be modeled using engine simulation software. EPA used Gamma Technologies GT-POWER engine simulation software to model future engine configurations based upon the Mazda 2.0L I4 SKYACTIV-G engine and the MAHLE turbocharged/downsized 1.2L I3 GDI Di3 engine. Computer-aided engineering tools, including GT-POWER, are commonly used during the initial stages of product development by automotive manufacturers and academia to establish the potential performance of engine design features, with respect to efficiency, emissions, and performance. GT-POWER is a physics based suite of software that combines predictive diesel or spark-ignition combustion models; CAD-based, preprocessed libraries of the physical layout of induction, exhaust and combustion systems; models of chemical kinetics; wave dynamics models; turbocharger turbine and compressor models with surge, reverse-flow and pressure wave prediction; induction turbulence models; a kinetic knock model; injector spray models and an ability to apply minor adjustments to model-predicted parameters using data from engine dynamometer measurements. Engine dynamometer data was also used to directly validate simulations of specific engine hardware configurations via comparisons of measured vs. modeled values for knock intensity, combustion phasing, FMEP, BTE and other parameters.

5.3.4.1.1 Low Friction Lubricants (LUB)

Based on the analysis for the 2017-2025 FRM, the agencies estimated the effectiveness of LUB to be 0.5 to 0.8 percent. EPA has reviewed this technology and finds the effectiveness estimate remains applicable for this Draft TAR.

The cost associated with making the engine changes needed to accommodate low friction lubes is equivalent to that used in the 2012 FRM except for updates to 2013 dollars. The costs are shown below.

Table 5.53 Costs for Engine Changes to Accommodate Low Friction Lubes (dollar values in 2013$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$3	1	$3	$3	$3	$3	$3	$3	$3	$3	$3
IC	Low2	2018	$1	$1	$1	$1	$1	$1	$1	$1	$1
TC			$4	$4	$4	$4	$4	$4	$4	$4	$4

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.3.4.1.2 Engine Friction Reduction (EFR1, EFR2)

Based on the analysis for the 2017-2025 FRM, EPA estimated the effectiveness of EFR1 at 2.0 to 2.7 percent. Based on the analysis for the 2017-2025 FRM, EPA estimated the effectiveness of EFR2 at 3.4 to 4.8 percent. EPA has reviewed this technology and finds the effectiveness estimate remains applicable for this Draft TAR.

The costs associated with engine friction reduction are equivalent to those used in the 2012 FRM except for updates to 2013 dollars. The costs are shown below first for engine friction reduction level 1 and then for level 2.

Table 5.54 Costs for Engine Friction Reduction Level 1 (dollar values in 2013$)

Engine	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
I3	DMC	$37	1	$37	$37	$37	$37	$37	$37	$37	$37	$37
I4	DMC	$50	1	$50	$50	$50	$50	$50	$50	$50	$50	$50
V6	DMC	$74	1	$74	$74	$74	$74	$74	$74	$74	$74	$74
V8	DMC	$99	1	$99	$99	$99	$99	$99	$99	$99	$99	$99
I3	IC	Low2	2018	$9	$9	$7	$7	$7	$7	$7	$7	$7
I4	IC	Low2	2018	$12	$12	$10	$10	$10	$10	$10	$10	$10
V6	IC	Low2	2018	$18	$18	$14	$14	$14	$14	$14	$14	$14
V8	IC	Low2	2018	$24	$24	$19	$19	$19	$19	$19	$19	$19
I3	TC		2018	$46	$46	$44	$44	$44	$44	$44	$44	$44
I4	TC		2018	$62	$62	$59	$59	$59	$59	$59	$59	$59
V6	TC		2018	$92	$92	$89	$89	$89	$89	$89	$89	$89
V8	TC		2018	$123	$123	$118	$118	$118	$118	$118	$118	$118

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.55 Costs for Engine Friction Reduction Level 2 (dollar values in 2013$)

Engine	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
I3	DMC	$81	1	$81	$81	$81	$81	$81	$81	$81	$81	$81
I4	DMC	$106	1	$106	$106	$106	$106	$106	$106	$106	$106	$106
V6	DMC	$155	1	$155	$155	$155	$155	$155	$155	$155	$155	$155
V8	DMC	$205	1	$205	$205	$205	$205	$205	$205	$205	$205	$205
I3	IC	Low2	2024	$20	$20	$20	$20	$20	$20	$20	$20	$16
I4	IC	Low2	2024	$26	$26	$26	$26	$26	$26	$26	$26	$20
V6	IC	Low2	2024	$38	$38	$38	$38	$38	$38	$38	$38	$30
V8	IC	Low2	2024	$50	$50	$50	$50	$50	$50	$50	$50	$39
I3	TC		2024	$101	$101	$101	$101	$101	$101	$101	$101	$97
I4	TC		2024	$131	$131	$131	$131	$131	$131	$131	$131	$126
V6	TC		2024	$193	$193	$193	$193	$193	$193	$193	$193	$185
V8	TC		2024	$254	$254	$254	$254	$254	$254	$254	$254	$244

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.3.4.1.3 Cylinder Deactivation (DEAC)

Within the analysis for the 2017-2025 FRM, EPA estimated an effectiveness of 6 percent for DEAC. EPA has reviewed this technology and changed the effectiveness estimate to 3.9 to 5.3 percent for this Draft TAR.

The costs associated with cylinder deactivation are equivalent to those used in the 2012 FRM except for updates to 2013 dollars and use of a new learning curve (curve 24). Note that the 2012 FRM did not carry a cost for cylinder deactivation on an I-4 engine. For this Draft TAR, we have used half the cost of cylinder deactivation on a V8 engine. The costs are shown below.

Table 5.56 Costs for Cylinder Deactivation (dollar values in 2013$)

Engine	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
I4	DMC	$86	24	$82	$80	$79	$78	$76	$75	$74	$73	$72
V6	DMC	$153	24	$146	$143	$141	$138	$136	$134	$132	$130	$129
V8	DMC	$172	24	$164	$161	$158	$155	$153	$151	$149	$147	$145
I4	IC	High1	2018	$48	$48	$29	$29	$29	$29	$29	$29	$29
V6	IC	Med2	2018	$59	$59	$44	$44	$44	$44	$44	$44	$43
V8	IC	Med2	2018	$66	$66	$49	$49	$49	$49	$49	$49	$49
I4	TC			$130	$129	$108	$107	$106	$105	$104	$103	$102
V6	TC			$205	$202	$184	$182	$180	$178	$176	$174	$172
V8	TC			$230	$227	$207	$205	$202	$200	$198	$196	$194

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.3.4.1.4 Intake Cam Phasing (ICP)

Within the analysis for the 2017-2025 FRM, EPA estimated an effectiveness of 2.1 to 2.7 percent for ICP. EPA has reviewed this technology and finds the effectiveness estimate remains applicable for this Draft TAR.

The costs associated with intake cam phasing are equivalent to those used in the 2012 FRM except for updates to 2013 dollars and use of a new learning curve (curve 24). The costs are shown below.

Table 5.57 Costs for Intake Cam Phasing (dollar values in 2013$)

Engine	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
OHC-I	DMC	$41	24	$39	$38	$37	$37	$36	$36	$35	$35	$34
OHC-V	DMC	$81	24	$78	$76	$75	$73	$72	$71	$70	$69	$68
OHV-V	DMC	$41	24	$39	$38	$37	$37	$36	$36	$35	$35	$34
OHC-I	IC	Low2	2018	$10	$10	$8	$8	$8	$8	$8	$8	$8
OHC-V	IC	Low2	2018	$20	$20	$16	$16	$16	$16	$16	$16	$16
OHV-V	IC	Low2	2018	$10	$10	$8	$8	$8	$8	$8	$8	$8
OHC-I	TC			$49	$48	$45	$44	$44	$43	$43	$42	$42
OHC-V	TC			$97	$96	$90	$89	$88	$87	$86	$85	$84
OHV-V	TC			$49	$48	$45	$44	$44	$43	$43	$42	$42

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.3.4.1.5 Dual Cam Phasing (DCP)

Based on the analysis for the 2017-2025 FRM, EPA estimated the effectiveness of DCP to be between 4.1 to 5.5 percent. EPA has reviewed this technology and finds the effectiveness estimate remains applicable for this Draft TAR.

The costs associated with dual cam phasing are equivalent to those used in the 2012 FRM except for updates to 2013 dollars and use of a new learning curve (curve 24). The costs are shown below.

Table 5.58 Costs for Dual Cam Phasing (dollar values in 2013$)

Engine	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
OHC-I	DMC	$74	24	$71	$70	$68	$67	$66	$65	$64	$63	$63
OHC-V	DMC	$160	24	$153	$150	$147	$145	$142	$140	$138	$136	$135
OHC-I	IC	Med2	2018	$29	$29	$21	$21	$21	$21	$21	$21	$21
OHC-V	IC	Med2	2018	$61	$61	$46	$46	$46	$46	$46	$46	$45
OHC-I	TC			$100	$98	$90	$89	$87	$86	$86	$85	$84
OHC-V	TC			$214	$211	$193	$190	$188	$186	$184	$182	$180

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.3.4.1.6 Discrete Variable Valve Lift (DVVL)

Based on the analysis for the 2017-2025 FRM, EPA estimated the effectiveness for DVVL at 4.1 to 5.6 percent. EPA has reviewed this technology and finds the effectiveness estimate remains applicable for this Draft TAR.

The costs associated with discrete variable valve lift are equivalent to those used in the 2012 FRM except for updates to 2013 dollars and use of a new learning curve (curve 24). The costs are shown below.

Table 5.59 Costs for Discrete Variable Valve Lift (dollar values in 2013$)

Engine	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
OHC-I	DMC	$127	24	$122	$119	$117	$115	$113	$112	$110	$109	$107
OHC-V	DMC	$184	24	$176	$173	$170	$167	$164	$162	$160	$158	$156
OHV-V	DMC	$263	24	$252	$247	$243	$239	$235	$231	$228	$225	$222
OHC-I	IC	Med2	2018	$49	$49	$37	$36	$36	$36	$36	$36	$36
OHC-V	IC	Med2	2018	$71	$71	$53	$53	$53	$53	$53	$53	$53
OHV-V	IC	Med2	2018	$101	$101	$76	$76	$75	$75	$75	$75	$75
OHC-I	TC			$171	$168	$154	$152	$150	$148	$146	$145	$144
OHC-V	TC			$247	$244	$223	$220	$217	$215	$212	$210	$208
OHV-V	TC			$353	$348	$318	$314	$310	$307	$303	$300	$297

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.3.4.1.7 Continuously Variable Valve Lift (CVVL)

Based on the analysis for the 2017-2025 FRM, EPA estimated the effectiveness for CVVL at 5.1 to 7.0 percent. EPA has reviewed this technology and finds the effectiveness estimate remains applicable for this Draft TAR.

The costs associated with continuously variable valve lift are equivalent to those used in the 2012 FRM except for updates to 2013 dollars and use of a new learning curve (curve 24). The costs are shown below.

Table 5.60 Costs for Continuously Variable Valve Lift (dollar values in 2013$)

Engine	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
OHC-I	DMC	$191	24	$182	$179	$176	$173	$170	$167	$165	$163	$161
OHC-V	DMC	$350	24	$334	$328	$322	$317	$312	$307	$303	$299	$295
OHV-V	DMC	$381	24	$365	$358	$351	$345	$340	$335	$330	$326	$322
OHC-I	IC	Med2	2018	$73	$73	$55	$55	$55	$55	$54	$54	$54
OHC-V	IC	Med2	2018	$135	$134	$100	$100	$100	$100	$100	$100	$100
OHV-V	IC	Med2	2018	$147	$147	$110	$109	$109	$109	$109	$109	$109
OHC-I	TC			$256	$252	$230	$227	$225	$222	$220	$217	$215
OHC-V	TC			$469	$462	$422	$417	$412	$407	$403	$399	$395
OHV-V	TC			$512	$504	$461	$455	$449	$444	$439	$435	$431

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.3.4.1.8 Investigation of Potential Future Non-HEV Atkinson Cycle Engine Applications

EPA initiated an internal study to investigate potential improvements in the incremental effectiveness of Atkinson Cycle engines through the application of cooled EGR, an increase in compression ratio, and 2/4 cylinder deactivation. Cooled EGR offered the potential for additional knock mitigation, increased compression ratio, and reduced pumping losses. The use of cylinder deactivation held potential for additional pumping loss reduction under light-load conditions. Initially, the potential for improvements was studied using 1-D gas dynamics/0-D combustion simulation software.[SS] A 2.0L Mazda SKYACTIV-G GDI Atkinson Cycle engine was thoroughly benchmarked by EPA with the engine dynamometer test facilities at the EPA-NVFEL laboratory in Ann Arbor, MI. Performance data and physical dimensions for the engine and its gas exchange and combustion processes were used to build and validate the simulation. Details of the study, including methods used to build the engine model, model validation and initial engine modeling results are provided in Lee et al. 2016.[520] Simulation results show potential for an approximately 3 percent to 9 percent incremental effectiveness in areas of operation of importance for the regulatory drive cycles using a combination of cooled EGR and a 1-point increase in compression ratio (14:1), with the largest improvements (6 to 9 percent incremental) occurring between 4-bar and 8-bar BMEP.

[SS] Gamma Technologies "GT-Power."

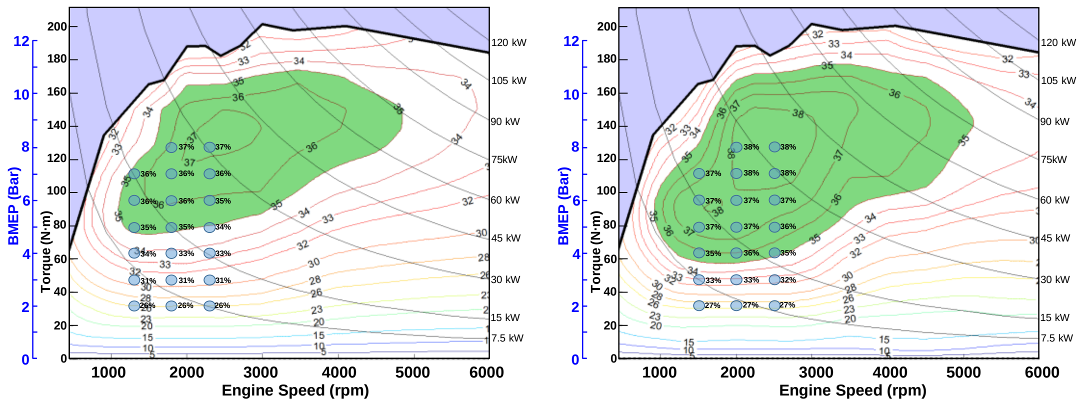


Figure 5.98 Comparison of a 2.0L Mazda SKYACTIV-G engine with a 13:1 geometric compression ratio to engine simulation results of a comparable engine with a 1-point increase in geometric compression ratio (14:1) and cooled, low-pressure EGR.[TT]

Simulation results show potential for an approximately 3 percent to 12 percent incremental effectiveness in areas of engine operation with significant importance for the regulatory drive cycles using a combination of cooled EGR, a 1-point increase in compression ratio (14:1), and with fixed (2-cylinder) cylinder deactivation below 5-bar BMEP and for engine speeds of 1000 rpm to 3000 rpm. Simulation results also show an incremental effectiveness of approximately 3 percent to 7 percent when comparing the cooled EGR/higher geometric compression ratio results with and without cylinder deactivation. This is consistent with other published results for both production and proof-of-concept fixed (not dynamic) cylinder deactivation.[525,526,527]

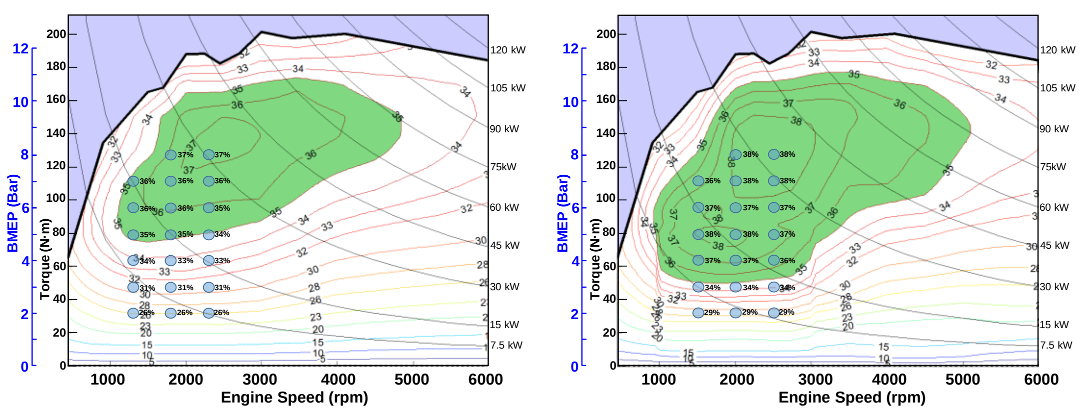


Figure 5.99 Comparison of a 2.0L Mazda SKYACTIV-G engine with a 13:1 geometric compression ratio to engine simulation results of a comparable engine with a 1-point increase in geometric compression ratio (14:1), cooled, low-pressure EGR and cylinder deactivation with operation on 2 cylinders at below 5-bar BMEP and 1000 - 3000 rpm.

[TT] The simulation results presented in Figure 5.98 and Figure 5.99 include kinetic knock modeling and calibration of the simulation to knock induction comparable to the original engine configuration for both Tier 2 certification test fuel (E0, 96 RON) and LEV III certification test fuel (E10, 88 AKI, 91 RON). An adequate representation of knock-limited torque within an engine simulation requires careful experimental validation of the kinetic knock model used by the simulation, which is currently under way at EPA-NVFEL. While the simulation results show comparable WOT torque between the different engine configurations, experimental validation of the achievable knock-limited torque at WOT was still underway at the time of publication of this assessment.

The EPA internal study on Atkinson Cycle engines has entered a second phase involving engine dynamometer validation of the simulation results using a EU-market version of the Mazda SKYACTIV-G engine with increased geometric compression ratio (14:1), a proof-of concept, low-pressure-loop, cooled EGR system, and the use of a dual-coil offset (DCO) ignition system to improve EGR tolerance of the engine (see Figure 5.100).[528,529] Initial results have been promising. The improved ignition characteristics of the DCO ignition system has allowed an increase in the range of part-load engine operation at relatively high rates (approximately 20 percent) of cooled EGR beyond that of the relatively conservative, fixed EGR map used in the simulation study. This allowed further reductions in part-load pumping losses while maintaining a COV of IMEP[UU] of less than 3-4 percent, which is comparable to that of the original engine configuration.

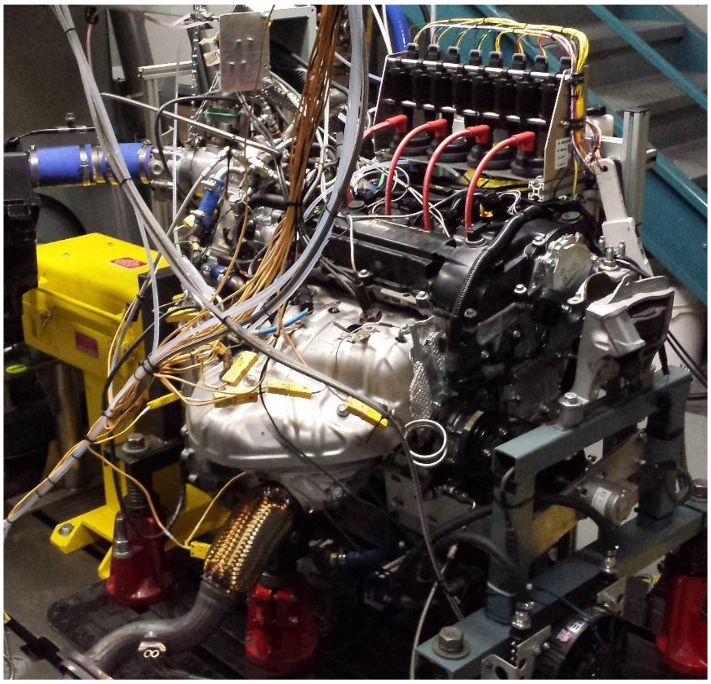


Figure 5.100 Mazda 2.0L SKYACTIV-G engine with 14:1 geometric compression ratio, cooled low-pressure external EGR system, DCO ignition system, and developmental engine management system undergoing engine dynamometer testing at the U.S. EPA-NVFEL facility in Ann Arbor, MI.

Future work will include validation of the engine model, particularly the kinetic knock model, and proof-of-concept dynamometer testing of fixed cylinder deactivation of cylinder numbers 2 and 3. Costs for this technology (future non-HEV Atkinson cycle, referred to as Atkinson-level 2 by EPA) are new as they were not part of the 2012 FRM. We have based our Atkinson-2 technology costs on the 2015 NAS report. Table S.2 of that report shows the cost estimates presented below. Note that the NAS costs include the costs of gasoline direct injection (shown as "DI" in the NAS report row header). EPA has removed those costs (using the NAS reported values) since EPA accounts for those costs separately rather than including them in the Atkinson-

[UU] Coefficient of variation of indicated mean effective pressure based on high-speed in-cylinder pressure measurements. This is a commonly used indicator of combustion instability and would typically be kept to values that are under 3% to 5% depending on operating conditions and engine application.

2 costs. Note also that EPA always includes costs for direct injection, along with variable valve timing and other costs when building an Atkinson-2 package.

Table 5.61 Direct Manufacturing Costs (DMC) for Atkinson-2 Technology (2010$)

Tech	Midsize Car I4 DOHC	Large Car V6 DOHC	Large Light Truck V8 OHV	Relative to
Stoichiometric Gasoline Direct Injection (NAS 2015)	164	246	296	Previous tech
Compression Ratio Increase (CR~13.1, exh. Scavenging, DI (e.g. SKYACTIV-G)) (NAS 2015)	250	375	500	Baseline
EPA estimate (Row 2 minus Row 1)	86	129	204	Stoich GDI

Consistent with the NAS report, we have considered the NAS costs to be 2025 costs in terms of 2010$. Adjusting to 2013$, applying a learning curve (22) that bases that cost in MY2025, and applying medium 2 level complexity in calculating indirect costs results in the costs presented below for each engine type in this Draft TAR analysis.

Table 5.62 Costs for Atkinson-2 Technology, Exclusive of Enablers such as Direct Inject and Valve Timing Technologies (dollar values in 2013$)

Engine	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
I3	DMC	$91	22	$107	$104	$102	$100	$98	$96	$94	$93	$91
I4	DMC	$91	22	$107	$104	$102	$100	$98	$96	$94	$93	$91
V6	DMC	$136	22	$160	$157	$154	$150	$147	$145	$142	$139	$136
V8	DMC	$215	22	$253	$248	$243	$238	$233	$229	$224	$219	$215
I3	IC	Med2	2024	$36	$36	$36	$36	$35	$35	$35	$35	$26
I4	IC	Med2	2024	$36	$36	$36	$36	$35	$35	$35	$35	$26
V6	IC	Med2	2024	$54	$54	$53	$53	$53	$53	$53	$53	$39
V8	IC	Med2	2024	$85	$85	$85	$84	$84	$84	$84	$83	$62
I3	TC			$142	$140	$138	$136	$134	$132	$130	$128	$117
I4	TC			$142	$140	$138	$136	$134	$132	$130	$128	$117
V6	TC			$214	$210	$207	$204	$201	$198	$195	$192	$175
V8	TC			$338	$333	$327	$322	$317	$312	$308	$303	$277

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

5.3.4.1.9 *GDI, Turbocharging, Downsizing*

The TDS24 and TDS27 configurations used by EPA within the FRM analysis were originally developed as part of engine and vehicle simulation work conducted by Ricardo, Inc. and SRA Corporation under contract with EPA, hereto referred in the Draft TAR as the "Ricardo Study."[530] In recent years, Ricardo has developed a number of turbocharged and downsized engine concepts with a number of characteristics in common.[531,532,533,534]

- Gasoline direct injection (GDI)
- Dual camshaft phasing and, in some cases, discrete variable valve lift

- Relatively high boost and subsequently high levels of BMEP (over 30-bar in some cases)
- Cooled, external EGR
- Advanced turbocharger boosting systems

Fuel mapping for different engine technologies was developed by Ricardo within the Study using a combination of dynamometer test results, 1D gas dynamics/0D combustion modeling, application of correction factors for displacement scaling, and use of engineering judgment. The development of fuel maps for turbocharged GDI engines within the Ricardo Study began with BSFC data obtained from Ricardo's EBDI engine development program.[531] Specifications for this engine are shown in Table 5.63 and a contour plot of BSFC versus engine speed and BMEP is shown in Figure 5.101.

Table 5.63 Specification of Ricardo 3.2L V6 Turbocharged, GDI "EBDI" Proof-of-concept Engine.

Base Engine	Prototype V6 with IEM
Swept Volume	3190cc
Max Power @ 5,000 rpm	450 hp on E85, 400 hp on 98 RON gasoline
Max Torque @ 3,000 rpm	900 Nm on E85, 775 Nm on 98 RON gasoline
Target Max BMEP	35 bar on E85, 30 bar on Indolene (98 RON)
Compression Ratio	10.0:1
Maximum Cylinder	180 bar
Cam Phaser Authority	50 degCA
Intake Boosting System	Twin, sequential turbochargers with charge air cooling after each boosting stage
Transient Torque Response Time	<1.5s to 90% SS torque at 1,500 rpm <1.0s to 90% SS torque at 2,000 rpm

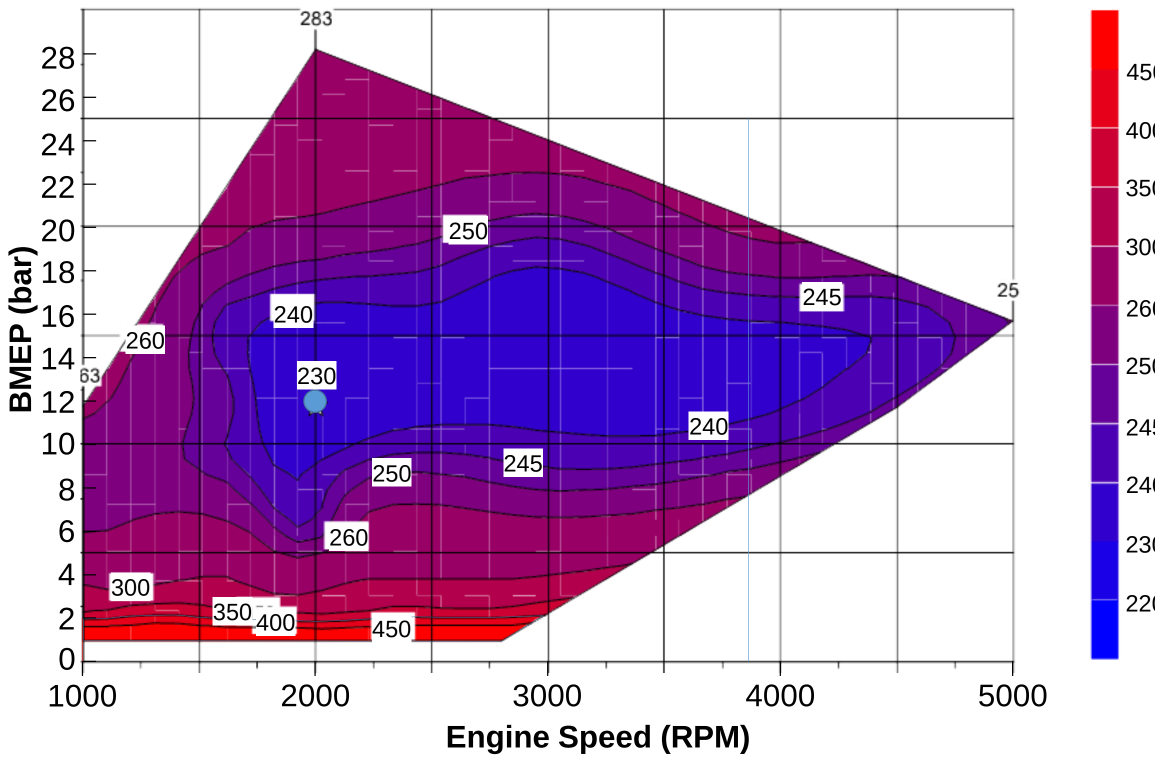


Figure 5.101 Contour plot of BSFC in g/kW-hr versus engine speed and BMEP for the Ricardo "EBDI" engine equipped with sequential turbocharging, DCP, DVVL, cEGR, IEM, and with a 10:1 compression ratio using 98 RON Indolene.

Although not captured within this map, Cruff et al. show performance data up to 30-bar BMEP with this engine configuration.

Technical direction from EPA included a peak BMEP limit of 27-bar, which obviated the necessity for some of the reciprocating assembly measures taken with the EBDI engine. Taking into account the capabilities of the combustion system, valvetrain configuration, EGR system, and reduced BMEP levels, Ricardo recommended a small increase in compression ratio (from 10:1 to 10.5:1) while maintaining protection for in-use fuel octanes of approximately 91 RON (e.g. 87 AKI E10). All fuel consumption results developed in the Ricardo Study assumed use of U.S. Certification Gasoline (95 RON, E0). A fuel consumption improvement of 3.5 percent was also applied to account for continued application of friction reduction from a combination of technology advances, including piston ring-pack improvements, bore finish improvements, low-friction coatings, improved valvetrain components, bearings improvements, and lower-viscosity crankcase lubricants. BMEP levels were held approximately constant for particular classes of engines within EPA's FRM analyses and analyses for the Draft TAR. A BSFC correction was applied as engine displacements were changed within an engine class in the Ricardo Study to account for different vehicle applications. This correction was predominantly a correction of thermal losses relative to combustion system surface-to-volume ratio and is expressed within the displacement correction shown in Figure 5.102. Boosting requirements over the reduced operational range for TDS24 (up to 24-bar BMEP) were assumed to be achievable using a VNT within EPA's analyses for the FRM and the Draft TAR. Sequential turbocharging was maintained for TDS27 within EPA analyses for the FRM, but TDS27 was not included within the analyses for the Draft TAR.

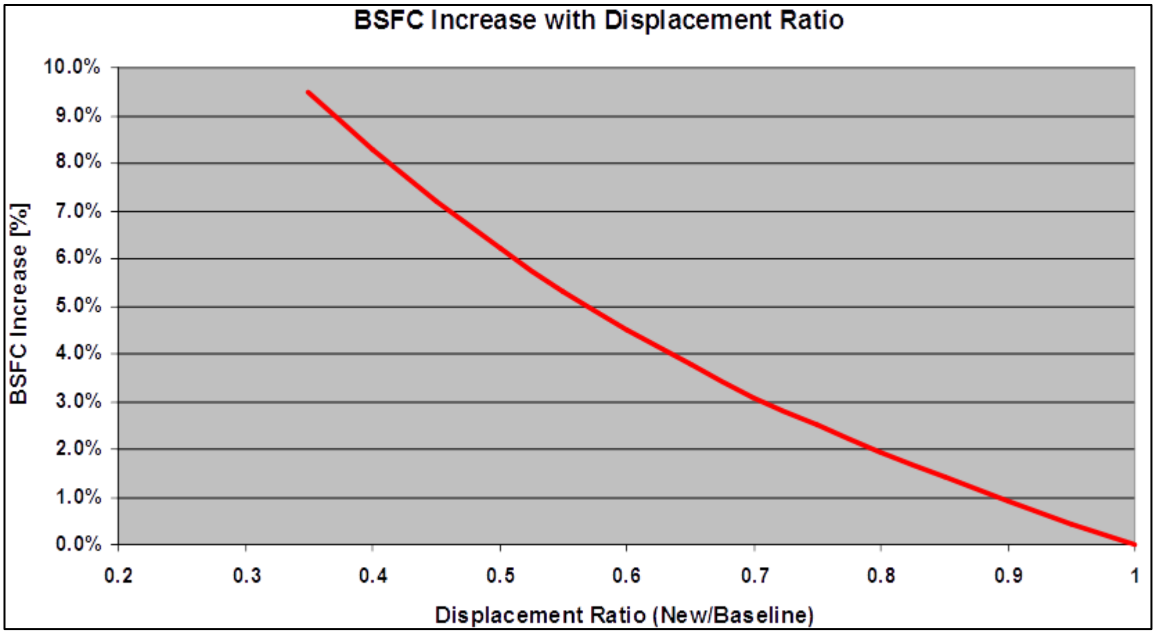


Figure 5.102 BSFC Multiplier Used For Scaling Engine Maps In The Ricardo Study Based On The Ratio:

$$\frac{Displacement_{[New]}}{Displacement_{[Baseline]}}$$

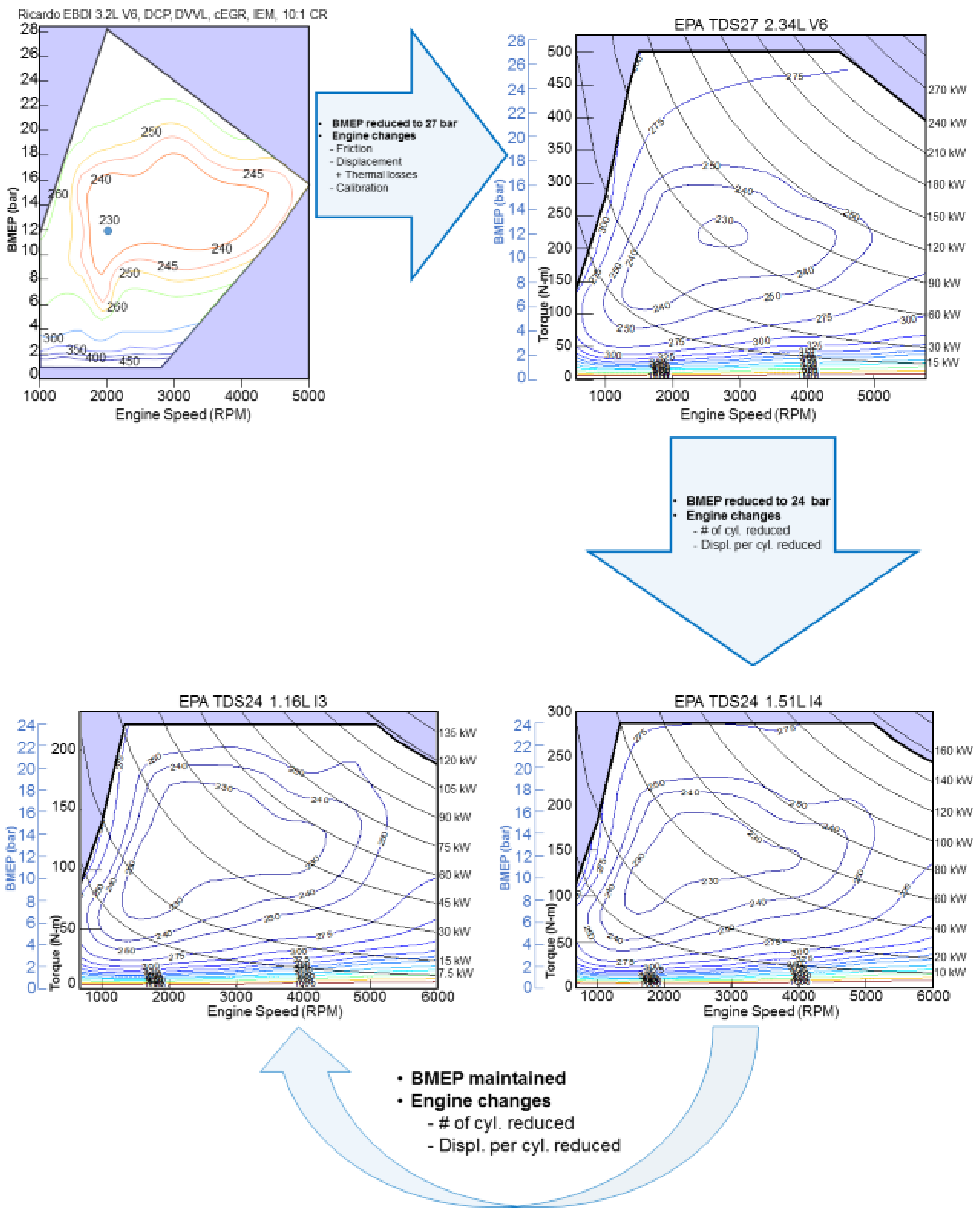


Figure 5.103 Schematic Representation of the Development of BSFC Mapping for TDS24

A graphical example of how BSFC maps were developed for varying displacements of TDS24 are shown in Figure 5.103. The brake thermal efficiency (BTE) of the modeled and corrected TDS24 engine maps are compared to contemporary turbocharged engines in Figure 5.104 through Figure 5.106.[535,536,537,538,539] The Honda 1.5L turbocharged GDI engine achieves higher peak break thermal efficiency than TDS24, and has a larger area of operation above 35 percent BTE. TDS24 had improved efficiency at low-speed, light load conditions, possibly from pumping loss improvements due to the use of discrete variable valve lift and cooled external EGR. The 2017 VW EA211 TSI EVO engine appears to have a broader area of operation above 34 percent BTE than TDS 24 and the BTE reported at 2-bar, 2000 rpm of 30 percent is higher than the corresponding operational point with TDS24. The coarseness of published BTE map for the VW EA211 precludes further comparison. The larger 2.0L VW EA888-3B engine was compared with a 1.51L variant of TDS24. The VW EA888 had a significantly larger area of operation above 35 percent BTE. Once again, TDS24 had improved efficiency at low-speed, light load conditions; possibly due to pumping loss reduction due to the greater extent of boosting and displacement downsizing and the use of discrete variable valve lift. On the whole, contemporary turbocharged engines can achieve higher peak BTE and high BTE over a broader range of engine operating conditions than TDS24 modeling results. TDS24 shows improved BTE at lower speeds and lighter loads. Further development of contemporary turbocharged engines from 2017 to 2022, including use of more advanced boosting systems (e.g., VNT or series sequential turbochargers), engine downsizing to 22-bar BMEP or greater, use of external cooled EGR, and use of variable valve lift systems would further improve low-speed, light load pumping losses and allow such engines to meet or exceed the BTE modeled for TDS24.

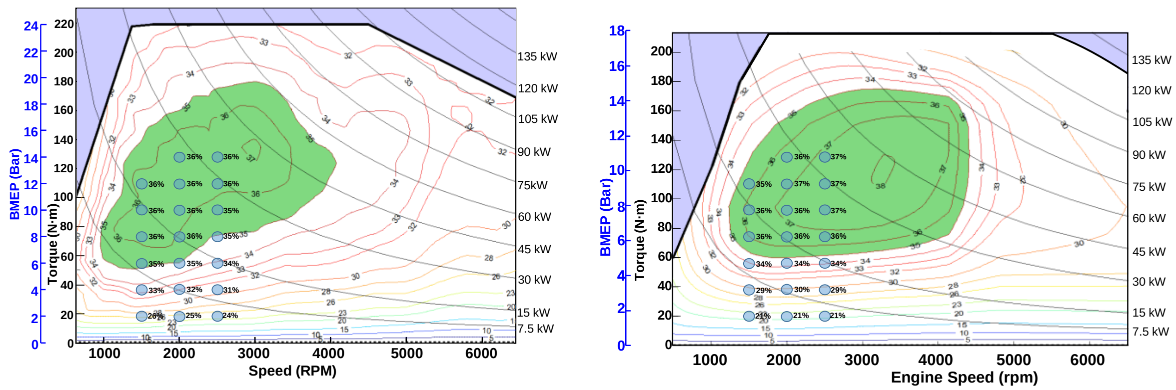


Figure 5.104 Comparison between a 1.15L I3 version of TDS24 (left)[VV] and the 1.5L turbocharged, GDI engine used in the 2017 Civic (right)[WW].

Dark green shading denotes areas of BTE>35%.

[VV] Adapted from Ricardo Study modeling results.
[WW] Adapted from Wada et al. 2016 and Nakano et al 2016.

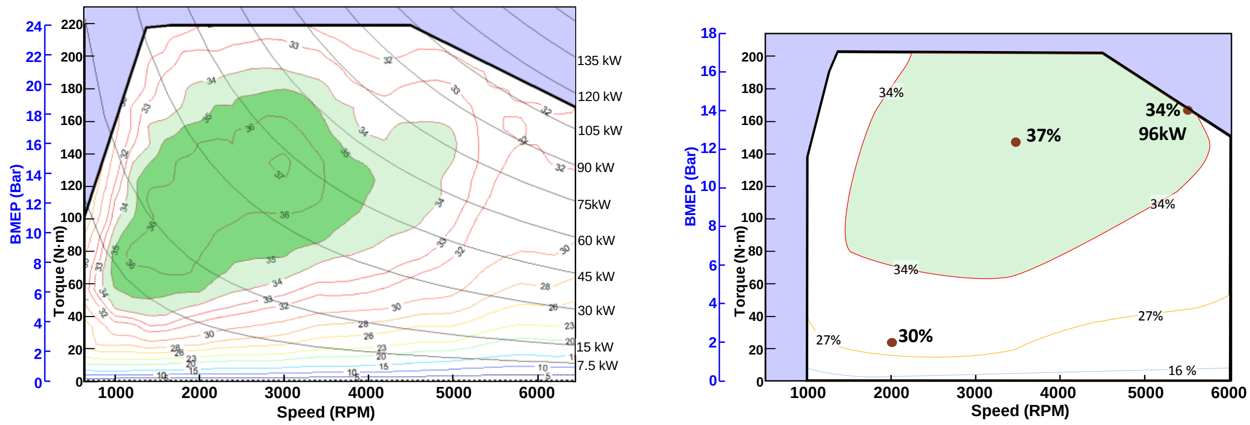


Figure 5.105 Comparison between a 1.15L I3 version of TDS24 (left)[XX] and the 2017 Golf 1.5L EA211 TSI EVO Engine[YY].

Light-green shading denotes areas of BTE>34%. Dark green shading denotes areas of BTE>35%. The area of BTE>35% for the VW EA211 is not discernable due to the coarseness of the data provided by the originally published source.

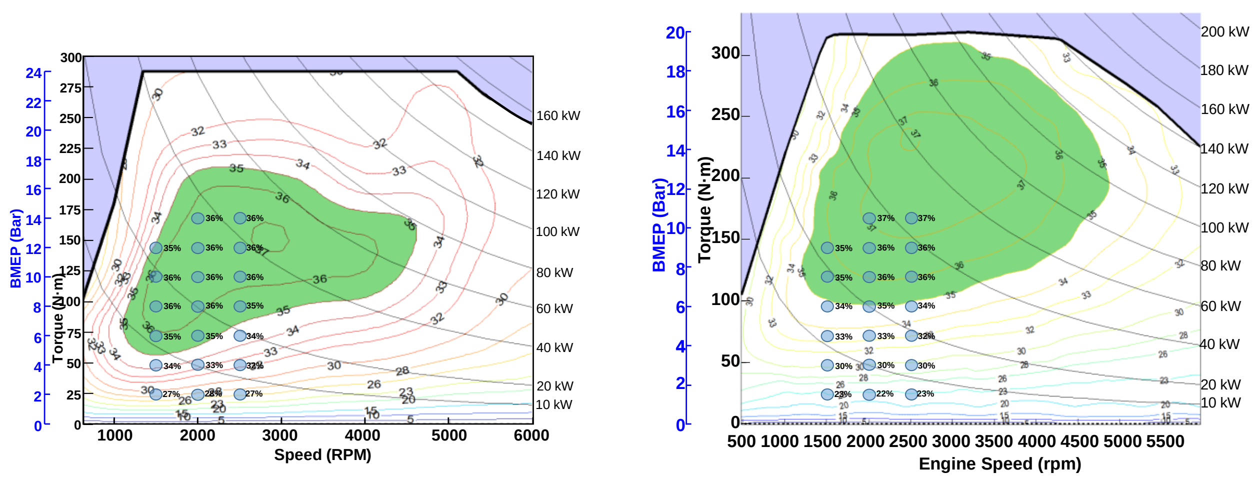


Figure 5.106 Comparison between a 1.51L I3 version of TDS24 (left)[XX] and the 2017 Audi A3 2.0L 888-3B Engine (right)[ZZ].

Dark green shading denotes areas of BTE>35%.

Since the FRM, a significant amount of new information has become available from production vehicles, industry data, benchmarking, and simulation to inform the effectiveness of engine technologies. The most notable changes from the FRM are the inclusion of non-hybrid Atkinson engines, Miller Cycle engines, and the reduction in effectiveness of turbocharged engines due to additional resolution in the ALPHA model. Table 5.64 compares the effectiveness (percent CO_2 improvement from the null vehicle) of several FRM and Draft TAR engine technology packages as used in OMEGA.

[XX] Adapted from Ricardo Study modeling results.
[YY] Adapted from Eichler et al. 2016.
[ZZ] Adapted from Wurms et al. 2015.

Table 5.64 FRM to Draft TAR Engine Technology Package Effectiveness Comparison

Engine Technology Package	Small Car FRM - TAR	Standard Car FRM - TAR	Large Car FRM - TAR	Small MPV FRM - TAR	Large MPV FRM - TAR	Truck FRM - TAR
PFI DOHC + VVT	4.1 - 4.1	5.2 - 5.2	5.5 - 5.5	4.1 - 4.1	5.1 - 5.1	4.9 - 4.9
SGDI DOHC + VVT	5.6 - 5.6	6.6 - 6.6	6.9 - 6.9	5.5 - 5.5	6.6 - 6.6	6.3 - 6.3
SGDI DOHC + VVT + DEAC + EFR1	10.5 - 9.9	12.8 - 12.1	13.5 - 12.7	10.4 - 9.8	12.8 - 12.0	12.1 - 11.4
18 Bar BMEP Turbo + SGDI	12.2 - 10.1	14.2 - 11.5	14.9 - 11.9	12.1 - 10.0	14.2 - 11.4	13.6 - 11.1
Atkinson + VVT + SGDI + EFR2	NA - 11.7	NA - 12.9	NA - 13.3	NA - 11.7	NA - 12.9	NA - 12.6
Atkinson + VVT + SGDI + CEGR + EFR2	NA - 19.3	NA - 19.4	NA - 19.5	NA - 19.3	NA - 19.4	NA - 19.4
24 Bar BMEP Turbo + SGDI + CEGR	19.4 - 17.2	22.1 - 19.1	23.0 - 19.7	19.3 - 17.1	22.1 - 19.1	21.3 - 18.6
Miller + SGDI + CEGR	NA - 23.0	NA - 23.3	NA - 23.4	NA - 23.0	NA - 23.3	NA - 23.2

Costs associated with gasoline direct injection are equivalent to those used in the FRM except for updates to 2013 dollars and use of a new learning curve (curve 23). The GDI costs incremental to port-fuel injection for I4, V6 and V8 engines are shown below.

Table 5.65 Costs for Gasoline Direct Injection on an I3 & I4 Engine (dollar values in 2013$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$234	23	$211	$208	$205	$202	$200	$197	$195	$193	$190
IC	Med2	2018	$89	$89	$67	$67	$67	$67	$66	$66	$66
TC			$301	$297	$272	$269	$266	$264	$261	$259	$257

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.66 Costs for Gasoline Direct Injection on a V6 Engine (dollar values in 2013$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$352	23	$319	$314	$309	$305	$301	$297	$293	$290	$287
IC	Med2	2018	$135	$135	$101	$101	$100	$100	$100	$100	$100
TC			$454	$448	$410	$405	$401	$397	$394	$390	$387

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.67 Costs for Gasoline Direct Injection on a V8 Engine (dollar values in 2013$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$423	23	$383	$377	$372	$367	$362	$357	$353	$349	$345
IC	Med2	2018	$162	$162	$121	$121	$121	$121	$120	$120	$120
TC			$545	$539	$493	$487	$482	$478	$473	$469	$465

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Costs associated with turbocharging are equivalent to those used in the FRM except for three important updates: (1) we have updated costs to 2013 dollars; and, (2) we are using of a new learning curve (curve 23); and, (3) we have added $44 (DMC, 2013$) to the costs of 24-bar turbocharging (and Miller cycle turbocharging) to reflect the use of a variable geometry turbocharger which was not properly accounted for in the 2012 FRM costs. The turbo costs incremental to naturally aspirated I-configuration and V-configuration engines are shown below.

Table 5.68 Costs for Turbocharging, 18/21 bar, I-Configuration Engine (dollar values in 2013$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$443	23	$401	$395	$389	$384	$379	$374	$369	$365	$361
IC	Med2	2018	$170	$169	$127	$126	$126	$126	$126	$126	$126
TC			$571	$564	$516	$510	$505	$500	$495	$491	$487

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.69 Costs for Turbocharging, 18/21 bar, V-Configuration Engine (dollar values in 2013$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$747	23	$676	$666	$656	$647	$638	$630	$623	$616	$609
IC	Med2	2018	$286	$286	$213	$213	$213	$213	$212	$212	$212
TC			$962	$951	$869	$860	$851	$843	$835	$828	$821

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.70 Costs for Turbocharging, 24 bar, I-Configuration Engine & for Miller-cycle I-Configuration Engine (dollar values in 2013$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$708	23	$641	$631	$622	$613	$605	$598	$591	$584	$578
IC	Med2	2024	$271	$271	$271	$270	$270	$269	$269	$269	$201
TC			$913	$902	$893	$884	$875	$867	$860	$853	$779

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.71 Costs for Turbocharging, 24 bar, V-Configuration Engine & for Miller-cycle V-Configuration Engine (dollar values in 2013$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$1,208	23	$1,094	$1,077	$1,061	$1,046	$1,032	$1,019	$1,007	$996	$985
IC	Med2	2024	$463	$462	$461	$461	$460	$459	$459	$458	$343
TC			$1,557	$1,539	$1,522	$1,507	$1,492	$1,479	$1,466	$1,454	$1,328

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Costs associated with engine downsizing are equivalent to those used in the FRM except for updates to 2013 dollars and use of new learning curves (curve 23 and 28). The downsizing costs incremental to the baseline engine configuration are shown below.

Table 5.72 Costs for Downsizing as part of Turbocharging & Downsizing (dollar values in 2013$)

Downsizing from & to	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
I4 DOHC to I3	DMC	-$212	23	-$192	-$189	-$186	-$183	-$181	-$179	-$176	-$174	-$173
I4 DOHC to I4	DMC	-$93	23	-$84	-$83	-$82	-$81	-$80	-$79	-$78	-$77	-$76
V6 DOHC to I4	DMC	-$600	23	-$543	-$535	-$527	-$520	-$513	-$506	-$500	-$495	-$489
V6 SOHC to I4	DMC	-$419	23	-$380	-$374	-$368	-$363	-$358	-$354	-$350	-$346	-$342
V6 OHV to I4	DMC	$296	28	$289	$283	$278	$273	$268	$264	$260	$256	$253
V8 DOHC to V6	DMC	-$300	23	-$272	-$268	-$264	-$260	-$257	-$253	-$250	-$248	-$245
V8 SOHC 3V to V6	DMC	-$170	23	-$154	-$152	-$150	-$147	-$145	-$144	-$142	-$140	-$139
V8 SOHC to V6	DMC	-$92	23	-$83	-$82	-$81	-$80	-$78	-$78	-$77	-$76	-$75
V8 OHV to V6	DMC	$345	28	$337	$330	$324	$318	$313	$308	$303	$299	$295
I4 DOHC to I3	IC	Med2	2018	$81	$81	$61	$60	$60	$60	$60	$60	$60
I4 DOHC to I4	IC	Med2	2018	$36	$36	$27	$27	$27	$27	$26	$26	$26
V6 DOHC to I4	IC	Med2	2018	$230	$229	$172	$171	$171	$171	$171	$171	$170
V6 SOHC to I4	IC	Med2	2018	$161	$160	$120	$120	$120	$119	$119	$119	$119
V6 OHV to I4	IC	Med2	2018	$114	$114	$85	$85	$85	$85	$85	$85	$84
V8 DOHC to V6	IC	Med2	2018	$115	$115	$86	$86	$86	$86	$85	$85	$85
V8 SOHC 3V to V6	IC	Med2	2018	$65	$65	$49	$49	$49	$49	$48	$48	$48
V8 SOHC to V6	IC	Med2	2018	$35	$35	$26	$26	$26	$26	$26	$26	$26
V8 OHV to V6	IC	Med2	2018	$133	$133	$99	$99	$99	$99	$99	$99	$99
I4 DOHC to I3	TC			-$111	-$108	-$125	-$123	-$120	-$118	-$116	-$114	-$112
I4 DOHC to I4	TC			-$49	-$47	-$55	-$54	-$53	-$52	-$51	-$50	-$49
V6 DOHC to I4	TC			-$313	-$305	-$355	-$348	-$342	-$335	-$330	-$324	-$319
V6 SOHC to I4	TC			-$219	-$213	-$248	-$243	-$239	-$234	-$230	-$226	-$223
V6 OHV to I4	TC			$404	$397	$363	$358	$353	$349	$345	$341	$337
V8 DOHC to V6	TC			-$157	-$153	-$178	-$174	-$171	-$168	-$165	-$162	-$160
V8 SOHC 3V to V6	TC			-$89	-$87	-$101	-$99	-$97	-$95	-$94	-$92	-$90
V8 SOHC to V6	TC			-$48	-$47	-$54	-$53	-$52	-$51	-$50	-$50	-$49
V8 OHV to V6	TC			$471	$463	$423	$417	$412	$407	$402	$398	$394

Note:
DMC=direct manufacturing costs; IC=indirect costs; TC=total costs;
the downsized configuration is always a DOHC.

Costs associated with turbocharging combined with engine downsizing (TDS) are similarly equivalent to those used in the FRM except for updates to 2013 dollars and use of new learning curves (curve 23 and 28). The TDS costs incremental to the baseline engine configuration are shown below. Note that the costs presented below do not include direct injection costs or other possible technologies such as cooled EGR. The costs presented are simply the combination of the above turbo costs and downsizing costs.

Table 5.73 Costs for Turbocharging & Downsizing (2013$)

Turbo	Downsize		2017	2018	2019	2020	2021	2022	2023	2024	2025
TURB18-I	I4 to I3	TC	$460	$457	$390	$387	$384	$382	$379	$377	$375
TURB18-I	I4 DOHC to I4	TC	$522	$517	$461	$456	$452	$448	$444	$441	$438
TURB18-I	V6 DOHC to I4	TC	$257	$259	$160	$162	$163	$165	$166	$167	$168
TURB18-I	V6 SOHC to I4	TC	$352	$351	$267	$267	$266	$266	$265	$265	$264
TURB18-I	V6 OHV to I4	TC	$974	$961	$878	$868	$858	$849	$840	$832	$824
TURB18-V	V8 DOHC to V6	TC	$805	$798	$691	$685	$680	$675	$670	$666	$661
TURB18-V	V8 SOHC 3V to V6	TC	$873	$864	$768	$761	$754	$748	$742	$736	$730
TURB18-V	V8 SOHC to V6	TC	$914	$904	$815	$806	$799	$791	$785	$778	$772
TURB18-V	V8 OHV to V6	TC	$1,433	$1,414	$1,292	$1,277	$1,263	$1,250	$1,237	$1,226	$1,215
TURB24-I	I4 to I3	TC	$802	$795	$767	$761	$755	$749	$744	$739	$666
TURB24-I	I4 DOHC to I4	TC	$864	$855	$838	$830	$822	$815	$809	$803	$729
TURB24-I	V6 DOHC to I4	TC	$599	$597	$537	$535	$534	$532	$530	$529	$460
TURB24-I	V6 SOHC to I4	TC	$694	$689	$644	$640	$636	$633	$630	$626	$556
TURB24-I	V6 OHV to I4	TC	$1,316	$1,300	$1,255	$1,241	$1,228	$1,216	$1,204	$1,194	$1,116
TURB24-V	V8 DOHC to V6	TC	$1,400	$1,386	$1,344	$1,332	$1,321	$1,311	$1,301	$1,292	$1,169
TURB24-V	V8 SOHC 3V to V6	TC	$1,468	$1,452	$1,421	$1,408	$1,395	$1,384	$1,373	$1,362	$1,238
TURB24-V	V8 SOHC to V6	TC	$1,509	$1,492	$1,468	$1,453	$1,440	$1,427	$1,416	$1,405	$1,279
TURB24-V	V8 OHV to V6	TC	$2,027	$2,002	$1,945	$1,924	$1,904	$1,886	$1,868	$1,852	$1,722

Note: TC=total costs; the downsized configuration is always a DOHC.

Costs associated with turbocharging combined with Atkinson-2 technology (i.e., Miller-cycle) are presented below. Note that the costs presented below do not include direct injection costs or other required technologies such as cooled EGR. The costs presented are simply the combination of the above turbo costs and Atkinson-2 costs presented in Section 5.3.4.1.8. Note also that the ATK2 engine as shown in the table is always a DOHC configuration engine so also not included in the table are the costs associated with converting, for example, a SOHC or OHV engine to a DOHC configuration. Those costs are presented below following the cooled EGR costs.

Table 5.74 Costs for Miller Cycle (2013$)

Turbo	ATK2 engine		2017	2018	2019	2020	2021	2022	2023	2024	2025
TURB24-I	I3	TC	$1,055	$1,043	$1,031	$1,019	$1,009	$999	$990	$981	$896
TURB24-I	I4	TC	$1,055	$1,043	$1,031	$1,019	$1,009	$999	$990	$981	$896
TURB24-V	V6	TC	$1,770	$1,749	$1,729	$1,710	$1,693	$1,676	$1,661	$1,646	$1,504
TURB24-V	V8	TC	$1,894	$1,871	$1,849	$1,829	$1,810	$1,791	$1,774	$1,757	$1,606

Note: TC=total costs; the downsized configuration is always a DOHC.

Costs associated with cooled EGR are equivalent to those used in the FRM except for updates to 2013 dollars and use of new learning curve (curve 23). The cooled EGR costs incremental to the baseline engine configuration are shown below.

Table 5.75 Costs for Cooled EGR (dollar values in 2013$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$258	23	$233	$230	$226	$223	$220	$217	$215	$212	$210
IC	Med2	2024	$99	$98	$98	$98	$98	$98	$98	$98	$73
TC			$332	$328	$325	$321	$318	$315	$313	$310	$283

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Costs associated with converting non-DOHC engines to a DOHC configuration without any engine downsizing are equivalent to those used in the 2012 FRM except for updates to 2013$ and use of new learning curves (curves 23 and 28). These costs are used when converting a non-DOHC engine to a DOHC configuration when downsizing is not also included. The primary example for this Draft TAR analysis is converting to a DOHC configuration to enable Atkinson-

2 technology. The costs are presented below and do not include other potential technologies such as variable valve timing or lift or cylinder deactivation, all of which are accounted for separately by EPA.

Table 5.76 Costs for Valvetrain Conversions from non-DOHC to DOHC (dollar values in 2013$)

Conversion	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
V6 SOHC to V6 DOHC	DMC	$181	23	$164	$161	$159	$157	$154	$153	$151	$149	$147
V6 OHV to V6 DOHC	DMC	$518	28	$506	$496	$486	$477	$469	$462	$455	$449	$443
V8 SOHC 3V to V8 DOHC	DMC	$130	23	$118	$116	$114	$113	$111	$110	$108	$107	$106
V8 SOHC to V8 DOHC	DMC	$208	23	$189	$186	$183	$181	$178	$176	$174	$172	$170
V8 OHV to V8 DOHC	DMC	$568	28	$554	$543	$532	$523	$514	$506	$498	$491	$485
V6 SOHC to V6 DOHC	IC	Med2	2018	$69	$69	$52	$52	$52	$52	$51	$51	$51
V6 OHV to V6 DOHC	IC	Med2	2018	$200	$200	$149	$149	$149	$148	$148	$148	$148
V8 SOHC 3V to V8 DOHC	IC	Med2	2018	$50	$50	$37	$37	$37	$37	$37	$37	$37
V8 SOHC to V8 DOHC	IC	Med2	2018	$80	$80	$60	$60	$59	$59	$59	$59	$59
V8 OHV to V8 DOHC	IC	Med2	2018	$219	$219	$163	$163	$163	$162	$162	$162	$162
V6 SOHC to V6 DOHC	TC			$233	$230	$210	$208	$206	$204	$202	$200	$199
V6 OHV to V6 DOHC	TC			$706	$695	$635	$626	$618	$610	$603	$597	$591
V8 SOHC 3V to V8 DOHC	TC			$168	$166	$151	$150	$148	$147	$145	$144	$143
V8 SOHC to V8 DOHC	TC			$269	$266	$243	$240	$238	$235	$233	$231	$229
V8 OHV to V8 DOHC	TC			$774	$761	$696	$686	$677	$668	$661	$653	$647

Note:
DMC=direct manufacturing costs; IC=indirect costs; TC=total costs;
the downsized configuration is always a DOHC.

5.3.4.2 Transmissions: Data and Assumptions for this Assessment

In assessing the effectiveness of transmission technology, EPA used multiple data sources. These data sources include benchmarking activities, conducted at both the National Vehicle and Fuel Emissions Lab (NVFEL) in Ann Arbor, Michigan and through contract work, technical literature, technical conferences, vehicle certification data and stakeholder meetings. To ensure the data were consistent, it was important to understand the assumptions made in determination of the effectiveness. It is also important to note the engine with which the transmission is being paired. Since much of the effectiveness associated with advanced transmissions is in the transmission's ability to alter the operation range of the engine, and thus minimize pumping losses, the engine efficiency in the area of operation is a major part of the effectiveness calculation. The National Academy of Science, in their 2015 report, noted that "as engines incorporate new technologies to improve fuel consumption, including variable valve timing and lift, direct injection, and turbocharging and downsizing, the benefits of increasing transmission ratios or switching to a CVT diminish."[540] This is not to say that transmissions are not an important technology going forward, but rather a recognition that future engines will have larger "islands" of low fuel consumption that potentially rely less on the transmission to improve the overall efficiency of the vehicle. Thus, effectiveness percentages reported for transmissions paired with unimproved engines would be expected to be reduced when the same transmission is paired with a more advanced engine. Regardless of the engine with which a particular transmission is mated, it is expected that vehicle manufacturers and suppliers will continue to improve the overall efficiency of the transmission itself by reducing friction and parasitic losses.

This approach to effectiveness calculation is consistent with the approach used in the analysis contained in the FRM, and with EPA's lumped parameter model (LPM) in use during the rulemaking. For example, in the LPM, an advanced eight-speed AT (with optimized shift logic, TC lockup, and high efficiency gearbox level 1) on a standard car had an effectiveness of 13.4 percent when paired with a null engine. When paired with an improved PFI engine (with dual cam phasing and engine friction reduction), the same transmission had an effectiveness of 11.7 percent. With a more advanced GDI engine (adding GDI, low friction lubrication, and more engine friction reduction), the effectiveness was 11.1 percent. Finally, with a turbo-downsized engine with EGR, the transmission effectiveness was 8.6 percent. Table 5.77 puts this example in table form.

Table 5.77 Standard Car Effectiveness

Engine Level	Effectiveness for an Advanced Eight-Speed AT (with optimized shift logic, TC lockup, and high efficiency gearbox level 1)
Null	13.4
Improved PFI Engine (with dual cam phasing and engine friction reduction)	11.7
Advanced GDI Engine (adding GDI, low friction lubrication, and more engine friction reduction)	11.1
Turbo-Downsized Engine with EGR	8.6

5.3.4.2.1 Assessment of Automated Transmissions (AT, AMT, DCT, CVT)

For this Draft TAR, EPA is assessing the baseline fleet in the following manner (MY2014):

1) All manufacturers have incorporated some level of early torque converter lockup, as well as an appropriate level of advanced shift logic, into automatic transmissions with six speeds and above.

2) All manufacturers have incorporated some level gear of box efficiency improvements (called out in the FRM as "high efficiency gearbox" or HEG), and advanced shift logic (called out in the FRM as "advanced shift logic" or ASL) into automatic transmissions with six speeds and above.
3) All types of automated transmissions will improve between now and 2025 MY. EPA expects that similar gains in efficiency can be made, independent of the transmission type. Figure 5.107 shows that all three of the main transmission types moving across their respective paths toward their ultimate level of efficiency. The term "Flexibility" here is denotes how well the transmission can keep the engine on its optimal efficiency line.

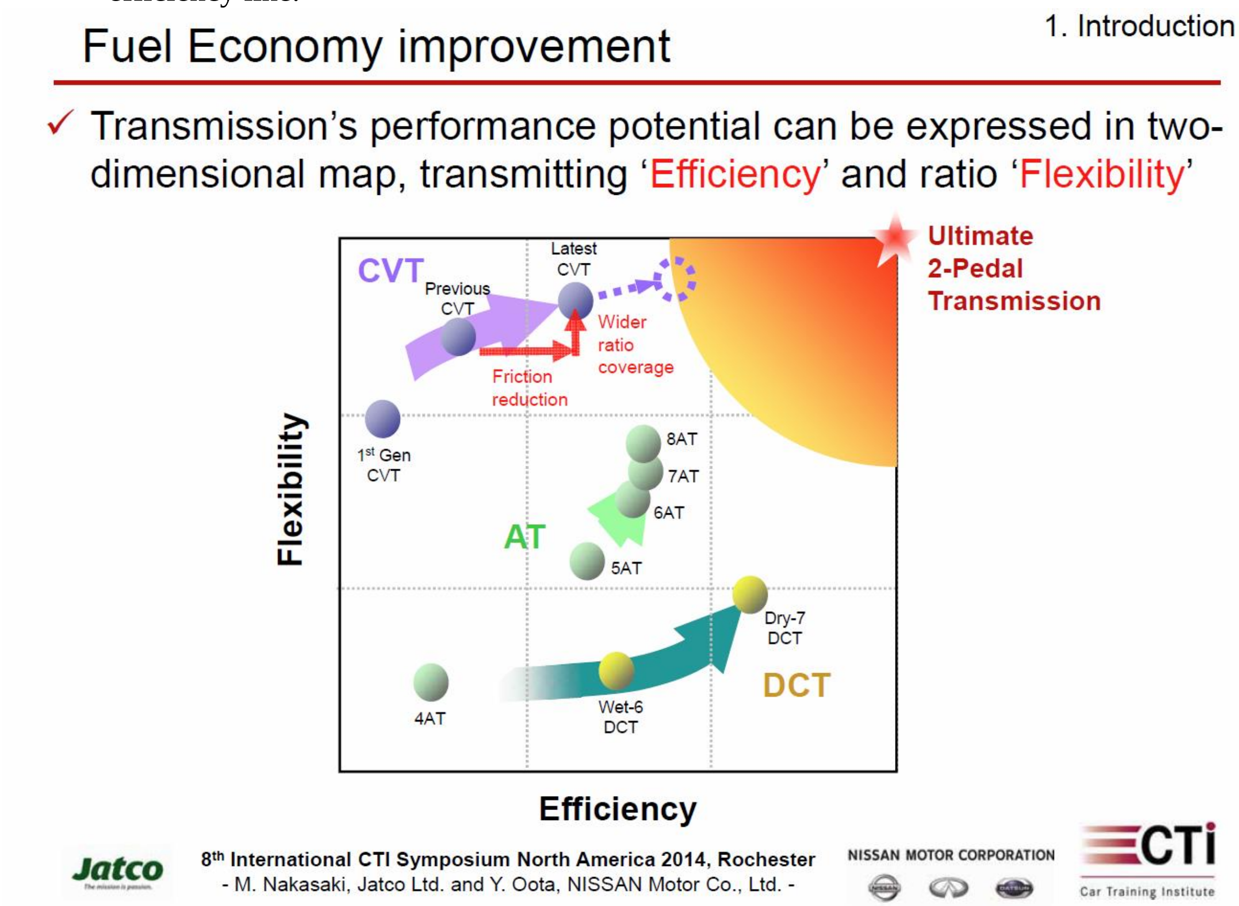


Figure 5.107 Comparison of the Different Transmission Types

4) The incremental effectiveness and cost for all automated transmissions are based on data from conventional automatics.

EPA does not believe that the technologies represented by HEG and ASL have been incorporated into all transmissions in the 2014 fleet, but are presumed included to be in both the base 6- speed and 8-speed transmission (higher-gear transmissions) in the 2014 fleet.

Under the premise that automated transmissions that are currently in the fleet demonstrate different effectiveness, and with the expectation that all automated transmissions will be improved between now and 2025 MY, 2014 transmissions were mapped to three different designations Null, TRX11 and TRX21. Table 5.78 shows the mapping between the existing transmissions in the 2014 baseline fleet and the transmission designations that have been established for this Draft TAR analysis. Note that manual transmission were left alone unless the vehicle was determined to need electrification in order to comply in which case it would be upgraded to either a hybrid or electric vehicle transmission. In the "TRX" numbering system the first digit specifies the number of gears in the transmission and the second digit specifies the HEG level. A "1" in the first digit represents an 8-speed transmission and a "2" in the first digit represents an 8-speed. Similarly, a "1" in the second digit represents HEG1 and a "2" in the second digit represents HEG2. An important aspect of using the TRX system is that it meant to estimate the effectiveness of both the current transmission technology and future transmission technology. This is appropriate because it allows EPA to account for technology already found in the baseline fleet, as well as apply future transmission technology as a means of improving vehicle efficiency. With the predominant transmission type in the 2014 MY baseline fleet (73.8 percent) being a conventional automatic transmission, EPA believes that this approach most closely approximates the overall incremental effectiveness and cost associated with all automated transmissions. In the future, if a particular transmission technology develops in such a way that it becomes more cost effective compared to our estimates, and it demonstrates the capability of meeting vehicle functional objectives, EPA expects that vehicle manufacturers may adopt that technology instead.

Table 5.78 Transmission Level Map

Trans code from Data	Transmission Type	Number of Gears	Transmission Level
A	Automatic	4	Null
A	Automatic	5	Null
A	Automatic	6	TRX11
A	Automatic	7	TRX21
A	Automatic	8	TRX21
A	Automatic	9	TRX21
AM	Automated Manual	5	Null
AM	Automated Manual	6	TRX11
AM	Automated Manual	7	TRX21
C	CVT	0	TRX11
D	Dual Clutch	6	TRX11
D	Dual Clutch	7	TRX21

The effectiveness associated with TRX11 is based on a benchmarked GM six-speed transmission from the 2013 Malibu[541]. The expectation is that transmission mapped to the TRX11 can still be improved to a level that that would bring the transmission effectiveness to the efficiency level of the TRX22 (with effectiveness based on a ZF 8 speed with HEG level 2). Table 5.79 shows the effectiveness of a TRX11 level transmission vs. the null transmission on the different vehicle types with a null engine. Table 5.79 also shows the effect of adding HEG level 2 to the GM 6 speed giving us TRX12.

Table 5.79 TRX11 and TRX12 Null Engine Effectiveness

Vehicle Type	Transmission Level	
	TRX11 (HEG1)	TRX12 (HEG2)
Small car	5.9	9.9
Standard car	7.3	11.9
Large car	7.5	11.9
Small MPV	6.1	10.6
Large MPV	7.1	11.3
Truck	5.5	9.4

The effectiveness of TRX21 is based on the benchmarked 845REeight-speed transmission (a ZF licensed FCA clone) from the 2014 Dodge Ram[542]. The expectation is that transmission mapped to the TRX21 can be improved to a level that that would bring the transmission effectiveness to the efficiency level of the TRX22 (ZF 8 speed with HEG level 2). Table 5.80 shows the effectiveness of a TRX21 level transmission vs. the null transmission on the different vehicle types with a null engine. Table 5.80 also shows TRX22 the effect of adding HEG level 2 to the ZF which was modeled using EPA's ALPHA model based on information in various SAE papers from ZF describing how they intend to create a future higher efficiency version of their current 8 speed transmission.

Table 5.80 TRX21 and TRX22 Null Engine Effectiveness

Vehicle Type	Transmission Level	
	TRX21 (HEG1)	TRX22 (HEG2)
Small car	11.5	14
Standard car	13.4	16.3
Large car	13.2	15.9
Small MPV	12.3	15.1
Large MPV	12.7	15.4
Truck	12.8	15.2

The aggregation of effectiveness values represents the best data available to EPA for the Draft TAR analysis. EPA plans on performing extensive CVT benchmarking and a cost tear-down in support of the Proposed Determination. EPA feels that these effectiveness values are appropriate since it allows a maximum of 9.7 percent improvement in effectiveness from a TRX11 to a TRX22. A 9.7 percent improvement in effectiveness is achievable given that most transmission can gain 6-10 percent from efficiency improvements alone, and designs for increased gear counts and wider ratio spans from 8-10 are expected.

Currently available CVT transmissions in the 2014 MY baseline fleet have been characterized as TRX11 level transmissions. However, a limitation was added to vehicles with CVT transmissions that prevented the transmissions from being improved to the TRX22 level.

Vehicles with CVTs can increase to TRX21 which is about a 6 percent effectiveness improvement. Most CVT transmissions are 85 percent efficient and are expected to be 90-94 percent efficient by 2025. They are also expected to have their ratio span increase from the current 6-7.3 to between 8 and 8.5.

Effectiveness for all transmission types will be evaluated after the Draft TAR as more data is available from the ALPHA model.

5.3.4.2.2 Technology Applicability and Costs

For future vehicles, it was assumed that the costs for transitioning from one technology level (TRX11-TRX22) to another level is the same for each transmission type (AT, AMT, DCT, and CVT). The costs used are based on AT transmission which make up 73.8 percent of transmissions in the 2014 fleet. This is a reasonable approach based on the costs used in the FRM for the different transmission types.

Transmission technology costs are presented in Table 5.81.

Table 5.81 Costs for Transmission Improvements for all Vehicles (dollar values in 2013$)

Tech	Cost type	DMC: base cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
TRX11	DMC	$39	23	$35	$35	$34	$34	$33	$33	$32	$32	$32
TRX12	DMC	$252	23	$228	$225	$222	$218	$216	$213	$210	$208	$206
TRX21	DMC	$171	23	$155	$152	$150	$148	$146	$144	$142	$141	$139
TRX22	DMC	$384	23	$348	$342	$337	$333	$328	$324	$320	$317	$313
TRX11	IC	Low2	2018	$17	$17	$14	$14	$13	$13	$13	$13	$13
TRX12	IC	Low2	2018	$111	$110	$89	$88	$88	$87	$87	$86	$86
TRX21	IC	Low2	2024	$75	$74	$74	$73	$73	$72	$72	$72	$58
TRX22	IC	Low2	2024	$169	$167	$166	$165	$164	$163	$162	$161	$131
TRX11	TC			$52	$52	$48	$47	$47	$46	$46	$45	$45
TRX12	TC			$339	$335	$310	$307	$303	$300	$297	$294	$291
TRX21	TC			$230	$227	$224	$221	$219	$217	$214	$212	$197
TRX22	TC			$516	$510	$504	$498	$492	$487	$483	$478	$444

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

As a comparison to how the Draft TAR transmission, or TRX, costs presented above would compare to the transmission costs EPA used in the FRM, see the table below. To construct this table, EPA has added various FRM transmission technologies (updated to 2013$) together on a year-over-year basis and presented them along with the conceptual intent behind the new TRX structure discussed above. Note that the FRM costs were presented in 2010$ and, importantly, EPA revised the FRM transmission costs in 2013 due to FEV-generated updates to the tear down costs used in the 2012 FRM.[543]The FRM costs presented in the table below reflect the updates made to the FRM costs by FEV. We present the updated values rather than the actual FRM values since the updated values, if they were being used in this Draft TAR analysis, are the values we would have used.

Table 5.82 Comparison of Transmission Costs Using the 2012 FRM Methodology to Draft TAR Costs for Transmissions (2013$)

Tech	Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025

6sp DCT-dry+ASL2+HEG1	TC	-$68	-$66	-$83	-$81	-$79	-$77	-$76	-$74	-$75
6sp DCT-wet+ASL2+HEG1	TC	-$29	-$28	-$39	-$38	-$37	-$36	-$35	-$35	-$35
6sp AT+ASL2+HEG1	TC	$24	$24	$23	$23	$22	$22	$22	$22	$20
TRX11	TC	$52	$52	$48	$47	$47	$46	$46	$45	$45
6sp DCT-dry+ASL2+HEG2	TC	$192	$190	$169	$167	$166	$164	$163	$162	$149
6sp DCT-wet+ASL2+HEG2	TC	$231	$228	$213	$210	$208	$206	$204	$202	$188
6sp AT+ASL2+HEG2	TC	$285	$280	$275	$271	$267	$264	$261	$258	$243
TRX12	TC	$339	$335	$310	$307	$303	$300	$297	$294	$291
8sp DCT-dry+ASL2+HEG1	TC	$89	$88	$87	$86	$85	$84	$83	$82	$76
8sp DCT-wet+ASL2+HEG1	TC	$185	$182	$180	$178	$176	$175	$173	$172	$158
8sp AT+ASL2+HEG1	TC	$120	$119	$111	$110	$108	$107	$106	$105	$103
TRX21	TC	$230	$227	$224	$221	$219	$217	$214	$212	$197
8sp DCT-dry+ASL2+HEG2	TC	$349	$344	$339	$334	$330	$326	$322	$319	$300
8sp DCT-wet+ASL2+HEG2	TC	$445	$438	$432	$426	$421	$416	$412	$408	$381
8sp AT+ASL2+HEG2	TC	$380	$374	$363	$358	$353	$349	$345	$341	$326
TRX22	TC	$516	$510	$504	$498	$492	$487	$483	$478	$444

5.3.4.3 Electrification: Data and Assumptions for this Assessment

As in the 2012 FRM analysis, this Draft TAR GHG assessment relies on estimates of cost and effectiveness of each GHG-reducing technology in order to project its expected role in fleet compliance with the standards. Electrification technologies represent a particularly broad range of cost and effectiveness, ranging from relatively low-cost technologies offering incremental degrees of effectiveness, such as stop-start and mild hybrids, to higher-cost, highly effective technologies such as plug-in hybrids and pure electric vehicles.

In this analysis, the costs associated with electrification are divided into battery and non-battery costs. The agencies' joint Section 5.2 reviewed industry developments in battery and non-battery technology since the 2012 FRM As anticipated in the FRM, many of these developments have resulted in cost reductions for both battery and non-battery components as the industry has gained in experience and production scale. For this Draft TAR analysis, EPA has reviewed its 2012 FRM projections of electrification costs for the 2022-2025 time frame, and revised them based on these developments.

Also as anticipated in the FRM, many of these developments have resulted in gradual improvements in effectiveness as the industry has continued to innovate and compete. EPA has therefore reviewed its FRM projections of electrification effectiveness for the 2022-2025 time frame, and have revised them based on these developments.

5.3.4.3.1 <u>Cost and Effectiveness for Non-hybrid Stop-Start</u>

For the 2012 FRM analysis, the agencies' primary reference for effectiveness of stop-start technology was the Ricardo simulation study. Based on this study the agencies estimated the on-cycle effectiveness of stop-start technology to be in the range of 1.8 to 2.4 percent, depending on vehicle class.

As reviewed in Section 5.2, several new implementations of stop-start have been produced, proposed or described in the literature since the 2012 FRM. These examples have provided a much broader picture of the potential effectiveness of stop-start technology. Based in part on these examples, EPA has chosen to update the effectiveness estimates for stop-start for use in this Draft TAR analysis to reflect an effectiveness of 3.0 to 4.0 percent depending on vehicle class, as shown in Table 5.83.

Table 5.83 GHG Technology Effectiveness of Stop-Start

Technology	Technology Effectiveness [%]						
	Small Car	Standard Car	Large Car	Small MPV	Large MPV	Small Truck	Large Truck
12V Stop-Start - 2012 FRM	*1.8*	*2.1*	*2.4*	*2.2*	*2.2*	*1.8*	*2.2*
12V Stop-Start - Draft TAR	**3.0**	**3.5**	**4.0**	**3.7**	**3.7**	**3.0**	**3.7**

We have assumed costs associated with stop-start equivalent to those used in the FRM except for updates to 2013 dollars and use of new learning curves (curve 25). The costs incremental to the baseline engine configuration for our different vehicle classes are shown below.

Table 5.84 Costs for Stop-Start for Different Vehicle Classes (dollar values in 2013$)

Tech	Cost type	DMC: base cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
Small car	DMC	$308	25	$260	$246	$235	$227	$219	$213	$208	$203	$198
Standard car	DMC	$308	25	$260	$246	$235	$227	$219	$213	$208	$203	$198
Large car	DMC	$349	25	$294	$279	$267	$257	$248	$241	$235	$230	$225
Small MPV	DMC	$349	25	$294	$279	$267	$257	$248	$241	$235	$230	$225
Large MPV	DMC	$349	25	$294	$279	$267	$257	$248	$241	$235	$230	$225
Truck	DMC	$383	25	$323	$306	$293	$282	$273	$265	$258	$252	$247
Small car	IC	Med2	2018	$117	$116	$87	$87	$86	$86	$86	$86	$86
Standard car	IC	Med2	2018	$117	$116	$87	$87	$86	$86	$86	$86	$86
Large car	IC	Med2	2018	$133	$132	$99	$98	$98	$98	$98	$97	$97
Small MPV	IC	Med2	2018	$133	$132	$99	$98	$98	$98	$98	$97	$97
Large MPV	IC	Med2	2018	$133	$132	$99	$98	$98	$98	$98	$97	$97
Truck	IC	Med2	2018	$146	$145	$108	$108	$107	$107	$107	$107	$107
Small car	TC			$377	$362	$322	$313	$306	$299	$294	$289	$284
Standard car	TC			$377	$362	$322	$313	$306	$299	$294	$289	$284
Large car	TC			$427	$411	$365	$355	$346	$339	$333	$327	$322
Small MPV	TC			$427	$411	$365	$355	$346	$339	$333	$327	$322
Large MPV	TC			$427	$411	$365	$355	$346	$339	$333	$327	$322
Truck	TC			$469	$451	$401	$389	$380	$372	$365	$359	$354

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.3.4.3.2 Cost and Effectiveness for Mild Hybrids

In the 2012 FRM analysis, the agencies based their cost and effectiveness estimates for mild hybrid technology on an analysis of BISG technology as exemplified by the General Motors eAssist. EPA sized the system using a 10 to 15 kW starter/generator and a 0.25 to 0.5 kWh Li-ion battery pack. The same effectiveness results were applied by both NHTSA and EPA. The absolute effectiveness for the CAFE analysis ranged from 8.5 to 11.6 percent depending on vehicle subclass. The effectiveness values include technologies that would be expected to be incorporated with BISG, which are stop-start (MHEV) and improved accessories (IACC1 and IACC2). The effectiveness values did not include electric power steering (EPS).

As reviewed in Section 5.2, several new implementations of mild hybrid technology have emerged since the 2012 FRM. These examples provide a much broader picture of the potential effectiveness of mild hybrid technology.

For this Draft TAR analysis, EPA has updated the assumed BISG configuration to include a 12 kW electric machine. The Lumped Parameter Model estimates that a BISG with 12 kW electric machine results in a GHG effectiveness estimate of 9.5 percent and 9.4 percent for small cars and standard (mid-size) cars, respectively. Based on this result as well as the examples discussed in Section 5.2, EPA has updated the GHG effectiveness of CISG P1 and TISG 48V P2 mild hybrids as shown in Table 5.85.

Table 5.85 GHG Technology Effectiveness of Mild Hybrids

Technology	Technology Effectiveness [%]						
	Small Car	Standard Car	Large Car	Small MPV	Large MPV	Small Truck	Large Truck
High voltage Mild Hybrid - 2012 FRM	*7.4*	*7.3*	*7.2*	*6.9*	*6.9*	*6.8*	*8.0*
12-15 kW BISG 48-120V Mild Hybrid - Draft TAR	**9.5**	**9.4**	**9.2**	**8.8**	**8.9**	**8.2**	**8.3**
20 kW CISG/TISG 48-120V Mild Hybrid - Draft TAR	**15.2**	**15.0**	**14.8**	**14.2**	**14.2**	**12.0**	**12.2**

For this Draft TAR analysis, EPA has updated the battery costs for high-voltage (non-48V) mild hybrids, as described in Section 5.3.4.3.7.2. Non-battery costs for high-voltage mild hybrids that were used in the 2012 FRM analysis have been retained for this analysis and updated to 2013$. In adding 48V mild hybrids to the analysis, new battery and non-battery costs were developed as discussed in Section 5.2.

5.3.4.3.3 Cost and Effectiveness for Strong Hybrids

In the 2012 FRM, P2 hybrid was the only hybrid architecture that was applied in the EPA analysis. Although PSHEV and 2MHEV technology were discussed because they were present in the market at the time of the FRM, they were not included in the analysis because the industry was expected to trend toward more cost-effective hybrid configurations such as P2.

The primary reference EPA used for strong hybrid effectiveness in the 2012 FRM was the Ricardo modeling study which modeled a P2 with a future DCT. On this basis EPA estimated an absolute CO_2 effectiveness for P2 strong hybrids ranging from 13.4 to 15.7 percent depending on vehicle class (see 2012 RIA, p. 1-18).

As reviewed in Section 5.2, several new production and research examples of strong hybrid technology have emerged since the 2012 FRM. These examples provide a much broader picture of the potential effectiveness of strong hybrid technology.

The ANL-VOLPE analysis found about 34.3 percent total GHG effectiveness (including other technologies present on the vehicle) for an input power-split HEV based on the 2010 Toyota

Prius with a 1.8L PFI Atkinson cycle engine and a combined electric motor-generator power of 77kW. The 34.3 percent GHG effectiveness estimate is comparable to the 33.3 percent GHG effectiveness of Toyota Camry power-split from the two-cycle combined results from certification test data when comparing the 2015 Toyota Camry HEV to the non-HEV, 4-cylinder version of the 2015 Camry. The ANL-VOLPE analysis also found approximately 32.6 percent GHG effectiveness for a P2 parallel hybrid with a 30 kW traction motor. The 32.6 percent GHG effectiveness of 30 kW P2 hybrid is comparable to 33.9 percent total GHG effectiveness of 2016 Hyundai Sonata P2 parallel hybrid calculated from a comparison of two-cycle combined certification test data between the 2016 Hyundai Sonata Hybrid with a 2.0L Atkinson cycle engine and a non-HEV 2015 Sonata with a 2.4L GDI engine. In the 2016 Hyundai Sonata P2 hybrid, a 38 kW traction motor and wet clutches are integrated into the transmission and replace the torque converter in a planetary gearset six-speed automatic transmission. A second, 10.5 kW high voltage Hybrid Starter Generator (HSG) BISG is incorporated for torque smoothing between the engine and the traction motor, automatic engine re-starting, and battery charging at idle in Hyundai Sonata hybrid.

Many aspects of hybrid technology effectiveness can be estimated by means of computational tools such as ANL-Autonomie, Gamma Technology GT-Power/GT-Suite, MSC EASY5, EPA-ALPHA and other vehicle models. A standalone hybrid vehicle model[544] was used to correlate recent ANL chassis dynamometer test data and 2010 Toyota Prius power-split hybrid and 2011 Hyundai Sonata P2 parallel hybrid model simulations over U.S. regulatory driving cycles. The model was successfully validated using ANL test data within 5 percent of test cycle fuel economy.

EPA also calculated overall strong hybrid effectiveness by comparing the non-hybrid variants from the same vehicle manufacturers. For example, the 2015 2.5L I4 engine non-hybrid Camry was used to estimate the overall effectiveness of 2015 2.5L Camry hybrid. The use of a PFI Atkinson Cycle engine, improved aero-dynamics, and reduced tire rolling resistance technology effectiveness were applied within the Lumped Parameter Model (LPM) to better estimate the overall system effectiveness of strong hybrid electrification since the Camry Hybrid vehicle package includes these differences in addition to the power-split HEV system. Two-cycle fuel economy (MPG) data over the city and highway drive cycles were used to estimate the relative effectiveness improvement of the hybrid electric vehicles. Hybrid technology effectiveness can then be estimated by subtracting the LPM/NRC-estimated effectiveness of non-hybrid technologies present on the vehicle from the total effectiveness.

Hybrid technology effectiveness of input power-split hybrids and P2 parallel hybrids appear to be converging and this appears to be confirmed by the fuel economy achieved with the 2017 Hyundai IONIQ P2 hybrid with a highly hybrid-optimized 6 speed DCT transmission. Hence, the GHG effectiveness was updated to 20.1 percent for mid-size standard car strong hybrids compared to the 15.5 percent effectiveness used in the 2012 FRM, as shown in Table 5.86.

Table 5.86 GHG Technology Effectiveness of Strong Hybrids

Technology	Technology Effectiveness [%]						
	Small Car	Standard Car	Large Car	Small MPV	Large MPV	Small Truck	Large Truck
P2 Full Hybrid Drivetrain - 2012 FRM	*15.5*	*15.5*	*15.4*	*14.6*	*14.6*	*13.4*	*15.7*
Strong Hybrid - Draft TAR	**19.0**	**20.1**	**19.9**	**18.8**	**19.1**	**17.2**	**17.7**

For this Draft TAR analysis, EPA has updated the battery costs for strong hybrids, as described in Section 5.3.4.3.7.2. Non-battery costs for strong hybrids that were used in the 2012 FRM analysis have been retained for this analysis and updated to 2014$.

5.3.4.3.4 *Cost and Effectiveness for Plug-in Hybrids*

Plug-in hybrid electric vehicles (PHEVs) utilize two sources of energy, electricity and liquid fuel, which are accounted for differently according to the effectiveness accounting methods established in the 2012 FRM.

As discussed in the 2012 TSD that accompanied the FRM, the overall GHG effectiveness potential of PHEVs depends on many factors, the most important being the energy storage capacity designed into the battery pack, and the vehicle's ability to provide all electric range to the operator. Section 3.4.3.6.4 of the TSD detailed the methods by which EPA and NHTSA estimated PHEV effectiveness. According to the method used by EPA, which estimates effectiveness based on the SAE J1711 utility factor calculation, the AER, and the vehicle class, the assumed effectiveness for a PHEV20 would be approximately 58 percent GHG reduction for a midsize car and approximately 47 percent GHG reduction for a large truck.

The 2012 FRM established an incentive multiplier for compliance purposes for PHEVs sold in MYs 2017 through 2021. This multiplier approach means that each PHEV would count as more than one vehicle in the manufacturer’s compliance calculation. The multiplier value for PHEVs starts at 1.6 in MY2017 and phases down to a value of 1.3 in MY2021. There is no PHEV multiplier for MYs 2022-2025.

The 2012 FRM also set the tailpipe compliance value for the electricity portion of PHEV energy usage to 0 g/mi for MYs 2017-2021, with no limit on the quantity of vehicles eligible for 0 g/mi tailpipe emissions accounting. For MYs 2022-2025, 0 g/mi will only be allowed up to a per-company cumulative sales cap: 1) 600,000 vehicles for companies that sell 300,000 BEV/PHEV/FCVs in MYs 2019-2021; 2) 200,000 vehicles for all other manufacturers. For sales above these thresholds, manufacturers will be required to account for the net upstream GHG emissions for the electric portion of operation, using accounting methodologies set out in the FRM.

As with other electrified vehicles, costs for PHEVs are separated into battery and non-battery costs. EPA has updated these costs as described in Sections 5.3.4.3.6 and 5.3.4.3.7.

5.3.4.3.5 *Cost and Effectiveness for Electric Vehicles*

The 2012 FRM established an incentive multiplier for compliance purposes for BEVs sold in MYs 2017 through 2021. This multiplier approach means that each BEV counts as more than one vehicle in the manufacturer's compliance calculation. The multiplier value for BEVs starts at 2.0 in MY2017 and phases down to a value of 1.5 in MY2021. There is no BEV multiplier for MYs 2022-2025.

The 2012 FRM also set the tailpipe compliance value for the electricity usage of BEVs to 0 g/mi for MYs 2017-2021, with no limit on the quantity of vehicles eligible for 0 g/mi tailpipe emissions accounting. For MYs 2022-2025, 0 g/mi will only be allowed up to a per-company cumulative sales cap: 1) 600,000 vehicles for companies that sell 300,000 BEV/PHEV/FCVs in MYs 2019-2021; 2) 200,000 vehicles for all other manufacturers. For sales above these thresholds, manufacturers will be required to account for the net upstream GHG emissions for the electric portion of operation, using accounting methodologies set out in the FRM. In this Draft TAR analysis, the GHG effectiveness of BEVs is unchanged from that used in the FRM, which is 100 percent GHG reduction.

As with other electrified vehicles, costs for BEVs are separated into battery and non-battery costs. EPA has updated these costs as described in Sections 5.3.4.3.6 and 5.3.4.3.7.

5.3.4.3.6 *Cost of Non-Battery Components for xEVs*

At this time, EPA is continuing to use the 2012 FRM cost assumptions for non-battery components as a basis for draft OMEGA runs. Costs for electric motors are slightly modified by changes in motor sizing resulting from the revised battery sizing methodology described below, but are based on the underlying motor cost assumptions of the FRM.

The 2015 NAS report correctly noted that raw material costs for propulsion motors tends to be a stronger function of torque output than of power output, and recommended that the agencies scale motor costs on a torque basis. While EPA acknowledges the technical basis of this recommendation, practical considerations make it difficult to do so while remaining compatible with other aspects of the analysis that require motors to be characterized by power output. Accurately converting between a torque basis and a power basis would require a greater amount of information to be specified about the individual propulsion systems and drivelines of each of the modeled PHEVs, possibly limiting the applicability of the analysis to a narrower range of configurations than intended. Further, through additional research and through stakeholder meetings with OEMs, EPA has found that it is not unusual to encounter motor cost projections or targets being expressed in terms of power, such as dollars per kilowatt. The US DRIVE cost targets for electric motors published by the Department of Energy are also expressed in dollars per kilowatt. Finally, the cost of the power electronics that accompany a propulsion motor system are closely related to the power specification of the propulsion motor, and are also commonly projected or targeted as a function of power. For these reasons, EPA has chosen to continue to scale motor and power electronics costs in terms of power rather than torque.

Several possible sources for updated non-battery costs may become available after the June 2016 publication of this Draft TAR but prior to the proposed determination.

In May 2016, CARB commissioned a study on non-battery costs for strong HEVs and PHEVs.[545] Initial results from this study may become available in late 2016 and will be considered for future inclusion in the EPA non-battery cost model. EPA is also considering commissioning a teardown study of a BEV or PHEV through a contractor, with the goal of further quantifying non-battery costs for these vehicles.

EPA is also studying the possibility of using US DRIVE cost targets for motors and power electronics, based on information gained through stakeholder meetings that suggests that some OEMs may already be meeting or exceeding some of these targets, or are on track to do so within the time frame of the rule.

EPA has also reviewed many cost estimates by applying engineering judgement informed by ongoing survey of industry literature, announcements of new products, and discussions with OEMs and suppliers.

For this Draft TAR, EPA has continued to use the same non-battery costs as used in the 2012 FRM with two exceptions: costs have been updated to 2013$; and, MHEV48V non-battery costs are new since they were not considered in the 2012 FRM. All applicable non-battery costs are presented in the tables below, first in terms of cost curves as were presented in the 2012 FRM, and then for each vehicle class at various mass reduction levels.

Table 5.87 Linear Regressions of Strong & Plug-in Hybrid Non-Battery System Direct Manufacturing Costs vs Net Mass Reduction Applicable in MY2012 (2013$)

Vehicle Class	Strong HEV	PHEV20	PHEV40
Small car	-$277x+$1,766	-$426x+$2,122	-$852x+$2,597
Standard car	-$412x+$1,958	-$672x+$2,443	-$1,343x+$3,175
Large car	-$737x+$2,293	-$1,390x+$3,214	-$2,780x+$4,705
Small MPV	-$349x+$1,874	-$601x+$2,344	-$1,203x+$2,997
Large MPV	-$533x+$2,164	n/a	n/a
Truck	-$683x+$2,287	n/a	n/a

Note: “x” in the equations represents the net weight reduction as a percentage.

Table 5.88 Linear Regressions of Battery Electric Non-Battery System Direct Manufacturing Costs vs Net Mass Reduction Applicable in MY2016 (2013$)

Vehicle Class	EV75	EV100	EV200
Small car	-$978x+-$134	-$978x+-$134	-$978x+-$133
Standard car	-$1,542x+$526	-$1,542x+$526	-$1,542x+$527
Large car	-$3,190x+$1,365	-$3,190x+$1,365	-$3,190x+$1,366
Small MPV	-$1,381x+-$516	-$1,381x+-$516	-$1,381x+-$516
Large MPV	n/a	n/a	n/a
Truck	n/a	n/a	n/a

Note: “x” in the equations represents the net weight reduction as a percentage.

Table 5.89 Costs for MHEV48V Non-Battery Items (dollar values in 2013$)

Vehicle Class	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
All	DMC	$440	23	$398	$392	$386	$381	$376	$371	$367	$362	$359
All	IC	Med2	2018	$168	$168	$126	$126	$125	$125	$125	$125	$125
All	TC			$567	$560	$512	$506	$501	$496	$492	$487	$483

Note:
DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.90 Costs for Strong Hybrid Non-Battery Items (dollar values in 2013$)

Vehicle Class	WRtech	WRnet	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	10	5	DMC	$1,752	23	$1,587	$1,562	$1,539	$1,517	$1,497	$1,479	$1,461	$1,444	$1,429
SmCar	15	10	DMC	$1,738	23	$1,574	$1,549	$1,526	$1,505	$1,485	$1,467	$1,449	$1,433	$1,418
SmCar	20	15	DMC	$1,725	23	$1,561	$1,537	$1,514	$1,493	$1,474	$1,455	$1,438	$1,422	$1,406
StCar	10	5	DMC	$1,937	23	$1,754	$1,727	$1,701	$1,678	$1,655	$1,635	$1,615	$1,597	$1,580
StCar	15	10	DMC	$1,917	23	$1,736	$1,708	$1,683	$1,660	$1,638	$1,617	$1,598	$1,580	$1,563
StCar	20	15	DMC	$1,896	23	$1,717	$1,690	$1,665	$1,642	$1,620	$1,600	$1,581	$1,563	$1,546
LgCar	10	5	DMC	$2,257	23	$2,043	$2,011	$1,981	$1,954	$1,928	$1,904	$1,882	$1,860	$1,840
LgCar	15	10	DMC	$2,220	23	$2,010	$1,978	$1,949	$1,922	$1,897	$1,873	$1,851	$1,830	$1,810
LgCar	20	15	DMC	$2,183	23	$1,976	$1,945	$1,917	$1,890	$1,865	$1,842	$1,820	$1,799	$1,780
SmMPV	10	5	DMC	$1,857	23	$1,681	$1,655	$1,630	$1,608	$1,586	$1,567	$1,548	$1,530	$1,514
SmMPV	15	10	DMC	$1,839	23	$1,665	$1,639	$1,615	$1,592	$1,572	$1,552	$1,533	$1,516	$1,500
SmMPV	20	15	DMC	$1,822	23	$1,649	$1,624	$1,600	$1,577	$1,557	$1,537	$1,519	$1,502	$1,485
LgMPV	10	6	DMC	$2,132	23	$1,930	$1,900	$1,872	$1,846	$1,822	$1,799	$1,778	$1,757	$1,738
LgMPV	15	11	DMC	$2,105	23	$1,906	$1,876	$1,849	$1,823	$1,799	$1,777	$1,755	$1,735	$1,717
LgMPV	20	16	DMC	$2,079	23	$1,882	$1,853	$1,825	$1,800	$1,776	$1,754	$1,733	$1,714	$1,695
Truck	10	6	DMC	$2,246	23	$2,034	$2,002	$1,972	$1,945	$1,919	$1,895	$1,873	$1,852	$1,831
Truck	15	11	DMC	$2,212	23	$2,003	$1,971	$1,942	$1,915	$1,890	$1,866	$1,844	$1,823	$1,804
Truck	20	16	DMC	$2,178	23	$1,972	$1,941	$1,912	$1,886	$1,861	$1,838	$1,816	$1,795	$1,776
SmCar	10	5	IC	High1	2018	$977	$975	$598	$598	$597	$597	$596	$595	$595
SmCar	15	10	IC	High1	2018	$969	$968	$594	$593	$592	$592	$591	$591	$590
SmCar	20	15	IC	High1	2018	$961	$960	$589	$588	$588	$587	$587	$586	$586
StCar	10	5	IC	High1	2018	$1,080	$1,078	$662	$661	$660	$660	$659	$658	$658
StCar	15	10	IC	High1	2018	$1,069	$1,067	$655	$654	$653	$653	$652	$651	$651
StCar	20	15	IC	High1	2018	$1,057	$1,055	$648	$647	$646	$646	$645	$644	$644
LgCar	10	5	IC	High1	2018	$1,258	$1,256	$771	$770	$769	$768	$767	$767	$766
LgCar	15	10	IC	High1	2018	$1,237	$1,235	$758	$757	$756	$756	$755	$754	$754
LgCar	20	15	IC	High1	2018	$1,217	$1,215	$745	$745	$744	$743	$742	$742	$741
SmMPV	10	5	IC	High1	2018	$1,035	$1,033	$634	$633	$633	$632	$631	$631	$630
SmMPV	15	10	IC	High1	2018	$1,025	$1,024	$628	$627	$627	$626	$626	$625	$624
SmMPV	20	15	IC	High1	2018	$1,016	$1,014	$622	$621	$621	$620	$620	$619	$619
LgMPV	10	6	IC	High1	2018	$1,189	$1,187	$728	$727	$727	$726	$725	$724	$724
LgMPV	15	11	IC	High1	2018	$1,174	$1,172	$719	$718	$717	$717	$716	$715	$715
LgMPV	20	16	IC	High1	2018	$1,159	$1,157	$710	$709	$708	$708	$707	$706	$706
Truck	10	6	IC	High1	2018	$1,252	$1,250	$767	$766	$765	$765	$764	$763	$763
Truck	15	11	IC	High1	2018	$1,233	$1,231	$755	$755	$754	$753	$752	$752	$751
Truck	20	16	IC	High1	2018	$1,214	$1,212	$744	$743	$742	$741	$741	$740	$739
SmCar	10	5	TC			$2,563	$2,537	$2,137	$2,115	$2,094	$2,075	$2,057	$2,040	$2,024
SmCar	15	10	TC			$2,543	$2,517	$2,120	$2,098	$2,078	$2,059	$2,041	$2,024	$2,008
SmCar	20	15	TC			$2,523	$2,497	$2,103	$2,082	$2,061	$2,042	$2,024	$2,008	$1,992
StCar	10	5	TC			$2,834	$2,805	$2,363	$2,338	$2,316	$2,294	$2,274	$2,255	$2,238
StCar	15	10	TC			$2,804	$2,775	$2,338	$2,314	$2,291	$2,270	$2,250	$2,231	$2,214
StCar	20	15	TC			$2,774	$2,745	$2,313	$2,289	$2,266	$2,246	$2,226	$2,207	$2,190
LgCar	10	5	TC			$3,301	$3,267	$2,752	$2,724	$2,697	$2,672	$2,649	$2,627	$2,606
LgCar	15	10	TC			$3,247	$3,214	$2,707	$2,679	$2,653	$2,629	$2,606	$2,584	$2,564
LgCar	20	15	TC			$3,193	$3,160	$2,662	$2,635	$2,609	$2,585	$2,562	$2,541	$2,521
SmMPV	10	5	TC			$2,716	$2,688	$2,264	$2,241	$2,219	$2,199	$2,179	$2,161	$2,144
SmMPV	15	10	TC			$2,691	$2,663	$2,243	$2,220	$2,198	$2,178	$2,159	$2,141	$2,124
SmMPV	20	15	TC			$2,665	$2,637	$2,222	$2,199	$2,177	$2,157	$2,138	$2,121	$2,104
LgMPV	10	6	TC			$3,119	$3,087	$2,600	$2,573	$2,548	$2,525	$2,503	$2,482	$2,462
LgMPV	15	11	TC			$3,080	$3,048	$2,568	$2,541	$2,516	$2,493	$2,471	$2,451	$2,432

LgMPV	20	16	TC			$3,041	$3,009	$2,535	$2,509	$2,485	$2,462	$2,440	$2,420	$2,401
Truck	10	6	TC			$3,286	$3,252	$2,739	$2,711	$2,685	$2,660	$2,637	$2,615	$2,594
Truck	15	11	TC			$3,236	$3,202	$2,698	$2,670	$2,644	$2,620	$2,597	$2,575	$2,555
Truck	20	16	TC			$3,186	$3,153	$2,656	$2,629	$2,603	$2,579	$2,557	$2,535	$2,515

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.91 Costs for 20 Mile Plug-in Hybrid Non-Battery Items (dollar values in 2013$)

Vehicle Class	WRtech	WRnet	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	15	6	DMC	$2,097	23	$1,898	$1,869	$1,841	$1,815	$1,792	$1,769	$1,748	$1,728	$1,710
SmCar	20	11	DMC	$2,075	23	$1,879	$1,850	$1,822	$1,797	$1,773	$1,751	$1,730	$1,711	$1,692
StCar	15	6	DMC	$2,402	23	$2,175	$2,141	$2,109	$2,080	$2,053	$2,027	$2,003	$1,980	$1,959
StCar	20	11	DMC	$2,369	23	$2,145	$2,111	$2,080	$2,051	$2,024	$1,999	$1,975	$1,953	$1,931
LgCar	15	5	DMC	$3,145	23	$2,847	$2,803	$2,761	$2,723	$2,687	$2,654	$2,622	$2,592	$2,564
LgCar	20	10	DMC	$3,075	23	$2,784	$2,741	$2,700	$2,663	$2,628	$2,595	$2,564	$2,535	$2,508
SmMPV	15	6	DMC	$2,307	23	$2,089	$2,056	$2,026	$1,998	$1,972	$1,947	$1,924	$1,902	$1,882
SmMPV	20	11	DMC	$2,277	23	$2,062	$2,030	$2,000	$1,972	$1,946	$1,922	$1,899	$1,877	$1,857
LgMPV	15	4	DMC	$2,797	23	$2,533	$2,493	$2,456	$2,422	$2,390	$2,360	$2,332	$2,306	$2,281
LgMPV	20	9	DMC	$2,750	23	$2,490	$2,450	$2,414	$2,381	$2,349	$2,320	$2,293	$2,267	$2,242
Truck	15	6	DMC	$2,943	23	$2,664	$2,623	$2,584	$2,548	$2,514	$2,483	$2,454	$2,426	$2,400
Truck	20	11	DMC	$2,884	23	$2,611	$2,571	$2,533	$2,497	$2,465	$2,434	$2,405	$2,378	$2,352
SmCar	15	6	IC	High1	2018	$1,169	$1,167	$716	$715	$714	$714	$713	$712	$712
SmCar	20	11	IC	High1	2018	$1,157	$1,155	$709	$708	$707	$707	$706	$705	$705
StCar	15	6	IC	High1	2018	$1,339	$1,337	$820	$819	$819	$818	$817	$816	$816
StCar	20	11	IC	High1	2018	$1,321	$1,318	$809	$808	$807	$806	$806	$805	$804
LgCar	15	5	IC	High1	2018	$1,753	$1,750	$1,074	$1,073	$1,072	$1,071	$1,070	$1,069	$1,068
LgCar	20	10	IC	High1	2018	$1,714	$1,712	$1,050	$1,049	$1,048	$1,047	$1,046	$1,045	$1,044
SmMPV	15	6	IC	High1	2018	$1,286	$1,284	$788	$787	$786	$786	$785	$784	$783
SmMPV	20	11	IC	High1	2018	$1,270	$1,267	$778	$777	$776	$775	$775	$774	$773
LgMPV	15	4	IC	High1	2018	$1,559	$1,557	$955	$954	$953	$952	$951	$950	$950
LgMPV	20	9	IC	High1	2018	$1,533	$1,530	$939	$938	$937	$936	$935	$934	$934
Truck	15	6	IC	High1	2018	$1,640	$1,638	$1,005	$1,004	$1,003	$1,002	$1,001	$1,000	$999
Truck	20	11	IC	High1	2018	$1,608	$1,605	$985	$984	$983	$982	$981	$980	$979
SmCar	15	6	TC			$3,067	$3,035	$2,557	$2,531	$2,506	$2,483	$2,461	$2,441	$2,421
SmCar	20	11	TC			$3,036	$3,005	$2,531	$2,505	$2,481	$2,458	$2,436	$2,416	$2,397
StCar	15	6	TC			$3,514	$3,478	$2,930	$2,900	$2,871	$2,845	$2,820	$2,797	$2,775
StCar	20	11	TC			$3,465	$3,429	$2,889	$2,859	$2,831	$2,805	$2,781	$2,758	$2,736
LgCar	15	5	TC			$4,600	$4,553	$3,835	$3,796	$3,759	$3,724	$3,692	$3,661	$3,632
LgCar	20	10	TC			$4,499	$4,452	$3,751	$3,712	$3,676	$3,642	$3,610	$3,580	$3,552
SmMPV	15	6	TC			$3,376	$3,341	$2,814	$2,785	$2,758	$2,733	$2,709	$2,686	$2,665
SmMPV	20	11	TC			$3,332	$3,297	$2,778	$2,749	$2,722	$2,697	$2,673	$2,651	$2,630
LgMPV	15	4	TC			$4,092	$4,050	$3,411	$3,376	$3,343	$3,312	$3,284	$3,256	$3,230
LgMPV	20	9	TC			$4,022	$3,981	$3,353	$3,319	$3,286	$3,256	$3,228	$3,201	$3,176
Truck	15	6	TC			$4,305	$4,260	$3,589	$3,552	$3,517	$3,485	$3,454	$3,426	$3,399
Truck	20	11	TC			$4,219	$4,176	$3,518	$3,481	$3,447	$3,416	$3,386	$3,358	$3,331

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.92 Costs for 40 Mile Plug-in Hybrid Non-Battery Items (dollar values in 2013$)

Vehicle Class	WRtech	WRnet	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	20	6	DMC	$2,546	23	$2,305	$2,269	$2,235	$2,204	$2,175	$2,148	$2,122	$2,098	$2,076
StCar	20	5	DMC	$3,108	23	$2,814	$2,770	$2,729	$2,691	$2,656	$2,623	$2,592	$2,562	$2,534
LgCar	20	3	DMC	$4,622	23	$4,185	$4,119	$4,058	$4,002	$3,949	$3,900	$3,854	$3,810	$3,769
SmMPV	20	7	DMC	$2,912	23	$2,637	$2,596	$2,557	$2,522	$2,489	$2,457	$2,428	$2,401	$2,375
LgMPV	20	0	DMC	$3,850	23	$3,486	$3,432	$3,381	$3,334	$3,290	$3,249	$3,210	$3,174	$3,140
Truck	20	5	DMC	$4,133	23	$3,742	$3,683	$3,629	$3,579	$3,532	$3,487	$3,446	$3,407	$3,370
SmCar	20	6	IC	High1	2018	$1,419	$1,417	$869	$868	$867	$867	$866	$865	$864
StCar	20	5	IC	High1	2018	$1,733	$1,730	$1,062	$1,060	$1,059	$1,058	$1,057	$1,056	$1,055
LgCar	20	3	IC	High1	2018	$2,577	$2,572	$1,578	$1,577	$1,575	$1,573	$1,572	$1,571	$1,569
SmMPV	20	7	IC	High1	2018	$1,624	$1,621	$995	$993	$992	$991	$991	$990	$989
LgMPV	20	0	IC	High1	2018	$2,147	$2,143	$1,315	$1,314	$1,312	$1,311	$1,310	$1,308	$1,307
Truck	20	5	IC	High1	2018	$2,304	$2,300	$1,411	$1,410	$1,408	$1,407	$1,406	$1,404	$1,403
SmCar	20	6	TC			$3,724	$3,685	$3,105	$3,073	$3,043	$3,015	$2,988	$2,963	$2,940
StCar	20	5	TC			$4,547	$4,500	$3,791	$3,752	$3,715	$3,681	$3,649	$3,618	$3,590
LgCar	20	3	TC			$6,761	$6,692	$5,637	$5,579	$5,524	$5,473	$5,426	$5,381	$5,338
SmMPV	20	7	TC			$4,261	$4,216	$3,552	$3,515	$3,481	$3,449	$3,419	$3,390	$3,364
LgMPV	20	0	TC			$5,633	$5,575	$4,696	$4,648	$4,602	$4,560	$4,520	$4,482	$4,447
Truck	20	5	TC			$6,046	$5,984	$5,041	$4,989	$4,940	$4,894	$4,852	$4,811	$4,773

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.93 Costs for 75 Mile BEV Non-Battery Items (dollar values in 2013$)

Vehicle Class	WRtech	WRnet	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	10	10	DMC	-$232	28	-$226	-$222	-$217	-$213	-$210	-$207	-$203	-$201	-$198
SmCar	15	15	DMC	-$281	28	-$274	-$268	-$263	-$258	-$254	-$250	-$246	-$243	-$240
SmCar	20	20	DMC	-$329	28	-$322	-$315	-$309	-$303	-$298	-$294	-$289	-$285	-$282
StCar	10	10	DMC	$371	28	$363	$355	$348	$342	$336	$331	$326	$322	$317
StCar	15	15	DMC	$294	28	$288	$282	$276	$271	$267	$262	$258	$255	$252
StCar	20	20	DMC	$217	28	$212	$208	$204	$200	$197	$194	$191	$188	$186
LgCar	10	10	DMC	$1,046	28	$1,022	$1,000	$981	$963	$947	$932	$918	$905	$894
LgCar	15	15	DMC	$886	28	$866	$848	$831	$816	$802	$790	$778	$767	$757
LgCar	20	20	DMC	$727	28	$710	$695	$681	$669	$658	$648	$638	$629	$621
SmMPV	10	10	DMC	-$654	28	-$639	-$626	-$614	-$603	-$593	-$583	-$575	-$567	-$559
SmMPV	15	15	DMC	-$723	28	-$707	-$692	-$678	-$666	-$655	-$645	-$635	-$626	-$618
SmMPV	20	20	DMC	-$792	28	-$774	-$758	-$743	-$730	-$718	-$706	-$696	-$686	-$677
LgMPV	10	5	DMC	$359	28	$351	$343	$337	$331	$325	$320	$315	$311	$307
LgMPV	15	10	DMC	$250	28	$244	$239	$234	$230	$226	$223	$219	$216	$213
LgMPV	20	15	DMC	$141	28	$137	$134	$132	$129	$127	$125	$123	$122	$120
Truck	10	10	DMC	-$653	28	-$638	-$624	-$612	-$601	-$591	-$582	-$573	-$565	-$558
Truck	15	15	DMC	-$787	28	-$769	-$753	-$738	-$725	-$713	-$701	-$691	-$682	-$673
Truck	20	20	DMC	-$921	28	-$900	-$881	-$864	-$848	-$834	-$821	-$809	-$798	-$787
SmCar	10	10	IC	High2	2024	$178	$178	$177	$177	$177	$177	$176	$176	$113
SmCar	15	15	IC	High2	2024	$216	$215	$215	$214	$214	$214	$214	$213	$137
SmCar	20	20	IC	High2	2024	$253	$253	$252	$252	$251	$251	$251	$250	$161
StCar	10	10	IC	High2	2024	$285	$285	$284	$284	$283	$283	$283	$282	$182
StCar	15	15	IC	High2	2024	$226	$226	$225	$225	$225	$224	$224	$224	$144
StCar	20	20	IC	High2	2024	$167	$167	$166	$166	$166	$166	$165	$165	$106
LgCar	10	10	IC	High2	2024	$803	$802	$800	$799	$798	$797	$796	$795	$512
LgCar	15	15	IC	High2	2024	$681	$680	$678	$677	$676	$675	$674	$674	$434
LgCar	20	20	IC	High2	2024	$558	$557	$556	$555	$555	$554	$553	$552	$356
SmMPV	10	10	IC	High2	2024	$503	$502	$501	$500	$499	$499	$498	$497	$320
SmMPV	15	15	IC	High2	2024	$556	$555	$554	$553	$552	$551	$551	$550	$354
SmMPV	20	20	IC	High2	2024	$609	$608	$607	$606	$605	$604	$603	$602	$388
LgMPV	10	5	IC	High2	2024	$276	$275	$275	$274	$274	$273	$273	$273	$176
LgMPV	15	10	IC	High2	2024	$192	$192	$191	$191	$191	$190	$190	$190	$122
LgMPV	20	15	IC	High2	2024	$108	$108	$108	$107	$107	$107	$107	$107	$69
Truck	10	10	IC	High2	2024	$502	$501	$500	$499	$498	$498	$497	$496	$320
Truck	15	15	IC	High2	2024	$605	$604	$602	$601	$601	$600	$599	$598	$385
Truck	20	20	IC	High2	2024	$708	$706	$705	$704	$703	$702	$701	$700	$451
SmCar	10	10	TC			-$48	-$44	-$40	-$36	-$33	-$30	-$27	-$24	-$85
SmCar	15	15	TC			-$59	-$53	-$48	-$44	-$40	-$36	-$33	-$30	-$102
SmCar	20	20	TC			-$69	-$62	-$57	-$52	-$47	-$43	-$39	-$35	-$120
StCar	10	10	TC			$648	$640	$633	$626	$620	$614	$609	$604	$499
StCar	15	15	TC			$514	$507	$501	$496	$491	$487	$483	$479	$396
StCar	20	20	TC			$379	$374	$370	$366	$363	$359	$356	$353	$292
LgCar	10	10	TC			$1,825	$1,802	$1,781	$1,762	$1,745	$1,729	$1,714	$1,700	$1,405
LgCar	15	15	TC			$1,547	$1,527	$1,509	$1,493	$1,479	$1,465	$1,453	$1,441	$1,191
LgCar	20	20	TC			$1,268	$1,252	$1,238	$1,225	$1,213	$1,201	$1,191	$1,182	$977
SmMPV	10	10	TC			-$136	-$124	-$113	-$103	-$93	-$85	-$77	-$69	-$239
SmMPV	15	15	TC			-$151	-$137	-$125	-$113	-$103	-$93	-$85	-$76	-$264
SmMPV	20	20	TC			-$165	-$150	-$137	-$124	-$113	-$102	-$93	-$84	-$289
LgMPV	10	5	TC			$626	$618	$611	$605	$599	$593	$588	$584	$482
LgMPV	15	10	TC			$436	$430	$425	$421	$417	$413	$409	$406	$336
LgMPV	20	15	TC			$245	$242	$239	$237	$235	$232	$230	$229	$189
Truck	10	10	TC			-$136	-$124	-$112	-$102	-$93	-$84	-$76	-$69	-$238
Truck	15	15	TC			-$164	-$149	-$136	-$123	-$112	-$102	-$92	-$83	-$287
Truck	20	20	TC			-$192	-$175	-$159	-$144	-$131	-$119	-$108	-$97	-$336

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.94 Costs for 100 Mile BEV Non-Battery Items (dollar values in 2013$)

Vehicle Class	WRtech	WRnet	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	10	8	DMC	-$212	28	-$207	-$203	-$199	-$195	-$192	-$189	-$186	-$184	-$181
SmCar	15	13	DMC	-$261	28	-$255	-$250	-$245	-$240	-$236	-$233	-$229	-$226	-$223
SmCar	20	18	DMC	-$310	28	-$303	-$296	-$291	-$285	-$281	-$276	-$272	-$268	-$265
StCar	10	7	DMC	$418	28	$408	$399	$392	$385	$378	$372	$367	$362	$357
StCar	15	12	DMC	$341	28	$333	$326	$319	$314	$308	$304	$299	$295	$291
StCar	20	17	DMC	$264	28	$257	$252	$247	$243	$239	$235	$231	$228	$225
LgCar	10	8	DMC	$1,110	28	$1,084	$1,061	$1,040	$1,022	$1,005	$989	$974	$961	$948
LgCar	15	13	DMC	$950	28	$928	$909	$891	$875	$860	$847	$834	$823	$812
LgCar	20	18	DMC	$791	28	$772	$756	$741	$728	$716	$705	$694	$685	$676
SmMPV	10	7	DMC	-$613	28	-$599	-$586	-$575	-$564	-$555	-$546	-$538	-$531	-$524
SmMPV	15	12	DMC	-$682	28	-$666	-$652	-$640	-$628	-$618	-$608	-$599	-$591	-$583
SmMPV	20	17	DMC	-$751	28	-$734	-$718	-$704	-$692	-$680	-$669	-$659	-$650	-$642
LgMPV	10	3	DMC	$403	28	$393	$385	$378	$371	$365	$359	$353	$349	$344
LgMPV	15	8	DMC	$293	28	$287	$281	$275	$270	$266	$261	$258	$254	$251
LgMPV	20	13	DMC	$184	28	$180	$176	$173	$170	$167	$164	$162	$160	$157
Truck	10	7	DMC	-$572	28	-$559	-$547	-$537	-$527	-$518	-$510	-$503	-$496	-$489
Truck	15	12	DMC	-$707	28	-$690	-$676	-$663	-$651	-$640	-$630	-$620	-$612	-$604
Truck	20	17	DMC	-$841	28	-$821	-$804	-$788	-$774	-$761	-$749	-$738	-$728	-$718
SmCar	10	8	IC	High2	2024	$163	$163	$162	$162	$162	$162	$161	$161	$104
SmCar	15	13	IC	High2	2024	$201	$200	$200	$199	$199	$199	$199	$198	$128
SmCar	20	18	IC	High2	2024	$238	$238	$237	$237	$236	$236	$236	$236	$152
StCar	10	7	IC	High2	2024	$321	$320	$320	$319	$319	$318	$318	$318	$204
StCar	15	12	IC	High2	2024	$262	$261	$261	$260	$260	$260	$259	$259	$167
StCar	20	17	IC	High2	2024	$202	$202	$202	$201	$201	$201	$201	$200	$129
LgCar	10	8	IC	High2	2024	$853	$851	$849	$848	$847	$846	$844	$843	$543
LgCar	15	13	IC	High2	2024	$730	$729	$727	$726	$725	$724	$723	$722	$465
LgCar	20	18	IC	High2	2024	$607	$606	$605	$604	$603	$602	$602	$601	$387
SmMPV	10	7	IC	High2	2024	$471	$470	$469	$468	$468	$467	$467	$466	$300
SmMPV	15	12	IC	High2	2024	$524	$523	$522	$521	$520	$520	$519	$518	$334
SmMPV	20	17	IC	High2	2024	$577	$576	$575	$574	$573	$572	$572	$571	$368
LgMPV	10	3	IC	High2	2024	$309	$309	$308	$308	$307	$307	$306	$306	$197
LgMPV	15	8	IC	High2	2024	$225	$225	$225	$224	$224	$224	$223	$223	$144
LgMPV	20	13	IC	High2	2024	$142	$141	$141	$141	$141	$140	$140	$140	$90
Truck	10	7	IC	High2	2024	$440	$439	$438	$437	$437	$436	$436	$435	$280
Truck	15	12	IC	High2	2024	$543	$542	$541	$540	$539	$538	$538	$537	$346
Truck	20	17	IC	High2	2024	$646	$645	$644	$643	$642	$641	$640	$639	$412
SmCar	10	8	TC			-$44	-$40	-$37	-$33	-$30	-$27	-$25	-$22	-$77
SmCar	15	13	TC			-$54	-$49	-$45	-$41	-$37	-$34	-$31	-$28	-$95
SmCar	20	18	TC			-$65	-$59	-$53	-$49	-$44	-$40	-$36	-$33	-$113
StCar	10	7	TC			$729	$720	$711	$704	$697	$691	$685	$679	$561
StCar	15	12	TC			$594	$587	$580	$574	$568	$563	$558	$554	$458
StCar	20	17	TC			$460	$454	$449	$444	$440	$436	$432	$429	$354
LgCar	10	8	TC			$1,936	$1,912	$1,890	$1,870	$1,851	$1,834	$1,819	$1,804	$1,491
LgCar	15	13	TC			$1,658	$1,637	$1,618	$1,601	$1,585	$1,571	$1,557	$1,545	$1,277
LgCar	20	18	TC			$1,380	$1,362	$1,346	$1,332	$1,319	$1,307	$1,296	$1,285	$1,062
SmMPV	10	7	TC			-$128	-$116	-$106	-$96	-$87	-$79	-$72	-$65	-$224
SmMPV	15	12	TC			-$142	-$129	-$118	-$107	-$97	-$88	-$80	-$72	-$249
SmMPV	20	17	TC			-$157	-$142	-$129	-$118	-$107	-$97	-$88	-$79	-$274
LgMPV	10	3	TC			$703	$694	$686	$678	$672	$666	$660	$655	$541
LgMPV	15	8	TC			$512	$506	$500	$494	$490	$485	$481	$477	$394
LgMPV	20	13	TC			$322	$317	$314	$310	$307	$305	$302	$300	$248
Truck	10	7	TC			-$119	-$108	-$99	-$90	-$81	-$74	-$67	-$61	-$209
Truck	15	12	TC			-$147	-$134	-$122	-$111	-$101	-$91	-$83	-$75	-$258
Truck	20	17	TC			-$175	-$159	-$145	-$132	-$120	-$109	-$98	-$89	-$307

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.95 Costs for 200 Mile BEV Non-Battery Items (dollar values in 2013$)

Vehicle Class	WRtech	WRnet	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	20	8	DMC	-$211	28	-$206	-$202	-$198	-$194	-$191	-$188	-$185	-$183	-$180
StCar	20	8	DMC	$403	28	$394	$386	$378	$371	$365	$359	$354	$349	$345
LgCar	20	10	DMC	$1,047	28	$1,023	$1,001	$982	$964	$948	$933	$920	$907	$895
SmMPV	20	8	DMC	-$626	28	-$612	-$599	-$587	-$577	-$567	-$558	-$550	-$542	-$535
LgMPV	20	4	DMC	$380	28	$372	$364	$357	$350	$344	$339	$334	$329	$325
Truck	20	8	DMC	-$597	28	-$583	-$571	-$560	-$550	-$540	-$532	-$524	-$517	-$510
SmCar	20	8	IC	High2	2024	$162	$162	$161	$161	$161	$161	$160	$160	$103
StCar	20	8	IC	High2	2024	$310	$309	$309	$308	$308	$307	$307	$307	$197
LgCar	20	10	IC	High2	2024	$805	$803	$802	$800	$799	$798	$797	$796	$513
SmMPV	20	8	IC	High2	2024	$481	$480	$479	$479	$478	$477	$477	$476	$307
LgMPV	20	4	IC	High2	2024	$292	$292	$291	$291	$290	$290	$289	$289	$186
Truck	20	8	IC	High2	2024	$459	$458	$457	$456	$455	$455	$454	$454	$292
SmCar	20	8	TC			-$44	-$40	-$36	-$33	-$30	-$27	-$25	-$22	-$77
StCar	20	8	TC			$704	$695	$687	$679	$673	$667	$661	$656	$542
LgCar	20	10	TC			$1,828	$1,804	$1,784	$1,765	$1,747	$1,731	$1,716	$1,703	$1,407
SmMPV	20	8	TC			-$131	-$119	-$108	-$98	-$89	-$81	-$73	-$66	-$229
LgMPV	20	4	TC			$664	$655	$648	$641	$635	$629	$623	$619	$511
Truck	20	8	TC			-$125	-$113	-$103	-$94	-$85	-$77	-$70	-$63	-$218

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.96 Costs for In-Home Charger Associated with 20 Mile Plug-in Hybrid (dollar values in 2013$)

Vehicle Class	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
All	DMC	$32	26	$52	$49	$46	$44	$42	$40	$39	$37	$36
All	IC	High1	2024	$19	$19	$19	$19	$19	$19	$19	$19	$11
All	TC			$72	$68	$65	$63	$61	$59	$57	$56	$47

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.97 Costs for In-Home Charger Associated with 40 Mile Plug-in Hybrid (dollar values in 2013$)

Vehicle Class	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	DMC	$169	26	$273	$256	$242	$231	$220	$211	$203	$196	$190
StCar	DMC	$197	26	$317	$298	$282	$268	$256	$246	$236	$228	$221
LgCar	DMC	$215	26	$347	$326	$308	$293	$280	$268	$258	$249	$241
SmMPV	DMC	$215	26	$347	$326	$308	$293	$280	$268	$258	$249	$241
LgMPV	DMC	$215	26	$347	$326	$308	$293	$280	$268	$258	$249	$241
Truck	DMC	$215	26	$347	$326	$308	$293	$280	$268	$258	$249	$241
SmCar	IC	High1	2024	$102	$101	$100	$99	$99	$98	$98	$97	$59
StCar	IC	High1	2024	$119	$117	$116	$116	$115	$114	$113	$113	$69
LgCar	IC	High1	2024	$130	$128	$127	$126	$125	$125	$124	$123	$75
SmMPV	IC	High1	2024	$130	$128	$127	$126	$125	$125	$124	$123	$75
LgMPV	IC	High1	2024	$130	$128	$127	$126	$125	$125	$124	$123	$75
Truck	IC	High1	2024	$130	$128	$127	$126	$125	$125	$124	$123	$75
SmCar	TC			$375	$357	$343	$330	$319	$310	$301	$294	$249
StCar	TC			$436	$415	$398	$383	$371	$360	$350	$341	$289
LgCar	TC			$477	$454	$435	$419	$405	$393	$382	$373	$316
SmMPV	TC			$477	$454	$435	$419	$405	$393	$382	$373	$316
LgMPV	TC			$477	$454	$435	$419	$405	$393	$382	$373	$316
Truck	TC			$477	$454	$435	$419	$405	$393	$382	$373	$316

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.98 Costs for In-Home Charger Associated with All BEVs (dollar values in 2013$)

Vehicle Class & Range	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
All	DMC	$215	26	$347	$326	$308	$293	$280	$268	$258	$249	$241
All	IC	High1	2024	$130	$128	$127	$126	$125	$125	$124	$123	$75
All	TC			$477	$454	$435	$419	$405	$393	$382	$373	$316

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.99 Costs for Labor Associated with All In-Home Chargers for Plug-in & BEV (dollar values in 2013$)

Vehicle Class & Range	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
All	DMC	$1075	1	$1,075	$1,075	$1,075	$1,075	$1,075	$1,075	$1,075	$1,075	$1,075
All	IC	None	n/a	$0	$0	$0	$0	$0	$0	$0	$0	$0
All	TC			$1,075	$1,075	$1,075	$1,075	$1,075	$1,075	$1,075	$1,075	$1,075

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.3.4.3.7 Cost of Batteries for xEVs

In order to develop cost estimates for electrified vehicles, it is necessary to determine the specifications of battery and non-battery components that can deliver the desired energy management, driving range and acceleration performance goals. Once known, their properties can then be input to a costing methodology to develop detailed projections of their cost.

Battery costs have many drivers, and future cost projections derived by any methodology are subject to significant uncertainties. The choice of costing methodology is therefore an important consideration. For costing of battery components, EPA uses BatPaC,[546] a peer-reviewed battery costing model developed by Argonne National Laboratory (ANL). As described later in Section 5.3.4.3.7.3, the ANL BatPaC model employs a rigorous, bottom-up, bill-of-materials approach to battery cost analysis, and has undergone continual development and review since the 2012 FRM.

BatPaC requires numerous input assumptions, including battery energy capacity, battery output power, and many other assumptions describing the chemistry, construction, and other aspects of the battery.

A first step in this process is the determination of battery energy capacity and battery output power. The following sections describe: (a) how EPA determined battery energy capacity and power for a population of modeled electrified vehicles; (b) how EPA selected other input assumptions to BatPaC that influence battery cost, and (c) how the inputs and assumptions that EPA employed in the FRM analysis were updated for this Draft TAR analysis. Source data for many of the charts in this section are available in the Docket.[547]

5.3.4.3.7.1 Battery Sizing Methodology for BEVs and PHEVs

This section discusses how EPA sized the batteries for BEVs and PHEVs (referred to collectively here as PEVs). For HEVs, EPA used a different methodology that is described in the next section.

Sizing a PEV battery pack primarily involves determining the necessary energy storage capacity (in kWh) and power capability (in kW) to provide a desired driving range and level of acceleration performance. Energy storage capacity has a strong influence on the weight of the pack as well as its overall cost because it determines the amount of active energy storage material that must be included in the battery. Power capability has an influence on weight and also has a strong influence on cost because it determines how the materials are arranged as well as the relative proportion of active materials to inactive materials in each cell.

Because most PEV battery chemistries are known to experience degradation in power and energy capacity over time (also known as power fade and capacity loss respectively), it is also important to consider how performance at end-of-life might differ from beginning-of-life, and consider the need for increasing the target capacity or power to ensure that performance goals can be met for the life of the vehicle.

The choice of battery energy capacity is primarily a function of the energy efficiency of the vehicle and the target driving range. Because range may decline over time due to battery degradation, this raises the question of whether the target range should be considered a beginning-of-life or end-of-life criterion. Current regulatory practice, as exemplified by the EPA labeling guidelines for PHEVs and BEVs,[548] measures range at beginning-of-life and omits any adjustment for future capacity degradation. For PHEVs, however, current regulatory practice for the EPA GHG standards effectively requires vehicle manufacturers to consider degradation in range as it will directly affect the calculated in-use emissions when tested for compliance at any time during full useful life.[AAA] Accordingly, for PHEVs, manufacturers typically use a combination of battery oversizing and an energy management strategy that provides for a consistent range throughout the useful life. For BEVs, however, rather than oversizing the battery sufficiently to maintain the original EPA range over time, manufacturers have tended to make the customer aware of the possibility of range loss and in some cases have warranted the battery to a specified degree of capacity retention over a specified period of time. For example, Nissan warrants their 24-kWh Leaf battery to retain nine of 12 capacity bars (corresponding to about 70 percent capacity) for 60 months or 60,000 miles, and warrants their 30-kWh battery for 96 months or 100,000 miles. As another example, Tesla does not warrant against a specific degree of capacity loss but makes it clear that some capacity loss is normal and provides the customer with recommendations for preserving battery capacity.

The choice of battery power capability is primarily governed by vehicle performance expectations. In the case of BEVs and many longer-range PHEVs, the battery is sufficiently large that its power capability is likely to naturally exceed that needed for acceleration performance alone. These batteries effectively have a power reserve that provides a natural buffer against power fade. Smaller batteries, such as those of shorter-range PHEVs, may lack this advantage and may need to be sized deliberately to meet a target power capability, in which

[AAA] As noted in Section 5.3.4.3.4, PHEV GHG emissions are calculated using the SAE J1711 utility factor and AER. Accordingly, if range degrades during useful life, the utility factor correction would change and thus, the calculated GHG emissions would increase. As EPA's GHG emission standards are full useful life standards and vehicles are considered noncompliant if their emissions exceed the certified emission level by more than 10 percent during the useful life, manufacturers must account for degradation or risk exceeding the GHG standards in-use.

case power fade should be factored in to the sizing process because it could lead to loss of performance and loss of utility factor over the life of the vehicle.

At the time of the 2012 FRM, the task of assigning battery capacity and power for the many PEV configurations to be analyzed was a very difficult task, with few well-developed techniques and tools available. Further, it was necessary to choose assumptions to reflect an expected state of technology in the 2020-2025 time frame, even though few production vehicles were available at the time to either serve as a reference for the current state of technology or to establish trends for its advancement. As described below, the EPA methodology therefore employed a wide variety of simplifying assumptions and estimation methods in order to conduct the effort in a practical way while using calculation tools that are easily accessible to external reviewers.

For the FRM analysis, EPA determined battery energy capacities and power capabilities for modeled PEVs using a spreadsheet-based sizing methodology that was described in Section 3.4.3.8.1 of the 2012 TSD. Because battery capacity and power requirements are strongly influenced by vehicle weight, and battery weight is a function of capacity and power while also being a large component of vehicle weight, sizing the battery for a BEV or PHEV requires an iterative solution. This problem is well suited to the iteration function available in common spreadsheet software. A spreadsheet-based methodology was therefore selected as being sufficiently powerful while remaining accessible to public inspection using standard commercially available software. EPA used Microsoft Excel for this purpose, with the Iteration setting enabled and set to 100 iterations.

This Draft TAR analysis is based on the same methodology, with significant refinements to reflect developments in the industry since the FRM and to improve the fidelity of the sizing estimates. The general methodology is reviewed below, followed by a review of the refinements.

EPA built a battery and motor sizing methodology to estimate the required battery capacity and power output capability for a large array of modeled PEVs. The array included five electrified vehicle types (EV75, EV100, EV200, PHEV20, and PHEV40), six baseline vehicle classes of different curb weights (Small Car, Standard Car, Large Car, Small MPV, Large MPV, and Truck); and five levels of target curb weight reduction (0, 2, 7.5, 10, and 20 percent). This resulted in a total of 150 PEV vehicle instances,BBB each characterized by a driving range, a baseline curb weight, and a level of target curb weight reduction, as shown in Figure 5.108. A sizing spreadsheet determined battery energy capacities and battery power requirements for each vehicle, in conjunction with ANL BatPaC which determined battery specific energy (kWh/kg) for use by the sizing spreadsheet, and ultimately a pack cost estimate. Pack cost, electric drive power ratings, and the necessary level of mass reduction applied to the glider (the baseline vehicle minus powertrain components) for each vehicle were then utilized by the OMEGA model.

[BBB] For each of the 150 vehicles, two battery cathode chemistries (NMC622 and blended LMO/NMC) and four production volumes (50K, 125K, 250K and 450K) were also considered, resulting in the generation of 1,200 individual battery cost estimates.

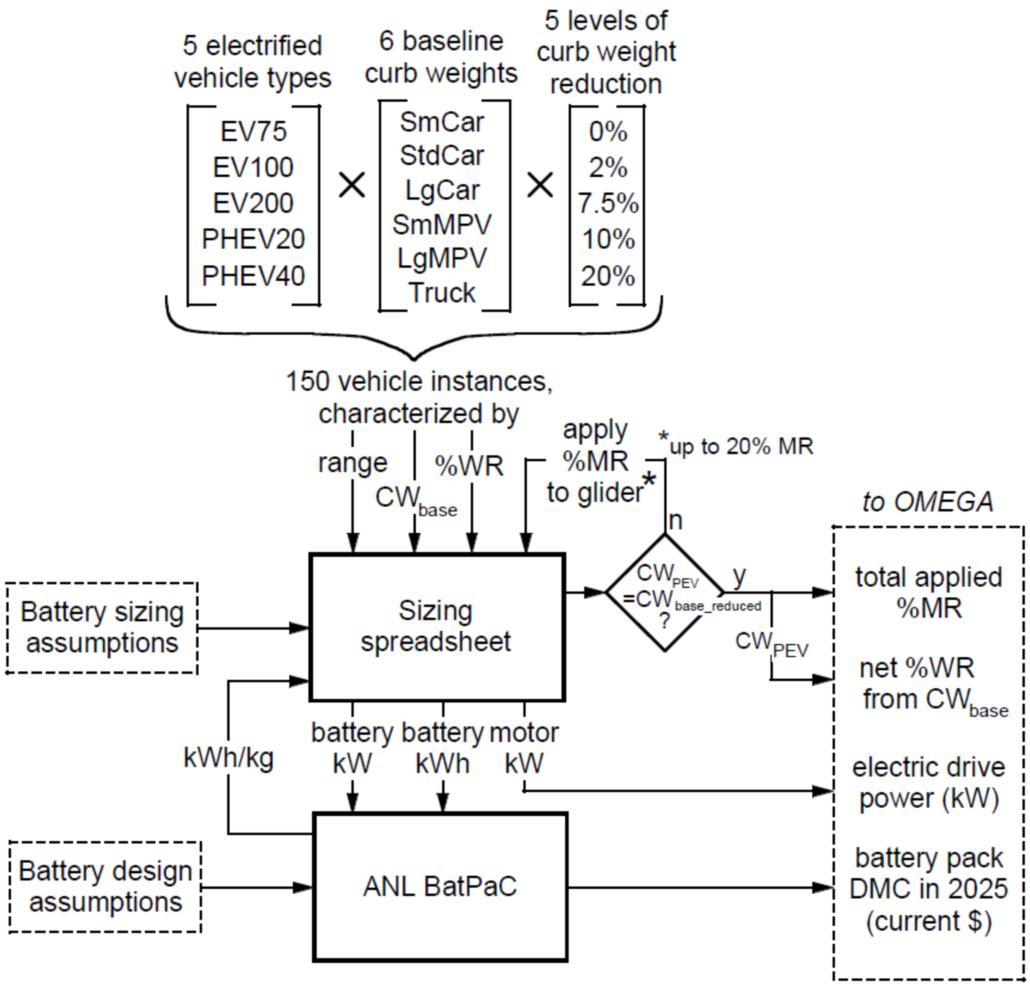


Figure 5.108 EPA PEV Battery and Motor Sizing Method

Method for Sizing of Battery Energy Capacity

Battery energy capacity was considered to be a function of desired driving range (mi) and vehicle energy consumption (Wh/mi).

Driving range was defined by the various range configurations (EV75, EV100, EV200, PHEV20, and PHEV40) and was considered to be an approximate real-world, EPA-label range. The 2012 FRM analysis considered PHEV range to be an all-electric range without assistance from the engine under any vehicle operating conditions, and therefore all PHEVs in that analysis were modeled with a range-extended electric vehicle (REEV) architecture rather than a blended-operation architecture. The Draft TAR analysis modifies this approach by adopting a blended configuration for PHEV20 but retaining REEV configuration for PHEV40.

Energy consumption had to be estimated by an appropriate method that took into account the weight of the battery necessary to deliver this range, and many other factors.

To estimate energy consumption for a given PEV instance, first its curb weight was estimated as equal to the curb weight CW_{base} of the corresponding baseline conventional vehicle, modified by any applicable curb weight reduction WR_{target} (2, 7.5, 10, or 20 percent), and further modified by subtraction of the weight of conventional powertrain components (for BEVs) and addition of the weight of electric content (for BEVs and PHEVs), as shown in Equation 2 through Equation 5.

Equation 2. Target curb weight reduction

$$WR_{target} = \%WR * CW_{base}$$

Equation 3. Weight-reduced curb weight

$$CW_{base\_reduced} = CW_{base} - WR_{target}$$

Equation 4. Raw curb weight of BEV

$$CW_{BEV} = CW_{base\_reduced} - W_{ICE\_powertrain} + W_{electric\_content}$$

Equation 5. Raw curb weight of PHEV

$$CW_{PHEV} = CW_{base\_reduced} + W_{electric\_content}$$

The curb weights CW_{base} of conventional baseline vehicles (detailed in Table 5.109 on page 5-331) were derived from the applicable MY baseline fleet (MY2008 in the FRM, updated to MY2014 in this Draft TAR analysis) for each vehicle class (Small Car, Standard Car, Large Car, Small MPV, Large MPV, and Truck).

The assumed weights of the removed conventional powertrain components ($W_{ICE\_powertrain}$) varied for the six vehicle classes and are shown in Table 5.100.

Table 5.100 Baseline ICE-Powertrain Weight Assumptions (Pounds), By Vehicle Class

Class	Engine	Transmission*	Fuel system*	Engine mounts*	Exhaust	12V battery	**Total**
Small car	250	125	50	25	20	25	**495**
Std car	300	150	60	25	25	30	**590**
Large car	375	175	70	25	30	35	**710**
Small MPV	300	150	60	25	25	30	**590**
Large MPV	400	200	80	25	30	40	**775**
Truck	550	200	100	25	40	50	**965**

Note:
*Transmission minus differential; fuel system 50% fill; engine mounts include NVH treatments.

Electric content weight ($W_{electric\_content}$) consisted of estimated battery weight and electric drive weight (motor and power electronics). Since the weight of this content is strongly influenced by total vehicle weight and many other variables, it is not a constant figure but is iteratively computed by the spreadsheet. The computation included estimates of battery specific energy and motor specific power applicable to the 2020 time frame. While the FRM used a fixed value for specific energy, this Draft TAR analysis utilizes a direct link to BatPaC to pull in dynamically updated values, as described later. For BEVs, a gearbox weight of 50 pounds was also added.

The "raw" curb weight calculations of Equation 4 and Equation 5, if used directly, would typically generate estimated PEV curb weights that are significantly larger than the curb weights of the baseline vehicles on which they are based, due to the added weight of the large battery which may weigh more than the removed components. For several reasons noted below, EPA chose to further constrain the iteration by forcing the projected curb weight (CW_{BEV} or CW_{PHEV}) of each PEV to match the curb weight ($CW_{base\_reduced}$) of the corresponding baseline vehicle. In order to achieve this objective, EPA solved for the exact percentage of mass reduction that would need to be applied to the glider in order to offset the difference in curb weight, and applied that level of mass reduction to cause the curb weights to match. In cases where more than 20 percent mass reduction technology would have been necessary to offset the difference, it was capped at 20 percent and only in these cases was the curb weight of the electrified vehicle allowed to vary.

In part, EPA chose to constrain the PEV curb weights in this way because it helps to differentiate between "applied" mass reduction and "net" curb weight reduction throughout the analysis. EPA differentiates between applied and net reduction because they are used in different ways in the analysis. Net curb weight reduction refers to a reduction in curb weight, and is used for estimating energy consumption. Applied mass reduction refers to percentage mass reduction applied to the glider, and is used for estimating the cost of mass reduction technology that has been embodied in the vehicle. Often, to achieve a given amount of net curb weight reduction, more mass reduction technology might need to be applied to electrified vehicles than to conventional vehicles because of the added weight of the electric content.

For example, the FRM analysis indicated that a typical EV150 battery pack and associated motors and other BEV-specific equipment may increase curb weight by roughly 18 percent. As a result, as shown in Table 5.101, an EV150 that applied 20 percent mass reduction technology to the glider would have a net curb weight reduction of only about 2 percent. In such a case, EPA would base the estimate of EV150 mass reduction technology costs on a 20 percent applied mass reduction, while basing the estimate of EV150 battery and motor costs on battery and motor sizings that are based on the energy and power requirements associated with only a 2 percent net curb weight reduction.

Table 5.101 Example Net Curb Weight Reduction for BEVs and PHEVs With 20% Applied Mass Reduction Technology

	EV75	EV100	EV150	PHEV20	PHEV40
Actual %MR vs. base vehicle: 2008 Baseline (FRM)					
Small car	19%	14%	2%	12%	7%
Standard car	18%	13%	2%	12%	7%
Large car	19%	13%	2%	12%	7%
Small MPV	18%	13%	1%	12%	7%
Large MPV	18%	13%	1%	12%	7%
Truck	19%	14%	3%	11%	6%

In theory, rather than constraining the PEV curb weights, a similar result could have been achieved by applying the various weight reduction cases directly to the glider and allowing the curb weights to grow as they might. This would have generated a different set of applied and net reduction data points, with more data points representing little or no applied mass reduction, higher curb weight, and higher energy consumption and larger batteries as a result. However, because the high cost of battery capacity tends to improve the cost effectiveness of mass reduction technology in PEV applications, EPA expects that manufacturers are likely to implement significant mass reduction in most PEVs, meaning that cases with little or no applied mass reduction are of limited interest to the analysis. The chosen method generates a greater density of points at the higher percentages of applied weight reduction that are most likely to represent industry practice.

After determining the PEV curb weight (which in most cases was constrained to match the baseline curb weight, but now carries a specific degree of applied mass reduction in order to do so), EPA then computed the loaded vehicle weight (also known as inertia weight or equivalent test weight (ETW)) by adding 300 pounds to the curb weight:

Equation 6. Equivalent test weight (ETW) of PEVs

$$\mathrm{ETW_{PEV}}(lb) = \mathrm{CW_{PEV}}(lb) + 300$$

EPA then used this test weight to develop an energy consumption estimate. First, EPA estimated the fuel economy (mi/gal) for a conventional light-duty vehicle (LDV) of that test weight by a regression formula derived from the relationship between 2-cycle fuel economy and inertia weight as described in the EPA Trends Report for MY2008 (from Table M-80 of the 2008 Trends Report). Figure 5.109 depicts fuel economy trendlines derived from this source for all LDVs, and also for cars and SUVs alone.

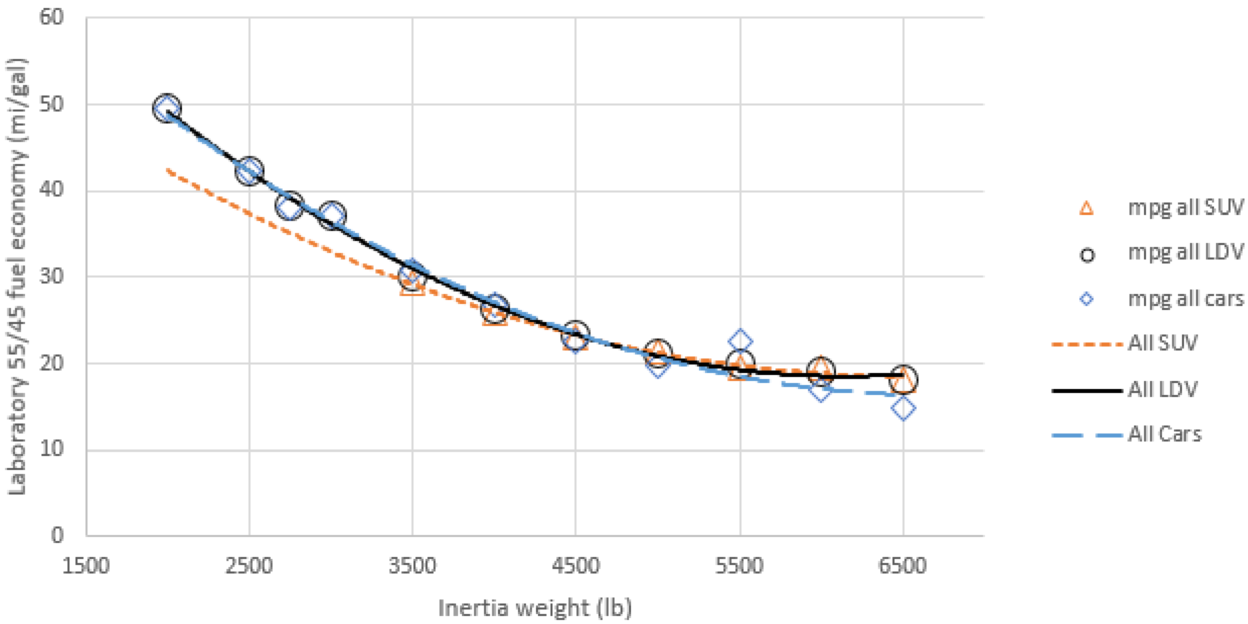


Figure 5.109 Average LDV Fuel Economy Based On Inertia Weight from MY2008 FE Trends Data

The MY2008 trendline was retained for this Draft TAR analysis because it represents the null technology case, relative to which improvements in road load technology such as aerodynamic drag and rolling resistance are accounted for. As will be discussed later, electrified vehicles are assumed to include a specific degree of aerodynamic drag and rolling resistance improvement relative to the 2008 baseline.

EPA used the All LDV fuel economy trendline (the solid black line) to characterize the relationship between ETW and fuel economy for this analysis. Because the LDV fuel economy trendline is derived from all MY2008 light-duty vehicles, it does not account for potential differences in aerodynamic drag coefficients and frontal areas among the various vehicle classes (for example, cars and MPVs, which are likely to have different frontal area and aerodynamic features). However, the All Cars trendline agrees well with the All LDV trendline, suggesting that use of the LDV trendline is accurate for the car classes within the range of weights modeled. Within the range of vehicle weights represented by MY2008 SUVs (3500 pounds and higher), the differences in fuel economy are also small, suggesting that the LDV trendline is also reasonably applicable to MPVs. EPA then derived a regression formula for the All LDV fuel economy trendline, which is shown in Equation 7.

Equation 7. MY2008 conventional LDV fuel economy regression formula

$$FE_{conv}(mi/gal) = 0.0000017894 \times \mathrm{ETW_{PEV}}^2 - 0.0219693 \times \mathrm{ETW_{PEV}} + 85.988$$

This was then converted to a gross Wh/mile figure, assuming 33,700 Wh of energy per gallon of gasoline as shown in Equation 8:

Equation 8. Gross energy consumption (Wh/mile)

$$E_{gross\_FTP}(Wh/mi) = (\frac{1}{FE_{conv}}) \times 33{,}700$$

This figure was then brought into electrified vehicle space by applying a series of adjustments representing assumed differences in energy losses between conventional vehicles and electrified vehicles. This required making assumptions for several powertrain efficiencies:

(a) Brake efficiency: For conventional vehicles, this is the percentage of chemical fuel energy converted to energy at the engine crankshaft. For electrified vehicles, it is the percentage of stored battery energy converted to shaft energy entering the transmission. It therefore includes battery discharge efficiency and inverter and motor efficiency.

(b) Driveline efficiency: the percentage of brake energy entering the transmission and delivered through the driveline to the wheels. It includes transmission efficiency and downstream losses (such as wheel bearing, axle, and brake drag losses), but not tire rolling resistance.

(c) Cycle efficiency: the percentage of energy delivered to the wheels that is used to overcome road loads in moving the vehicle (that is, the portion of wheel energy that is not later lost to friction braking). This efficiency is larger for vehicles with regenerative braking.

The efficiencies assumed for baseline conventional vehicles were based on efficiency terms derived from EPA's lumped parameter model. Brake efficiency for conventional vehicles was estimated at 24 percent, driveline efficiency at 81.3 percent, and cycle efficiency at 76.9 percent.

In the FRM, brake efficiency for BEVs was estimated at 85 percent (the result of assuming a roughly 95 percent efficiency for each of the battery (discharge), motor, and power electronics). Driveline efficiency was estimated at 93 percent (based on the value calculated by the lumped parameter model for an advanced 6-speed dual-clutch transmission). Cycle efficiency was estimated at 97 percent (representing regenerative braking recovering the bulk of braking energy rather than dissipating it in friction brakes). EPA has since revised some of these values for the current analysis as described later.

PEV road loads were also adjusted relative to conventional vehicles to represent assumed reductions in aerodynamic drag, rolling resistance, and vehicle weight applicable to these vehicles. All PEVs modeled for the 2012 FRM analysis were given a 10 percent reduction in both aerodynamic drag and rolling resistance, in addition to the varying levels of net and applied mass reduction. For example, in the case of an EV100 with a 20 percent mass reduction applied to the glider (resulting in about 15 percent net curb weight reduction) and an assumed 10 percent reduction in rolling resistance and aerodynamic drag, road loads (as calculated by the LP model) were reduced to about 87 to 88 percent of the baseline conventional vehicle.

The estimated energy consumption of each PEV is therefore derived from the energy consumption of a corresponding baseline conventional vehicle by applying a ratio of the road loads of the PEV ($\%Roadload_{PEV}$) to those of the baseline vehicle ($\%Roadload_{conv} = 1$) and a ratio of the assumed efficiencies of the respective powertrains, as shown in Equation 9.

Equation 9. PEV unadjusted energy consumption

$$E_{P/EV\_FTP}(Wh/mi) = E_{gross\_FTP} * \left(\frac{\%Roadload_{P/EV}}{\%Roadload_{conv}} * \frac{\eta_{vehicle\_conv}}{\eta_{vehicle\_P/EV}}\right)$$

Equation 9 yields a laboratory (unadjusted) two-cycle FTP energy consumption estimate. To represent a real-world energy consumption, the 2012 FRM analysis applied a derating factor of 70 percent to convert unadjusted fuel economy to real-world fuel economy. This is consistent with the EPA 5-cycle fuel economy labeling rule as well as the EPA range labeling rule, both of which specify a default derating factor for converting two-cycle figures to five-cycle figures. The EPA range labeling rule specifies a default derating factor of 70 percent, with provisions for using a different (custom) factor based on optional 5-cycle testing.

In energy consumption space, a 70 percent derating of fuel economy corresponds to a 43 percent increase in energy consumption (1/0.70). Applying this factor (as shown in Equation 10) results in the PEV on-road energy consumption estimate that EPA used to determine the required battery pack capacity for the vehicle.[CCC]

Equation 10. PEV on-road energy consumption

$$E_{onroad}(Wh/mi) = E_{P/EV\_FTP} * (\frac{1}{0.70})$$

Finally, as shown by

Equation 11, EPA determined the required battery energy capacity (BEC) as the on-road energy consumption in Wh/mile, multiplied by the desired range in miles, divided by the usable portion of the battery capacity, or usable SOC design window. The assumed usable SOC design window (*SOC%*) varied between BEVs and PHEVs and is discussed in a later section.

[CCC] As described later, this Draft TAR analysis uses a 70 percent factor for most PEVs but applies a custom derating factor of 80 percent for EV200 based on examples of recent industry practice.

$$BEC(Wh) = \frac{E_{onroad}(\frac{Wh}{mi}) \times range(mi)}{SOC\%}$$

Equation 11. Required battery pack energy capacity for PEVs

As mentioned previously, the intensively iterative nature of the battery capacity sizing problem means that all of the preceding calculations are constructed in a spreadsheet as circular references and performed iteratively by the spreadsheet software until the estimated weights, ranges, and energy consumption figures converge.

Method for Sizing of Battery Power Capability

Another input to the battery sizing process is the required power capability of the battery. Battery power capability was derived from an assigned peak motor power, which in turn was considered to be a function of desired acceleration performance.

In this analysis, PHEV40 was conceptualized as a range-extended electric vehicle, with a motor and battery sized to be capable of providing pure all-electric range in all driving situations, while PHEV20 was modeled as a blended-operation vehicle where the motor is often assisted by the engine during the charge depletion phase. This means that PHEV40 motor power ratings in this analysis are likely to be higher than would apply to a blended-operation PHEV40. PHEVs were configured with a single propulsion motor, in contrast to some production PHEV designs that split the total power rating between two motors. Most PHEVs also include a second electric machine used primarily as a generator. The analysis does not explicitly assign a weight to this component but considers it as part of the weight of the conventional portion of the powertrain, which retains its original weight despite the likelihood of downsizing in a PHEV application.

In the FRM analysis, acceleration performance was represented by the average power-to-weight ratio of conventional vehicles in each vehicle class. This meant that once the curb weight for a PEV was estimated, a simple linear calculation determined the peak motor power needed to meet the target power-to-weight ratio. The battery power was then estimated as 15 percent greater than the peak motor power, to account for losses in the motor. As with battery capacity, motor and battery power both interact with battery and vehicle weight, and the calculation must be performed iteratively in the spreadsheet as part of the overall battery sizing process.

In preparation for this Draft TAR analysis, EPA studied trends in PEV motor sizing in production vehicles and used this information to improve the method for determining the assigned peak motor power as a function of acceleration performance goals. Other assumptions were also revised. These improvements, along with those affecting capacity sizing, are described below.

Improvements to Battery Sizing Assumptions and Methodology

Since the 2012 FRM, the emergence of a variety of production PEVs has provided an opportunity to validate the assumptions and methods of the 2012 FRM analysis. Further, the industry appears to have begun proceeding toward stabilizing certain variables of PEV design that help to constrain the battery sizing problem. As a result, EPA has significantly updated and refined the methods and input assumptions for assigning battery capacity, battery power, motor power, and other aspects of the PEV modeling problem. The major changes include:

(a) improvements to weight estimation for non-battery components;

(b) improvements to weight estimation for battery packs;

(c) improvements to the assignment of electric drive motor power;

(d) updated curb weights, representing a 2014 baseline;

(e) increase in usable battery capacity for BEVs and some PHEVs;

(f) an increase in the assumed electric drive efficiency;

(g) an increase in the battery power rating for PHEVs;

(h) an increase in battery power to compensate for battery power degradation;

(i) an increase in applied aerodynamic drag and rolling resistance reduction;

(j) a change in range derating factor for EV200; and

(k) a change in PHEV20 motor sizing to represent a blended PHEV configuration.

These changes are described in detail in the following subsections (a) through (k).

(a) Improved weight estimation for non-battery components

At the time of the 2012 FRM, little data was available to characterize the weight of PEV non-battery components (propulsion motor, power electronics, and cabling) due to the limited number of PEV models being produced. Weight of non-battery components was therefore estimated in the 2012 FRM analysis as a function of total battery capacity, on the expectation that larger vehicles with larger battery packs would generally require larger non-battery components. The FRM analysis thus estimated the combined weight of electric content (battery and non-battery components together) by assuming an overall specific energy of 120 Wh/kg, assessed on total battery capacity. This figure embodied an assumed battery specific energy of 150 Wh/kg combined with nominal estimates for the weight of non-battery content as suggested by teardown data and other sources.

Ideally, the weight of electric power components would more properly be estimated by means of a specific power metric (such as kW/kg) applicable to the component in question. An appropriate metric could be determined by teardown study of a variety of electrified vehicles of varying power capability. Although EPA was unable to conduct additional teardown studies of specific PHEVs or BEVs in time for this analysis, in the time since the FRM additional options have become available for characterizing the specific power of non-battery components.

Performance targets for non-battery components published by US DRIVE provide one reference point. US DRIVE[549] is a consortium involving the U.S. Department of Energy, USCAR (an organization of the major U.S. automakers), and several other organizations including major energy companies and public energy utilities. This industry collaboration has established a number of cost and performance targets for automotive traction motors, inverters, chargers, and other power electronics components for the 2015 and 2020 time frames.[550] These include targets for specific power of electric propulsion motors and power electronics, both separately and alone, as shown in Table 5.102. These metrics are particularly relevant to the problem of component sizing.

Table 5.102 U.S. Drive Targets for Non-Battery Specific Power for 2015 and 2020

Component	U.S Drive Target (kW/kg)	
	2015	2020
Electric motor and power electronics	1.2	**1.4**
Electric motor alone	1.3	1.6
Power electronics alone	12	14.1

Since the EPA battery sizing methodology does not distinguish the power rating of the power electronics from that of the drive motor, the US DRIVE target that would be most relevant to the EPA analysis is the specific power of electric motor and power electronics combined, which US DRIVE places at 1.4 kW/kg for the 2020 time frame.

This figure has some support in the literature. A presentation by Bosch[551] at The Battery Show 2015 states that the electric motor and power electronics for a 100 kW, 20 kWh BEV system in the 2025 time frame is expected to comprise about 37 percent of electric content weight, with battery weight comprising the remaining 63 percent. Assuming the 20 kWh battery pack has a specific energy of about 140 Wh/kg (as indicated by BatPaC for an NMC622 pack at 115 kW net battery power), and a corresponding weight of 143 kg, the non-battery content would be estimated at about 53 kg. The 100 kW system would then represent 100 kW/53 kg or 1.88 kW/kg, making the US DRIVE figure of 1.4 kW/kg appear conservative.

Although the US DRIVE figures are targets and therefore not necessarily indicative of industry status, EPA has confidence that the targets for specific power represent attainable goals during the 2022-2025 time frame. This is based in part on the observation that the 2020 specific power target for electric motor and power electronics combined is very close to levels that were already being attained by some production vehicles at the time they were set.[552] Also, confidential business information conveyed to EPA through private stakeholder meetings with OEMs conducted since the FRM suggests that some of these targets are already being met or exceeded in production components today, or are expected to be met within the time frame of the rule.

This Draft TAR analysis therefore estimates the weight of non-battery PEV components using the 2020 US DRIVE specific power target for motor and power electronics combined, at 1.4 kW/kg.

As mentioned above, teardown studies would be another source of validation. As an alternative to conducting its own teardown studies, EPA has collected data on xEV component weights from a comprehensive teardown database produced by A2Mac1,[553] an automotive benchmarking firm. This database includes detailed weight analyses for the battery and non-battery electrical components of several BEVs and PHEVs produced for U.S. and global markets up to 2015. It therefore could provide a good source of data for the specific power of non-battery components that were produced in the 2012-2015 time frame, for comparison with the 1.4 kW/kg US DRIVE target. Although EPA was unable to complete this analysis in time to include it as part of this Draft TAR analysis, EPA plans to complete the analysis prior to the proposed determination.

(b) Improved weight estimation for battery components

In the 2012 FRM analysis, EPA had estimated battery pack weights by applying a constant specific energy value of 120 Wh/kg to account for the combined mass of the battery pack, electric motor, wiring, and power electronics. This factor was applied to BEVs and PHEVs of all driving ranges and was based in part on an assumed specific energy of 150 Wh/kg for the battery pack alone.

In practice, the specific energy of a battery pack will vary depending on its power-to-energy (P/E) ratio and its energy capacity. In general, smaller more power-optimized batteries tend to show a lower specific energy than larger energy-optimized batteries.

For this Draft TAR analysis, EPA therefore modified the method to allow the weight estimate for the battery pack to be more sensitive to the P/E ratio of the battery. This was done by directly linking the battery sizing spreadsheets to the BatPaC model to retrieve the specific power computed by BatPaC for each individual battery pack. This greatly improves the accuracy of the battery weight calculation. This adjustment causes the battery weight calculation to increase slightly for PHEVs due to their typically higher P/E ratio, and to decrease slightly for longer-range BEVs.

Accordingly, as shown by the selected examples in Table 5.103 and Table 5.104, the pack-level specific energy figures EPA uses in this Draft TAR analysis vary significantly, ranging from about 140 to 180 Wh/kg for EV75 to EV200 (assuming NMC622 cathode), to about 140 to 145 Wh/kg for PHEV40 (also NMC622), and about 110 to 125 Wh/kg for PHEV20 (assuming blended NMC/LMO cathode).

Table 5.103 Examples of Pack-Level Specific Energy Calculated By BatPac for Selected PEV Configurations (0% WR)

	EV75 (NMC622-G)		EV100 (NMC622-G)		EV200 (NMC622-G)		PHEV20 (NMC75%/ LMO25%-G)		PHEV40 (NMC622-G)	
	Wh/kg	P/E ratio	Wh/kg	P/E ratio	Wh/kg	P/E ratio	Wh/kg	P/E ratio	Wh/kg	P/E ratio
Small Car	142.4	4.43	153.5	3.32	162.0	2.01	117.9	6.69	146.3	7.17
Standard Car	146.3	5.56	158.9	4.17	170.6	2.52	118.1	8.41	139.1	9.01
Large Car	141.5	8.97	157.6	6.73	171.1	4.07	111.2	13.56	107.3	14.54
Small MPV	150.1	4.67	162.0	3.50	169.3	2.12	120.2	7.05	147.8	7.56
Large MPV	159.8	5.63	167.9	4.23	175.6	2.56	124.3	8.52	138.5	9.13
Truck	161.0	6.04	173.6	4.53	180.5	2.74	125.4	9.13	137.6	9.79

Table 5.104 Examples of Pack-Level Specific Energy Calculated By BatPac for Selected PEV Configurations (20% WR)

	EV75 (NMC622-G)		EV100 (NMC622-G)		EV200 (NMC622-G)		PHEV20 (NMC75%/ LMO25%-G)		PHEV40 (NMC622-G)	
	Wh/kg	P/E ratio	Wh/kg	P/E ratio	Wh/kg	P/E ratio	Wh/kg	P/E ratio	Wh/kg	P/E ratio
Small Car	142.3	4.12	149.1	3.12	160.1	1.94	116.5	6.46	146.6	7.00
Standard Car	142.0	5.17	154.8	3.91	168.6	2.45	117.2	8.07	141.1	8.81
Large Car	141.8	8.42	157.0	6.40	170.4	4.01	111.2	13.12	107.3	14.54
Small MPV	145.7	4.32	157.9	3.27	167.5	2.05	118.8	6.76	147.7	7.37
Large MPV	154.7	5.20	163.9	3.95	173.8	2.47	123.9	8.19	138.9	8.93
Truck	158.5	5.52	169.1	4.21	178.4	2.63	125.4	8.78	137.9	9.65

While these figures may appear very aggressive compared to batteries seen in 2012-2016MY applications, it should be noted that the technology assumptions in BatPaC are forecasts for the 2020 time frame. For comparison, in January 2016, GM announced that the 60 kWh Chevy Bolt BEV pack weighs 435 kg, suggesting that this EV200 pack has already achieved a specific energy of 138 Wh/kg today.[554] The same specific energy was already seen in the 85 kWh Tesla Model S as early as 2012.[555] Similarly, the 18.4 kWh pack of the 2016 Chevy Volt PHEV weighs 183 kg, suggesting this PHEV53 pack has achieved 101 Wh/kg today. As has occurred in the time since the FRM, the level of industry activity in battery development suggests that similar advances are likely to continue through the 2022-2025 time frame.

(c) Improved method for assignment of electric drive motor power

In the FRM, in order to maintain acceleration performance equivalent to that of conventional vehicles, EPA assigned power-to-weight ratios for PEVs to be equal to those of MY2008 conventional vehicles of their respective classes. Weight was modeled as equivalent test weight (ETW), which is curb weight plus 300 pounds payload. Table 5.105 below shows the power-to-ETW ratios assigned in the FRM for each vehicle class.

Table 5.105 Power-to-ETW Ratios Assigned to xEVs in the FRM

Class	hp/lb ETW	kW/kg ETW
Small Car	0.04364	0.07175
Standard Car	0.05269	0.08662
Large Car	0.08101	0.13318
Small MPV	0.04266	0.07013
Large MPV	0.05289	0.08695
Truck	0.05825	0.09576

These ratios were derived from published engine power ratings of conventional vehicles. However, it is well known that electric motors develop torque and power differently from internal combustion engines, and so may translate a rated power to an acceleration performance differently as well. Therefore, EPA conducted further analysis to determine whether targeting PEV acceleration performance by sizing PEV motor power ratings based on engine power ratings is appropriate.

One of the most common metrics of acceleration performance is the time it takes a vehicle to accelerate from zero to sixty miles per hour, also known as the 0-to-60 time. Although there are other metrics that describe acceleration performance, including metrics such as 0-to-30 time, 30-to-60 time, and quarter-mile time (and grade-ability metrics as well), 0-to-60 time is likely the most familiar metric for understanding the acceleration performance of a vehicle.

While in widespread popular use, this metric is not reported by manufacturers to EPA nor is its measurement subject to uniform standards. As an alternative, acceleration times of vehicles with conventional powertrains are sometimes estimated by means of a methodology developed by Malliaris et al.[556] The Malliaris methodology predicts 0-to-60 time as a function of the power-to-ETW ratio of the vehicle and two numerical coefficients empirically obtained from a least-squares fit of vehicle performance data. The Malliaris equation is depicted in Equation 12 below, with the coefficients 0.892 and 0.805 representing conventional vehicles with automatic transmissions.

$$t = 0.892 \left(\frac{hp}{lb\ ETW} \right)^{-0.805}$$

Equation 12. Malliaris equation for 0-60 acceleration time in seconds

At the time of the FRM, EPA had historically used this equation and coefficients to estimate acceleration performance of vehicles for pre-2014 editions of the annual Trends Report.[557] Subsequent editions have used a newer method developed by MacKenzie et al.[558] that EPA believes to be more accurate, particularly for newer vehicles. The latter method relies on a more detailed set of input parameters and tends to estimate slightly faster 0-to-60 times than the previous method. By the MacKenzie method, average 0-to-60 time for cars in MY2008 was at 8.9 seconds and fell to 8.4 seconds in MY2014 (with trucks falling from 9.0 seconds to 8.1 seconds). The MacKenzie method is not directly applicable to electric powertrains due to the requirement for ICE-specific inputs.

The existence of these methods means that power-to-ETW ratios assigned to PEVs in the FRM can therefore be converted to approximate acceleration times (for the ICE-powered conventional vehicles on which they were based). Since the Malliaris method was in effect at the time of the FRM, that method is used to estimate the 0-60 times depicted in Table 5.106 below. By this method, the power-to-weight ratios assigned to PEVs in the FRM analysis were equivalent to 0-60 acceleration times between 8.8 and 11.3 seconds, with Large Car an outlier at 6.75 seconds.

Table 5.106 Estimated 0-60 mph Target Acceleration Times Corresponding to FRM Assumptions for xEV hp/lb ETW

Class	hp/lb ETW	0-60 mph (sec)
Small Car	0.04364	11.1
Standard Car	0.05269	9.5
Large Car	0.08101	6.8
Small MPV	0.04266	11.3
Large MPV	0.05289	9.5
Truck	0.05825	8.8

The practice of using ICE-based hp/lb to size the electric propulsion motor of an xEV assumes that the power ratings of electric powertrains translate to acceleration times in the same way as the power ratings of conventional powertrains. At the time of the FRM, the small number of production BEVs made it difficult to validate this assumption.

Since the FRM, a significant number of BEV models have entered the market and now provide an opportunity to better predict BEV acceleration performance as a function of motor power and weight. Although comprehensive estimates of 0-60 acceleration time are not published by any single authority, estimates for many PEVs have been published by manufacturers and press organizations and provide a readily available source of empirical data.

Figure 5.110 plots the approximate 0-60 mph acceleration times of MY2012-2016 BEVs and PHEVs as a function of their power-to-ETW ratio, as expressed by rated peak motor power (kW) divided by test weight (the published curb weight in kg, plus 136 kg payload).[DDD] Acceleration times were collected from publicly available sources including manufacturers and press organizations, and in some cases were averaged when estimates from different sources had slight variation. PHEVs for which an all-electric (battery only) acceleration time could not be established were not included.

An empirical trendline was derived from this data and is shown in the Figure as a thin orange line. For comparison, the acceleration times that would be predicted by the Malliaris equation for the same range of power-to-ETW ratios is shown in the Figure as a heavy black line. As shown by Equation 13, the empirical trendline has the same equation form as the Malliaris equation, but with different coefficients of 0.9504 and 0.795 that result from a least-squares fit to the PEV data as expressed in SI units for power and weight.

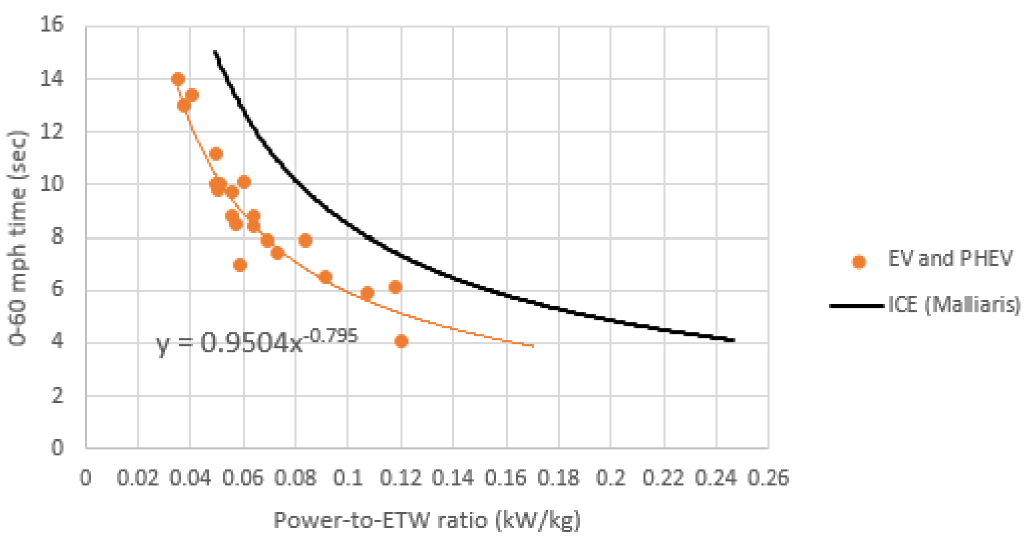


Figure 5.110 Acceleration Performance of MY2012-2016 PEVs Compared To Targets Generated By Malliaris Equation

[DDD] Tesla high-performance vehicles represented by 85 kWh Model S.

$$t = 0.9504 \left(\frac{kW}{kg\ ETW}\right)^{-0.795}$$

Equation 13. Empirical equation for 0-60 all-electric acceleration time of MY2012-2016 PEVs

The plot of Figure 5.110 suggests that use of the Malliaris equation to size the motor power rating of an electric powertrain results in higher power ratings and faster acceleration times for PEVs than intended in the FRM. For example, to target a 0 to 60 mph acceleration time of 10 seconds, the Malliaris equation (shown by the heavy line) would indicate that the motor should be sized to achieve a power-to-ETW ratio of 0.08 kW/kg. However, the empirical PEV trendline indicates that this power-to-ETW ratio would actually provide an electric powertrain with an acceleration time of about 7 seconds. The degree to which 0-60 performance was likely over specified in the FRM is shown in Table 5.107. It appears that the 2012 FRM therefore assumed significantly greater motor power ratings (and by extension, battery power ratings) than required for the intended acceleration times.

Table 5.107 PEV Acceleration Performance Intended in the FRM and Projected Probable Performance

	0-60 mph time (sec)	
Class	**FRM intent**	**FRM actual**
Small Car	11.1	7.7
Standard Car	9.5	6.6
Large Car	6.8	4.7
Small MPV	11.3	7.9
Large MPV	9.5	6.6
Truck	8.8	6.1

One option for improving the assignment of PEV power ratings would adopt the empirical trendline of Equation 13 in place of the Malliaris equation to assign the necessary motor power to match the originally targeted performance levels for each vehicle class. According to the EPA Trends Report for 2015, average 0-to-60 time for cars in MY2014 as estimated by the Malliaris method was equal to that of MY2008 at 9.6 seconds (with trucks showing a slight performance increase from 9.7 seconds to 9.1 seconds), suggesting that the original power-to-ETW ratios targeted in the FRM remain reasonably valid for the current time frame.

A second option would adopt the empirical trendline of Equation 13 while also updating the power-to-ETW ratios to values more representative of today's fleet. This option retains good comparability with the original methodology, while allowing the performance targets to be updated to reflect changes in the fleet since MY2008.

EPA has therefore updated the power-to-ETW targets for each PEV vehicle class to values derived from the MY2014 baseline. These new values are shown in Table 5.108.

Table 5.108 Changes in PEV Power-To-Weight Ratios and 0-60 Targets for Draft TAR

	Power-to-weight ratio (hp/lb ETW)		Estimated equivalent 0-60 time (sec)	
Class	**FRM**	**Draft TAR**	**FRM**	**Draft TAR**
Small Car	0.04364	**0.04718**	11.1	**10.4**
Standard Car	0.05269	**0.05916**	9.5	**8.7**
Large Car	0.08101	**0.09740**	6.8	**5.8**
Small MPV	0.04266	**0.05000**	11.3	**9.9**
Large MPV	0.05289	**0.06205**	9.5	**8.4**
Truck	0.05825	**0.06569**	8.8	**8.0**

The revised power-to-ETW values are slightly greater than the values assumed in the 2012 FRM, leading to slightly faster acceleration times. EPA has carefully considered whether it is appropriate to target greater power levels in this Draft TAR analysis, since this would tend to divert some of the anticipated GHG benefit of the modeled vehicles toward vehicle performance rather than GHG reduction. However, increased performance has in many cases been a factor in the marketing of some PEVs, with many production and announced PEVs targeting faster acceleration times than similarly appointed conventional vehicles.

This adjustment to motor sizing should therefore allow the EPA PEV modeling methodology to better match the power-to-weight ratios and acceleration performance that PEV manufacturers appear to be following. Assigning a more accurate power rating to PEV powertrains will allow greater fidelity in the projected cost of both the battery and non-battery components of PEVs. Further, basing the motor power sizing explicitly on an empirically derived estimate of 0-60 acceleration time for each modeled vehicle will more clearly demonstrate the performance neutrality of the modeled PEVs.

(d) Updated baseline curb weights

For the FRM, the target curb weights for the six vehicle classes were based on the MY2008 baseline. For this Draft TAR, the baseline was updated to MY2014. Also, PEVs were removed from the sample to better represent the weight and performance of conventional vehicles alone. Accordingly, the curb weights serving as inputs to the battery pack sizing analysis were updated to these non-PEV MY2014 values. Most curb weights increased, with the exception of Small Car and Standard Car which declined slightly. The new weights are shown in Table 5.109 below.

Table 5.109 Changes to Baseline Curb Weights from FRM MY2008 to Draft TAR MY2014

Vehicle Class	Curb weight (lb)		
	FRM (MY2008)	MY2014	Change
Small Car	2633 lb	**2628 lb**	**-0.19%**
Standard car	3306 lb	**3296 lb**	**-0.30%**
Large car	3897 lb	**4117 lb**	**+5.65%**
Small MPV	3474 lb	**3500 lb**	**+0.75%**
Large MPV	4351 lb	**4448 lb**	**+2.22%**
Truck	5108 lb	**5161 lb**	**+1.04%**

(e) Increase in usable battery capacity for BEVs and some PHEVs

Based on observations of trends in recent BEV and PHEV usable capacity (discussed in Section 5.2), the usable battery capacity was increased to 85 percent for EV75 and EV100, and to 90 percent for EV200. The use of 90 percent for EV200 was chosen on the recognition of two advantages associated with particularly high-capacity battery packs. First, because the total available range is significantly larger than the average daily trip distance, vehicles with a long driving range may on average utilize a smaller portion of the total battery capacity on a daily basis, leading to generally shallower charge-discharge cycles. Also, these longer-range vehicles require fewer charge-discharge cycles over the life of the battery to achieve a given lifetime mileage. Both factors may act to widen the usable portion of the battery for the purpose of measuring maximum range without unduly affecting battery life in typical use.

Since the battery of a PHEV40 is similar in size to that of a BEV, and based in part on the Chevy Volt example, the usable capacity for PHEV40 was increased from 70 percent to 75 percent. PHEV20 remained at 70 percent due to the smaller size of the battery.

(f) Increase in electric powertrain brake and driveline efficiency

In the 2012 FRM, brake efficiency and driveline efficiency for electric powertrains was assumed to be 85 percent and 93 percent respectively (or 79 percent combined). Since the 2012 FRM, some evidence has emerged that some electric powertrains are already performing beyond these levels. In 2013, a GM executive described the drive unit of the yet-to-be-released Chevy Spark EV as having an average DC current-to-wheels efficiency of 85 percent in the city cycle and 92 percent in the highway cycle[559]. This current-to-wheels metric appears similar to the product of brake and driveline efficiency, but neglecting battery discharge efficiency. Assuming an average battery discharge efficiency of 95 percent, and a standard 55/45 city/highway weighting (amounting to 88.15 percent combined), the product of brake and driveline efficiency for this powertrain would be about 83.75 percent.

To bring the FRM assumptions closer to this figure, for this Draft TAR analysis EPA adjusted the assumed brake and driveline efficiencies for BEVs to 87 percent and 95 percent respectively, or 82.7 percent combined. Because the charge-depleting mode of a PHEV with AER is similar in nature to BEV operation, brake efficiency for PHEVs was also increased to 87 percent, with driveline efficiency remaining at 93 percent to reflect the more complex nature of the PHEV driveline.

(g) Increase in PHEV battery power target

In the 2012 FRM, the battery pack power requirement for BEVs was assigned as 15 percent greater than the motor power rating. This adjustment represented estimated energy losses in the electric motor, assuming an 85 percent motor efficiency. Battery sizing for PHEVs did not employ this adjustment on the assumption that the engine could assist with acceleration. In retrospect, this assumption is inconsistent with PHEVs that operate as range-extended vehicles, where all acceleration must be achieved by the battery and electric motor alone. Further, since the FRM it has also appeared that some manufacturers of shorter-range, blended-operation PHEVs are trending toward providing a stronger electric drivetrain capable of keeping the engine off in a broader range of driving conditions. For these reasons, use of the adjustment factor has been extended to PHEV battery sizing as well in order to better reflect an increased capability of electric-only propulsion. Also, to reflect the assumed improvements in brake efficiency described above, the factor for both BEVs and PHEVs is reduced from 15 percent to 10 percent to reflect a 90 percent motor efficiency.

(h) Allowance for power fade in battery power calculation

As mentioned above, in the FRM analysis, the method of assigning motor power resulted in motor and battery power sizing that was significantly greater than that observed in later production PEVs. Having modified the method to result in more representative (lower) motor power ratings, battery power ratings are therefore also lower in the new analysis. This makes it more critical to account for power fade during the life of the battery, since the new analysis no longer over-sizes the battery as before.

Battery power targets for PEVs were therefore nominally increased by an oversizing factor of 20 percent to compensate for power fade. In cases where a sufficiently large PEV battery naturally results in an excess power capability greater than 20 percent, the oversizing factor does not have an impact on the design of the battery.

(i) Increase in applied aerodynamic drag and rolling resistance reduction

In the construction of technology packages for the OMEGA analysis in the FRM, BEV and PHEV technology packages included an aerodynamic drag reduction of 20 percent (the technology case known as AERO2), and a tire rolling resistance reduction of 20 percent (the case known as LRRT2). This was based in part on the expectation that manufacturers would find these technology improvements to be more cost effective for plug-in vehicles than for conventional vehicles due to the potential to reduce the size and cost of the battery. The package costs thus reflected the cost of application of AERO2 and LRRT2 relative the 2008 baseline. However, the battery sizing methodology of the FRM applied only a 10 percent reduction in each (AERO1 and LRRT1).

For consistency with the rest of the analysis, EPA has now revised the battery sizing methodology to apply AERO2 and LRRT2 in determining PEV energy consumption requirements. This adjustment causes the assumed costs to be more representative of the assumed level of technology application, and also tends to slightly reduce the estimated battery capacity for a given range target.

(j) Increase in derating factor for EV200

For certification purposes, EPA allows manufacturers to either use a default derating factor of 70 percent to convert a two-cycle range test result to a label value, or to derive a custom derating factor by undergoing complete five-cycle testing. Since the FRM, EPA certification data for 2012-2016MY EVs indicates that most BEV manufacturers have chosen to apply the default 70 percent derating factor in their certification tests. Tesla Motors is the only BEV manufacturer that has elected to use a custom derating factor derived from 5-cycle testing. Tesla has used a factor of 79.6 percent for the standard Model S configurations from 60 kWh to 90 kWh, and a factor ranging from 73 to 75 percent for higher-performance and AWD configurations of the Model S and Model X. Since the nearest current production example of an EV200 is the Tesla Model S standard configuration, this Draft TAR analysis adopts a derate factor of 80 percent for EV200. Because manufacturers of EV75 and EV100-type vehicles have only used the default 70 percent derating factor and have not derived custom factors, EPA has retained the 70 percent derating factor for EV75 and EV100. While these derating factors therefore represent the most recent trends in industry practice since the 2012 FRM, their appropriateness in modeling the label range of future PEVs will depend on the degree to which manufacturers continue to follow this pattern in selecting the derating factors used for certification.

(k) PHEV20 motor sized for blended operation rather than EREV with AER

Primarily in order to accommodate the high power requirements of the Large Car class as modeled in this analysis, the PHEV20 was assigned a lower motor power rating more in line with a blended-architecture PHEV rather than the EREV configuration of PHEV40. The blended motor power requirement was estimated as half of the power that would have been assigned to an EREV configuration. Modeling of PHEV20 as a blended PHEV is also consistent with the observation that many sub-20 mile PHEVs operate with at least a partially blended operating strategy rather than a strict EREV strategy that allows all-electric operation in all driving conditions. The reduction in motor power also allows the battery for Large Car to be sized with reasonable power requirements compatible with the specific chemistry formulations modeled in BatPaC.

Summary of Changes to Battery Sizing Assumptions

Table 5.110 reviews the major input assumptions to the battery sizing method and the changes that were made for this Draft TAR analysis.

Table 5.110 PEV Battery Sizing Assumptions and Changes from FRM to Draft TAR

Assumption	2012 FRM	2016 Draft TAR
Small Car base curb weight	2633 lb	**2628 lb**
Standard car base curb weight	3306 lb	**3296 lb**
Large car base curb weight	3897 lb	**4117 lb**
Small MPV base curb weight	3474 lb	**3500 lb**
Large MPV base curb weight	4351 lb	**4448 lb**
Truck base curb weight	5108 lb	**5161 lb**
Applied aero reduction from 2008 baseline	10%	**20%**
Applied tire reduction from 2008 baseline	10%	**20%**
Applied mass reduction to glider from 2008 baseline	Varies; max 20%	unchanged
Short range BEV (mi)	EV75	unchanged
Mid-range BEV (mi)	EV100	unchanged
Long range BEV (mi)	EV150	**EV200**
Short range PHEV (mi)	PHEV20	unchanged
Long range PHEV (mi)	PHEV40	unchanged
Usable battery capacity, HEV	40%	unchanged
Usable battery capacity, PHEV20	70%	unchanged
Usable battery capacity, PHEV40	70%	**75%**
Usable battery capacity, EV75	80%	**85%**
Usable battery capacity, EV100	80%	**85%**
Usable battery capacity, EV150/200	80%	**90%**
Electric content specific energy	120 Wh/kg	**N/A**
Battery specific energy	included with electric content	**Wh/kg computed by BatPaC**
Non-battery specific power	included with electric content	**1.4 kW/kg**
Motor sizing	Based on MY2008 baseline ICE hp/lb for each vehicle class	**Based on MY2014 baseline 0-60 performance estimate and new empirical equation for PEVs**
Brake efficiency, PEV	85%	**87%**
Driveline efficiency, BEV	93%	**95%**
Cycle efficiency, PEV	97%	unchanged
BEV battery power as fn of motor power	1.15x	**1.1x**
PHEV battery power as fn of motor power	1x	**1.1x**
Allowance for power fade	none	**20%**
Road loads, PEV	from LPM	unchanged
2-cycle to 5-cycle derating factor, PHEV and EV75/100	70%	**unchanged**
2-cycle to 5-cycle derating factor, EV200	70%	**80%**
PHEV20 motor sizing basis	EREV	**blended**

Analysis of Changes

The changes above result in significant changes to the projected sizing of PEV batteries and motors compared to those of the FRM. Table 5.111 shows examples of the battery capacities and motor power ratings generated by the revised sizing methodology and compares them to the corresponding estimates generated by the FRM analysis.

It can be seen that battery capacity estimates have declined under the new methodology. It can also be seen that estimated motor power ratings have declined in all cases (even for EV200, despite the increase in range and vehicle weight vs. EV150). The declines in motor power are largely the result of using the empirical trendline equation to assign the motor power rating necessary for the desired acceleration performance. For PHEV20, the motor power declines are also the result of adopting a blended powertrain architecture in place of an EREV architecture, which leads to lower motor power rating.

Table 5.111 Example Changes in Projected PEV Battery Capacity and Motor Power, FRM to Draft TAR (20% weight reduction case)

	EV75		EV100		EV150*/200**		PHEV20		PHEV40	
FRM (2008 baseline)										
	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)	Battery (kWh)*	Motor (kW)*	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)
Small Car	20.5	77.5	28.2	82.6	45.3	94.0	6.5	84.3	13.4	88.9
Standard Car	25.2	115.5	34.7	123.0	55.8	139.6	8.0	124.8	16.4	131.4
Large Car	29.9	206.2	41.1	219.6	66.2	249.5	9.5	223.5	19.5	235.4
Small MPV	26.7	98.7	36.7	105.1	59.0	119.2	8.4	105.5	17.3	111.1
Large MPV	33.6	150.0	46.5	160.0	74.8	181.9	10.7	161.6	21.9	170.3
Truck	38.6	189.6	53.0	201.8	85.3	229.1	12.4	209.6	25.4	220.6
Draft TAR analysis										
	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)	Battery (kWh)**	Motor (kW)**	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)
Small Car	17.3	54.0	23.5	55.6	41.2	60.6	6.1	29.7	11.7	61.9
Standard Car	21.4	83.8	29.1	86.2	50.2	93.4	7.5	45.8	14.4	96.3
Large Car	27.7	176.8	37.4	181.6	65.0	197.4	9.5	94.6	18.8	206.7
Small MPV	22.7	74.5	30.9	76.6	53.7	83.4	7.9	40.6	15.1	84.6
Large MPV	29.3	115.3	39.8	119.0	69.2	129.5	10.2	63.2	19.7	133.5
Truck	33.0	138.3	44.6	142.3	77.6	154.7	11.7	78.0	22.6	165.0
Change from FRM										
	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)	Battery (kWh)†	Motor (kW)†	Battery (kWh)	Motor (kW)††	Battery (kWh)	Motor (kW)
Small Car	-15.6%	-30.3%	-16.7%	-32.7%	-9.1%	-35.5%	-6.2%	-64.8%	-12.7%	-30.4%
Standard Car	-15.1%	-27.4%	-16.1%	-29.9%	-10.0%	-33.1%	-6.3%	-63.3%	-12.2%	-26.7%
Large Car	-7.4%	-14.3%	-9.0%	-17.3%	-1.8%	-20.9%	0.0%	-57.7%	-3.6%	-12.2%
Small MPV	-15.0%	-24.5%	-15.8%	-27.1%	-9.0%	-30.0%	-6.0%	-61.5%	-12.7%	-23.9%
Large MPV	-12.8%	-23.1%	-14.4%	-25.6%	-7.5%	-28.8%	-4.7%	-60.9%	-10.0%	-21.6%
Truck	-14.5%	-27.1%	-15.8%	-29.5%	-9.0%	-32.5%	-5.6%	-62.8%	-11.0%	-25.2%

Notes:
* For EV150
**For EV200
†Compares EV200 (Draft TAR) to EV150 (FRM)
††Compares blended PHEV20 (Draft TAR) to EREV PHEV20 (FRM)

The following figures compare the newly projected battery capacities to those observed in MY2012-2016 BEVs and PHEVs. Both figures show that the revised methodology produces capacity estimates that center more accurately on the 2012-2016 trendline than did the analogous FRM estimates reviewed in Section 5.2).

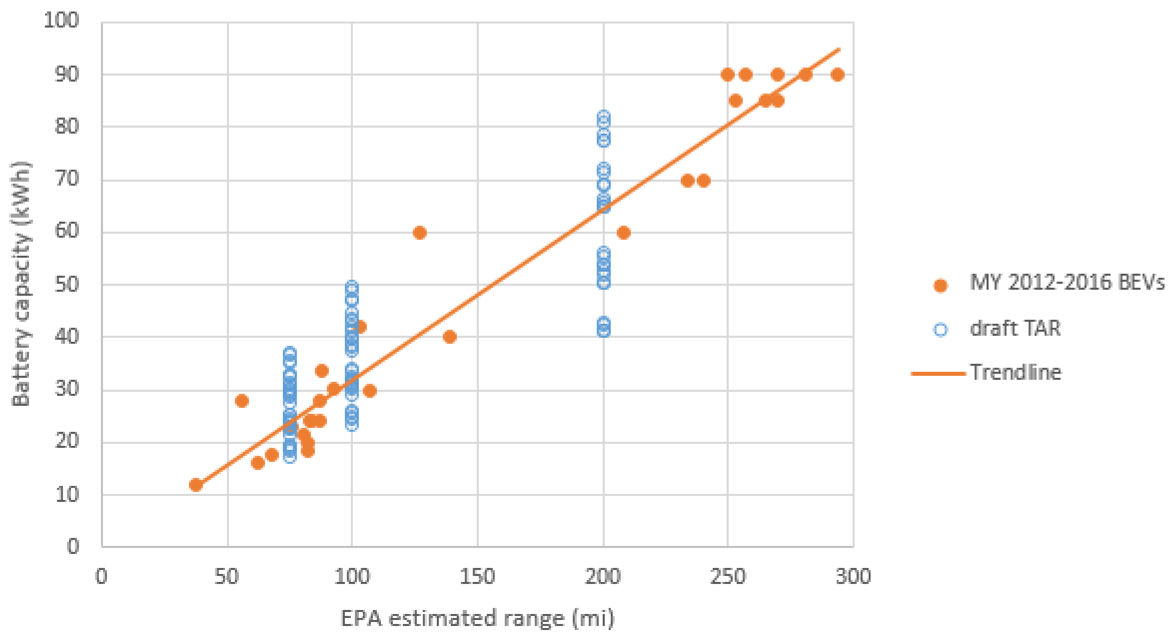


Figure 5.111 Comparison of Draft TAR Projected BEV Battery Capacities to MY2012-2016 BEVs

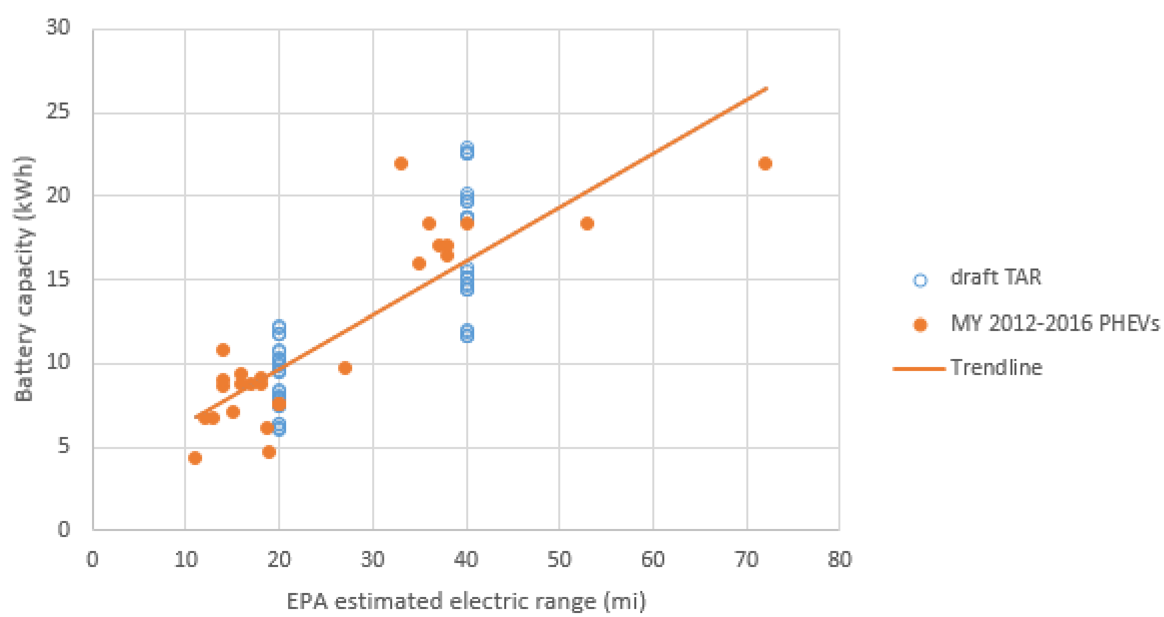


Figure 5.112 Comparison of Draft TAR Projected PHEV Battery Capacities to MY2012-2016 PHEVs

To compare the Draft TAR capacity projections to specific production vehicles, Table 5.112 and Table 5.113 show the projected battery capacities and assumed curb weights for each electrified vehicle type and vehicle class at 0 percent and 20 percent nominal weight reduction, respectively. These tables are useful for drawing comparisons of the projected battery capacities to those of specific production BEVs and PHEVs. In the battery sizing analysis, differences in energy consumption among the six vehicle classes (Small Car to Truck) is primarily derived from differences in curb weight. Therefore matching a production vehicle's curb weight, range and capacity to the values in these tables provides a fair comparison regardless of whether the indicated classification or weight reduction case matches that of the vehicle.

Table 5.112 Draft TAR Projected Battery Capacities and Assumed Curb Weights, 0% Nominal Weight Reduction

	EV75 (NMC622)		EV100 (NMC622)		EV200 (NMC622)		PHEV20 (25NMC/75LMO)		PHEV40 (NMC622)	
	Curb wt (lb)	kWh	Curb wt (lb)	kWh	Curb wt (lb)	kWh	Curb wt (lb)	kWh	Curb wt (lb)	kWh
Small Car	2628	19.5	2628	26.0	2628	42.9	2628	6.4	2628	12.0
Std Car	3296	23.9	3296	31.9	3296	52.7	3296	7.9	3296	14.8
Lg Car	4117	30.2	4117	40.3	4117	66.6	4117	10.0	4146	18.8
Sm MPV	3500	25.4	3500	33.9	3500	56.0	3500	8.4	3500	15.7
Lg MPV	4448	32.7	4448	43.7	4448	72.1	4448	10.8	4448	20.2
Truck	5161	37.2	5161	49.6	5161	82.0	5161	12.3	5161	23.0

Table 5.113 Draft TAR Projected Battery Capacities and Assumed Curb Weights, 20% Nominal Weight Reduction

	EV75 (NMC622)		EV100 (NMC622)		EV200 (NMC622)		PHEV20 (25NMC/75LMO)		PHEV40 (NMC622)	
	Curb wt (lb)	kWh	Curb wt (lb)	kWh	Curb wt (lb)	kWh	Curb wt (lb)	kWh	Curb wt (lb)	kWh
Small Car	2119	17.3	2192	23.5	2419	41.2	2363	6.1	2474	11.7
Std Car	2689	21.4	2775	29.1	3029	50.2	2968	7.5	3132	14.4
Lg Car	3505	27.7	3607	37.4	3948	65.0	3773	9.5	4148	18.8
Sm MPV	2849	22.7	2940	30.9	3227	53.7	3129	7.9	3277	15.1
Lg MPV	3617	29.3	3741	39.8	4100	69.2	3994	10.2	4237	19.7
Truck	4134	33.0	4263	44.6	4660	77.6	4701	11.7	4992	22.6

In most cases, the projected capacities are reasonably close to those of production vehicles, although somewhat larger. As one example, the 30 kWh trim of the Nissan Leaf was recently announced as achieving an EPA range of 107 miles at a curb weight of 1515 kg (3340 lb). On a curb weight basis, the closest match in the tables above would be EV100 Standard Car (Table 5.112) at 3296 lb. The projected battery capacity for this vehicle is 31.9 kWh. While this figure is larger than the 30 kWh capacity of the Leaf, it represents a vehicle with a 20 percent reduction in aerodynamic drag and rolling resistance from a 2008 baseline vehicle. If the Leaf applies more reduction than this, it could achieve its 107 mile range with a smaller battery.

As another example, the Chevy Bolt EV was announced in 2016 as an EV200 with a 60 kWh battery and a curb weight of 3580 lb. On a curb weight basis, the closest match in the tables above would be EV200 Small MPV at 3500 lb (this is also consistent with GM's description of this vehicle as a "crossover"). The projected battery capacity is 56 kWh, compared to the 60 kWh of the Bolt. While the projected capacity is lower than that of the Bolt, the Bolt is 80 pounds heavier than the example, and may have a driving range in excess of 200 miles (the driving range of the Bolt has not been rated by EPA but is commonly described as possibly exceeding 200 miles).

As a third example, the 60 kWh version of the Tesla Model S achieved an EPA range of 208 miles (EV200) at an advertised curb weight of 1961 kg (4323 lb). The closest EV200 match to this curb weight in the tables above would be about halfway between the two examples of Large MPV at 4100 and 4448 pounds (projected at 69.2 and 72.1 kWh respectively). The average battery capacity of the two is 70.65 kWh. While larger than the 60 kWh Tesla provides, part of the difference might be explained by the slightly larger 208-mile range of the vehicle

As a final example, the 2016 Chevy Volt PHEV achieves an EPA AER of 53 miles with an 18.4 kWh battery at a curb weight of 1607 kg (3543 lb). The closest match is to the PHEV40, 0 percent, Small MPV at 3500 lb, which projects a 15.7 kWh battery. The greater range of the Volt (53 miles vs. 40 miles) obscures the comparison, but is directionally correct.

By these examples, it is clear that the methodology tends to predict somewhat larger BEV battery capacity than 2012-2016 MY production BEVs, leading to a conservative assessment on the basis of battery capacity alone.

This trend is more clearly shown by normalizing the projected capacities to curb weight. Figure 5.113 compares the BEV battery capacity per unit curb weight (kWh/kg CW) projected by the revised methodology against that of production BEVs that are most comparable to the modeled vehicles. This comparison removes the effect of weight differences and more clearly expresses the efficiency with which gross battery capacity is converted to label range for a given vehicle weight. For the purpose of this plot, comparable BEVs are defined as BEVs that were available as 2016MY vehicles, but with D variants of the Tesla vehicles excluded (due to their dual-motor architecture which differs from other BEVs, and because only non-D variants were certified using a range derating factor similar to the 0.8 factor that was assumed for EV200). The Tesla Roadster, although not a 2016 vehicle, is included because of its powertrain similarities with other single-motor Tesla vehicles.

It is clear from this plot that the revised battery sizing methodology has significantly improved its prediction of battery capacity per unit curb weight compared to the methodology used in the 2012 FRM analysis. However, it does continue to assign BEVs a slightly higher battery capacity per unit weight than seen in production BEVs of the same range.

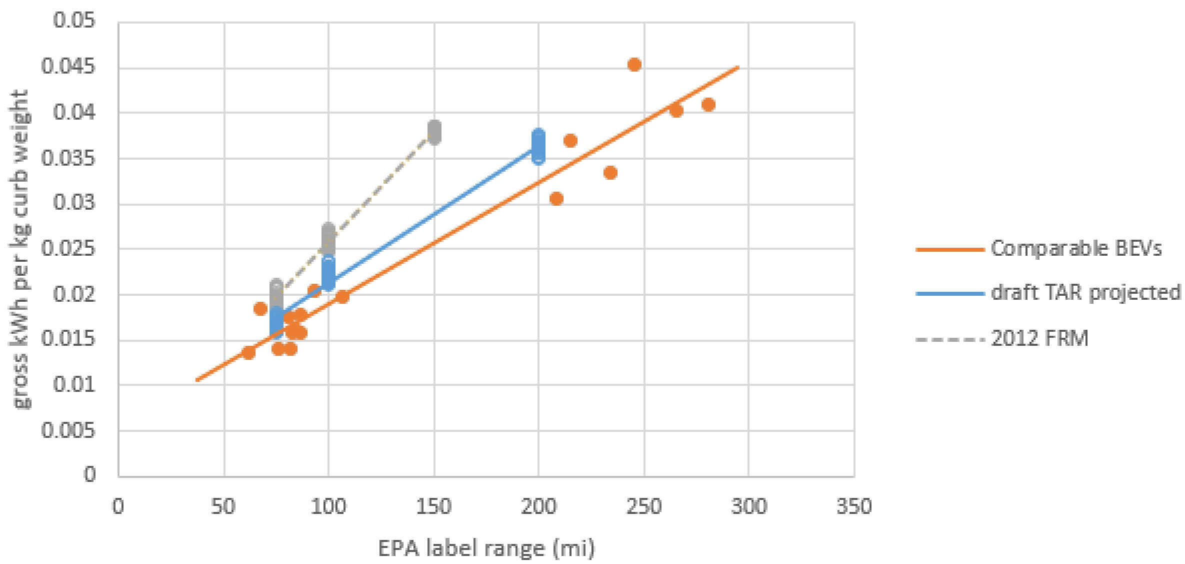


Figure 5.113 Projected BEV Battery Capacity per Unit Curb Weight Compared To Comparable BEVs

Seen another way, the plot suggests that at least some current production vehicles have been able to deliver a given range with slightly less battery capacity than this Draft TAR analysis predicts for a future time frame. While this supports a conservative estimate, this trend deserves further examination because the goal of the Draft TAR is to represent a future state of technology in 2022-2025.

There are several potential reasons why the capacity estimates generated by the battery sizing methodology may not match the capacities observed in specific production vehicles.

As previously observed, there could be differences in assumed powertrain efficiencies or differences in application of road load reducing technologies (mass reduction, aerodynamic drag reduction, and rolling resistance reduction) between the production vehicles and the modeled vehicles. For example, if xEV manufacturers are applying more than the 20 percent reduction in aerodynamic drag and rolling resistance (from a baseline vehicle) assumed in the analysis, or are applying more mass reduction, it could result in substantially smaller battery capacity requirements. Also, the larger battery capacity of longer-range BEVs may slightly improve their discharge efficiency relative to shorter range vehicles, because discharge would take place at a lower C rate. Efficiency of regenerative braking might also improve slightly for these vehicles. These factors could account for some of the disparity for longer-range vehicles.

While it is tempting to consider calibrating the battery sizing methodology to the observed 2012-2016MY battery capacities (perhaps by simply assigning battery capacities based on the 2012-2016MY trendline shown above), this would compromise the analysis' accounting for the cost of applied road load reduction technology, because the level of road load technologies applied to the vehicles that compose the trendline is not known, and probably varies from vehicle to vehicle. For example, even if the application level for one EV75 were known, the larger battery and weight of an EV100 or EV200 may have incentivized greater reductions which would have to be accounted for accurately as well.

In contrast, the current methodology applies known levels of road load reduction technology in order to clearly account for its cost and allow extrapolation to other application levels. If the cost of applying road load technologies in excess of these levels is similar to the value of the battery capacity saved, it is possible that smaller battery sizes could result, but not necessarily at a lower net vehicle cost.

5.3.4.3.7.2 Battery Sizing Methodology for HEVs

HEV battery packs were sized using a simpler methodology described below. This method is continued in the current analysis.

Because there is no "all-electric range" requirement for HEVs, battery pack sizes are relatively consistent for a given weight class. Furthermore, because battery pack sizes are at least an order of magnitude smaller for HEVs than for all-electric vehicles, the sensitivity of HEV vehicle weight (and hence energy consumption) to battery pack size is relatively insignificant. For these reasons, a more direct approach (rather than an iterative process) works for battery sizing of HEVs.

In the FRM analysis and the current analysis, HEV batteries were scaled similarly to the 2010 Fusion Hybrid battery, based on a metric of nominal battery energy per pound of equivalent test weight (ETW). Although the Fusion battery utilized a nickel-metal hydride (Ni-MH) chemistry in contrast to the lithium-ion chemistries of the current analysis, the energy window required for hybrid operation and thus gross battery sizing is expected to be similar for either chemistry.

The Fusion Hybrid Ni-MH battery had an ETW ratio of 0.37 Wh/lb. The battery was understood to utilize a 30 percent usable SOC window. The FRM analysis and the current analysis assumes 40 percent for HEVs in the 2020 time frame. The rationale for this assumption is outlined in more detail in Section 5.2.4.4.3. This results in a 25 percent reduction of the energy capacity of the base Fusion battery, or a 0.28 Wh/lb ETW ratio. This value was used to size strong HEV batteries for the analysis.

In comparing anecdotal data for HEVs, EPA assumed a slight weight increase of 4-5 percent for HEVs compared to baseline non-hybridized vehicles. The added weight of the Li-ion pack, motor and other electric hardware were offset partially by the reduced size of the base engine.

5.3.4.3.7.3 ANL BatPaC Battery Design and Cost Model

The U.S. Department of Energy (DOE) has established long term industry goals and targets for advanced battery systems as it does for many energy efficient technologies. Prior to the 2012 FRM, Argonne National Laboratory (ANL) was funded by DOE to provide an independent assessment of Li-ion battery costs because of their expertise in the field as one of the primary DOE National Laboratories responsible for basic and applied battery energy storage technologies for future HEV, PHEV and BEV applications. This led to the development of a Li-ion battery cost model, later named BatPaC.

A basic description of the battery cost model that formed the basis of BatPaC was published in a peer-reviewed technical paper presented at EVS-24.[560] ANL later extended the model to include analysis of manufacturing costs for BEVs and HEVs as well has PHEVs.[561] In early 2011, ANL issued a draft report detailing the methodology, inputs and outputs of their Battery Performance and Cost (BatPaC) model.[562] Soon after, EPA contracted a complete independent peer-review of the BatPaC model and its inputs and results for HEV, PHEV and BEV applications.[563] ANL also provided EPA with an updated report documenting the BatPaC model that fully addressed the issues raised within the peer review.[564] ANL has continued to develop the model on an ongoing basis, adding several new features and refinements to the latest version.[565] For this Draft TAR analysis, EPA used Version 3.0 of BatPac, which was provided to EPA on December 17, 2015.[566]

BatPaC is based on a bill of materials approach in addition to specific design criteria for the intended application of a battery pack. The costs include materials, manufacturing processes, the cost of capital equipment, plant area, and labor for each manufacturing step. The design criteria include detailed parameters such as power and energy storage capacity requirements, cathode and anode chemistry, and the number of cells per module and modules per battery pack. The model assumes use of a stiff-pouch, laminated multi-layer prismatic cell, and battery modules consisting of double-seamed rigid containers. The model supports both liquid-cooling and air-cooling, with appropriate accounting for the resultant structure, volume, cost, and heat rejection capacity of the modules. The model takes into consideration the cost of capital equipment, plant area and labor for each step in the manufacturing process for battery packs and places relevant limits on electrode coating thicknesses and other processes limited by existing and near-term manufacturing processes. The ANL model also takes into consideration annual pack production volume and economies of scale for high-volume production.

EPA chose to adopt the ANL BatPaC model for the following reasons. First, BatPaC has been described and presented in the public domain and does not rely upon confidential business information (which would therefore not be reviewable by the public). The model was developed by scientists at ANL who have significant experience in this area. The model uses a bill of materials methodology which the agencies believe is the preferred method for developing cost estimates. BatPaC appropriately considers the target power and energy requirements of the vehicle, which are two of the fundamental parameters when designing a lithium-ion battery for an HEV, PHEV, or BEV. BatPaC can estimate high volume production costs, which the agencies believe is appropriate for the 2025 time frame. Finally, its cost estimates are consistent with some of the supplier cost estimates EPA received from large-format lithium-ion battery pack manufacturers. A portion of that data was received from EPA on-site visits to vehicle manufacturers and battery suppliers in 2008.

Since the FRM, EPA has worked closely with ANL to test new versions of BatPaC and to guide the development of features that would support the midterm review and this Draft TAR analysis. ANL has since published several iterations of the model that incorporate updated costs, improved costing methods and other improvements.

EPA has worked closely with ANL since 2010 to evaluate each successive version of the BatPaC model, to make suggestions for its improvement, and to specifically request features to assist with its use for the purpose of battery costing for the rule. EPA also worked with ANL to arrange for an independent peer review of the model in 2011. This peer review along with EPA input led to many improvements that were described in the TSD that accompanied the 2012 FRM. ANL has continued to make improvements and add new features since the FRM, many at EPA request. Recent development has included: support for additional battery module topologies, improved modeling of impedance and electrode thickness, improved evaluation of battery thermal capabilities, revised electrode chemistries such as NMC622, improved accounting for plant costs and overhead, improved cost accounting for solvent recovery, customization of cell thickness parameters, generation of USABC parameters, and updated costs for all constituent cell materials.

To conduct this Draft TAR analysis, in December 2015 ANL provided EPA with a beta copy of BatPaC Version 3. After testing and evaluation, this version was used in this Draft GHG Assessment. A copy of this file is available in Docket EPA-HQ-OAR-2015-0827.

Basic user inputs to BatPaC include performance goals (power and energy capacity), choice of battery chemistry (of several predefined chemistries), the vehicle type for which the battery is intended (HEV, PHEV, or BEV), the desired number of cells and modules and their layout in the pack, and the volume of production. BatPaC then designs the electrodes, cells, modules, and battery pack, and provides a complete, itemized cost breakdown at the specified production volume.

BatPaC provides default values for engineering properties and material costs that allow the model to operate without requiring the user to supply detailed technical or experimental data. In general, the default properties and costs represent what the model authors consider to be reasonable values representing the state of the art expected to be available to large battery manufacturers in the year 2020. Users are able to edit these values as necessary to represent their own expectations or their own proprietary data.

In using BatPaC, it is extremely important that the user monitor certain properties of the cells, modules, and packs that it generates, to ensure that they stay within practical design guidelines, adjusting related inputs if necessary. In particular, pack voltage and individual cell capacity should be limited to appropriate ranges for the application. These design guidelines are not rigidly defined, but approximate ranges are beginning to emerge in the industry.

The cost outputs used by EPA to determine 2025 HEV, PHEV and BEV battery costs were based on the inputs and assumptions described in the next section. For engineering properties and material costs, and for other parameters not identified below, EPA used the defaults provided in the model.

5.3.4.3.7.4 Assumptions and Inputs to BatPaC

EPA chose basic user inputs to BatPaC as follows.

For performance goals, EPA used the power and energy requirements derived from the battery sizing analysis described in the previous section. Additional inputs include battery chemistry, vehicle type (BEV, PHEV, or HEV), cell and module layout, and production volumes, as outlined below.

In addition to these inputs, EPA monitored certain outputs to ensure that the resultant cell and pack specifications were realistic. In particular, pack voltages, electrode dimensions, cooling capability, and individual cell capacities were monitored to ensure that they were consistent with current and anticipated industry practice.

Additionally, EPA did not include warranty costs computed by BatPaC in the total battery cost because these are accounted for elsewhere in the analysis by means of indirect cost multipliers (ICMs).

Battery chemistry

In the 2012 FRM analysis, chemistries were chosen due to their known characteristics and to be consistent with both publicly available information on current and near term HEV, PHEV and BEV product offerings from OEMs as well as confidential business information on future products currently under development. Therefore in that analysis, BEV and PHEV40 packs were configured with NMC441 cathode chemistry, and PHEV20 and HEV packs were configured with LMO cathode chemistry. Although EPA considered NMC to be the preferred future chemistry for all xEV packs at the time of the FRM, the choice of LMO was necessary due to the relatively high power-to-energy ratio of PHEV20 and HEV, which precluded use of NMC as modeled by BatPaC. All packs had a graphite anode chemistry. These represented the most appropriate chemistry choices among those offered in Version 2 of BatPaC at the time.

Version 3 of BatPaC replaces NMC441 with NMC622, a more commonly cited formulation of NMC[567] with a long cycle life.[568] A blended NMC/LMO cathode option was also added, representing increasing popularity of blended cathodes over pure LMO. Therefore in this Draft TAR analysis, EPA selected NMC622 for BEV and PHEV40 packs, and a blended cathode (25 percent NMC and 75 percent LMO, the BatPaC default value) for PHEV20 and HEV packs. Although most current Li-Ion HEV packs are reported to be using NMC cathodes,[569] EPA found it necessary to model a blended HEV cathode because the default NMC formulations modeled by BatPaC did not always support the power-to-energy ratios required by some of the modeled HEV configurations. This might be due to variations in NMC formulations and particle morphologies that manufacturers might employ to optimize the chemistry for HEV use but which are not represented in the BatPaC default formulations.

Pack topology and cell capacity

In the 2012 FRM, the number of cells per module for all packs had been fixed at 32 cells and the pack topology (number of modules and their arrangement in rows) followed nominal rules and was not optimized. In this Draft TAR analysis, EPA optimized the pack topology for BEVs and PHEVs by choosing values for cells per module, number of modules and arrangement of modules to target a preferred cell capacity.

Since the number of modules per pack must be a whole number, varying the number of cells per module allows the number of cells per pack and their capacities to be better targeted. EPA varied the number of cells per module to between 24 and 36. Based in part on the 55.5 Ampere-hour cells that appear to be used by Nissan and GM in their recently announced 60-kWh packs, and larger cell sizes currently produced or recently announced by leading suppliers, EPA targeted an individual cell capacity of 60 A-hr for BEV packs (not to exceed 75 A-hr) and 45 A-hr for PHEV packs (not to exceed 50 A-hr). Although constraints such as pack voltage and pack capacity prevent matching these targets exactly, cell capacities now cluster more closely to the preferred values than in the 2012 FRM analysis. In many cases this tends to reduce pack costs by tending toward smaller numbers of cells of a larger capacity than assumed in the FRM. HEV packs, which consist of a single module, are configured with 32 cells as before.

Thermal management

In the FRM, BEV and PHEV packs were modeled with liquid cooling while HEV packs were modeled with passive air cooling. Since BatPaC did not provide an option for passive air cooling in which only the outside of the pack is cooled, EPA substituted the BatPaC cooling costs with costs derived from an FEV teardown of an HEV.[570]

As before, the current version of BatPaC continues to provide an option for active air cooling in which individual cells are separated by air passages through which cabin air or cooled air is circulated. Use of this option results in package volumes that are much larger than for a liquid cooled pack. Although passive air cooling continues to be prevalent in HEV packs at the time of this writing, some industry sources have indicated that liquid cooling may also be preferable for HEV packs in order to improve utilization of capacity and increase service life. Minimization of underhood package volume is also a growing concern. EPA therefore chose to utilize liquid cooling for HEV packs as well as BEV and PHEV packs for this Draft TAR analysis.

Pack voltage

For this Draft TAR analysis, EPA limited BEV and PHEV voltages to a slightly narrower range to reflect expected standardization of power electronics voltages. Based on knowledge of current practices and developing trends of battery manufacturers and OEMs, supplemented by discussions with the BatPaC authors, EPA targeted allowable pack voltage to approximately 120V for HEVs (except 48V HEVs) and approximately 300-400V for BEVs and PHEVs.

Electrode dimensions

For electrode coating thickness, the 100 micron maximum limit used in the FRM analysis is retained in this Draft TAR analysis.

Recent developments in pack design (as described in Section 5.2.4.4.6, Electrode Dimensions) suggest that the industry may be moving toward low-profile or flat floor-mounted packs. For this reason, in this Draft TAR analysis EPA has revised the 1.5:1 aspect ratio used in the FRM analysis and now adopts the BatPaC default aspect ratio of 3:1.

Manufacturing volumes

The assumed manufacturing volume for BEV, PHEV and HEV battery packs was retained at 450,000 per year as in the FRM. For a full discussion of considerations with regard to the assumed manufacturing volume, please refer to Section 5.2.4.4.7, Pack Manufacturing Volumes.

Summary of Battery Design Assumptions

Table 5.114 shows a summary of battery design assumptions used in the FRM and those adopted for the Draft TAR analysis.

Table 5.114 Battery Design Assumptions Input to BatPaC and Changes from 2012 FRM to 2016 Draft TAR

Assumption	2012 FRM	2016 Draft TAR
EV75 chemistry	NMC441-G	**NMC622-G**
EV100 chemistry	NMC441-G	**NMC622-G**
EV150/200 chemistry	NMC441-G	**NMC622-G**
PHEV20 chemistry	LMO-G	**25%NMC/75%LMO-G**
PHEV40 chemistry	NMC441-G	**NMC622-G**
HEV chemistry	LMO-G	**25%NMC/75%LMO-G**
Pack topology	varies	**optimized to target preferred cell capacity**
Maximum cell capacity (A-hr)	80	**BEV: target 60, max 75 PHEV: target 45, max 50**
Cells per module	32	**24 to 32**
BEV thermal medium	Liquid	unchanged
PHEV thermal medium	Liquid	unchanged
HEV thermal medium	Air	**Liquid**
BEV pack voltage range (V)	300V-600V	**300V to 400V**
PHEV pack voltage range (V)	300-400	**300V to 400V**
HEV pack voltage range (v)	~120V	unchanged
Maximum electrode thickness (microns)	100	unchanged
Electrode aspect ratio	1.5:1	**3:1**
BEV battery 2020 annual mfg volume	450000	unchanged
PHEV battery 2020 annual mfg volume	450000	unchanged
HEV battery 2020 annual mfg volume	450000	unchanged

5.3.4.3.7.5 Battery Cost Projections for xEVs

Table 5.116 through Table 5.121 show the battery pack direct manufacturing costs (DMC) that EPA used in this analysis, and the degree of change from those used in the FRM, for each level of applied mass reduction technology. The costs are quoted in 2013 dollars and the analysis assigns them to the year 2025 for EVs and PHEVs and the year 2017 for HEVs. This assignment follows the convention used in the 2012 FRM analysis, where HEV battery costs were assigned to the earlier year to reflect considerations such as the relatively larger number of HEV batteries that were in production relative to PHEV and BEV batteries.

The costs shown are BatPaC output figures minus warranty costs. The warranty costs computed by BatPaC are subtracted because the EPA analysis accounts for warranty costs by means of indirect cost multipliers (ICMs).

In the wider analysis, EPA uses these cost figures combined with a learning curve that assigns battery costs for each year over the full time frame of the rule. This curve was developed by first considering the BatPaC costs as applicable to the 2025 MY for EVs and PHEVs and to the 2017 MY for HEVs. EPA then unlearned those costs back to the present year using the curve shown in Section 5.3.2.1.4. This allows EPA to estimate costs applicable to MYs 2017 through 2025.

The changes in direct manufacturing costs from year-to-year reflect cost changes due to learning effects.

As shown in Table 5.115, projected battery costs for many electrified vehicle configurations have fallen substantially from those projected in the FRM. These changes are the result of many influences, including changes to cost assumptions and methodology inherent to BatPaC Version 3, changes to EPA sizing assumptions (usable battery capacity, motor power, energy efficiency, etc.) that have in many cases resulted in reductions to gross battery capacity and power requirements, and changes to EPA inputs to BatPaC (particularly, use of improved pack and module topologies).

Table 5.115 Average Change in Projected Battery Pack DMC from 2012 FRM to 2016 Draft TAR

Electrified Vehicle Type	Average change	
	Change in pack cost	Change in cost per kWh
EV75	-24.9%	-13.4%
EV100	-27.1%	-15.0%
EV150/200	-24.0%	-18.7%
PHEV40	-12.2%	-1.5%
PHEV20	-8.7%	-3.2%
HEV	29.6%	27.7%

Costs for EV75 and EV100 have fallen by an average of about 25 percent on a total cost basis and by about 13 to 15 percent on a cost per kWh basis. The main influences on this change stem from improvement to pack topology and cell sizing, reductions in pack capacity and P/E ratio, etc.

Although EV200 costs are not directly comparable because the FRM modeled EV150, projected costs have fallen by about 24 percent relative to EV150 despite the increase in range.

PHEV40 battery costs have fallen by about 13 percent, having benefited from forces similar to those that have reduced BEV costs, but not as much, because PHEV target battery power has increased relative to the FRM.

PHEV20 battery costs have decreased slightly. The main reason would be the decision to model PHEV20 as a blended PHEV with half the electric motor power of the previous EREV configuration. The reduction due to this is reduced by the increase in PHEV battery power requirements relative the FRM, which increases the P/E ratio and accordingly the cost.

HEV costs have increased significantly by an average of almost 30 percent. This appears to be a result of the change to a mixed NMC and LMO cathode, increased costs projected by BatPaC Version 3 relating in part to the use of thinner electrodes for a given power requirement, and the use of BatPaC liquid cooling costs instead of the FEV teardown costs for air cooling that were used in the FRM. It should be noted that BatPaC does not model passively cooled cell assemblies without significant air flow passages between the cells, which would probably have a lower cost than a liquid cooled pack. However, as modeled by BatPaC, liquid cooled HEV packs have a slightly lower cost than the available air cooled options.

Table 5.116 Estimated Direct Manufacturing Costs in MY2025 for EV75 Battery Packs

EV75* (450k/yr)	0% CWR		2% CWR		7.5% CWR		10% CWR		20% CWR	
FRM (2008 baseline)										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$ 5,115	$ 224	$ 5,098	$ 225	$ 4,996	$ 228	$ 4,962	$ 229	$ 4,768	$ 233
Standard Car	$ 6,021	$ 215	$ 5,965	$ 215	$ 5,818	$ 216	$ 5,755	$ 216	$ 5,509	$ 219
Large Car	$ 7,724	$ 232	$ 7,635	$ 232	$ 7,397	$ 231	$ 7,295	$ 231	$ 6,907	$ 231
Small MPV	$ 5,995	$ 203	$ 5,952	$ 204	$ 5,843	$ 206	$ 5,800	$ 207	$ 5,625	$ 211
Large MPV	$ 7,310	$ 195	$ 7,237	$ 196	$ 7,045	$ 196	$ 6,963	$ 196	$ 6,610	$ 197
Truck	$ 8,332	$ 193	$ 8,242	$ 193	$ 8,005	$ 193	$ 7,883	$ 194	$ 7,474	$ 194
Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$3,962	$203	$3,940	$205	$3,893	$208	$3,873	$210	$3,788	$219
Standard Car	$4,411	$184	$4,391	$186	$4,331	$189	$4,308	$190	$4,203	$196
Large Car	$5,807	$192	$5,752	$193	$5,603	$193	$5,538	$194	$5,404	$195
Small MPV	$4,514	$177	$4,489	$179	$4,431	$182	$4,406	$183	$4,301	$189
Large MPV	$5,380	$164	$5,351	$165	$5,278	$168	$5,248	$169	$5,121	$175
Truck	$5,856	$157	$5,805	$158	$5,674	$159	$5,614	$159	$5,457	$165
Change from FRM										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	-22.5%	-9.4%	-22.7%	-9.0%	-22.1%	-8.6%	-21.9%	-8.4%	-20.5%	-5.9%
Standard Car	-26.7%	-14.2%	-26.4%	-13.7%	-25.6%	-12.6%	-25.2%	-12.1%	-23.7%	-10.1%
Large Car	-24.8%	-17.2%	-24.7%	-17.0%	-24.3%	-16.4%	-24.1%	-16.1%	-21.8%	-15.5%
Small MPV	-24.7%	-12.7%	-24.6%	-12.5%	-24.2%	-11.9%	-24.0%	-11.7%	-23.5%	-10.3%
Large MPV	-26.4%	-15.9%	-26.1%	-15.5%	-25.1%	-14.2%	-24.6%	-13.7%	-22.5%	-11.0%
Truck	-29.7%	-18.5%	-29.6%	-18.3%	-29.1%	-17.6%	-28.8%	-17.6%	-27.0%	-14.8%

Note:

CWR = target percent reduction in vehicle curb weight.
Actual reduction will be less if it would require applying more than 20 percent mass reduction to glider.
*NMC622 cathode.

Table 5.117 Estimated Direct Manufacturing Costs in MY2025 for EV100 Battery Packs

EV100* (450k/yr)	0% CWR		2% CWR		7.5% CWR		10% CWR		20% CWR	
FRM (2008 baseline)										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$ 6,105	$ 201	$ 6,083	$ 201	$ 5,950	$ 204	$ 5,906	$ 205	$ 5,817	$ 206
Standard Car	$ 7,054	$ 189	$ 7,001	$ 189	$ 6,826	$ 190	$ 6,770	$ 191	$ 6,662	$ 192
Large Car	$ 8,630	$ 195	$ 8,535	$ 195	$ 8,283	$ 194	$ 8,175	$ 194	$ 7,999	$ 194
Small MPV	$ 7,293	$ 186	$ 7,237	$ 186	$ 7,096	$ 188	$ 7,039	$ 189	$ 6,953	$ 190
Large MPV	$ 8,641	$ 173	$ 8,571	$ 174	$ 8,392	$ 175	$ 8,321	$ 176	$ 8,215	$ 177
Truck	$ 9,962	$ 173	$ 9,879	$ 174	$ 9,676	$ 175	$ 9,554	$ 176	$ 9,392	$ 177
Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$4,533	$175	$4,511	$176	$4,450	$179	$4,428	$180	$4,345	$185
Standard Car	$5,306	$166	$5,278	$167	$5,207	$170	$5,179	$171	$5,095	$175
Large Car	$6,476	$161	$6,417	$161	$6,265	$162	$6,197	$162	$6,122	$164
Small MPV	$5,404	$159	$5,374	$160	$5,342	$164	$5,312	$165	$5,223	$169
Large MPV	$6,266	$144	$6,227	$144	$6,139	$147	$6,102	$148	$5,995	$151
Truck	$6,266	$135	$6,227	$135	$6,139	$137	$6,102	$138	$5,995	$142
Change from FRM										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	-25.8%	-13.1%	-25.8%	-12.7%	-25.2%	-12.3%	-25.0%	-12.0%	-25.3%	-10.6%
Standard Car	-24.8%	-11.9%	-24.6%	-11.6%	-23.7%	-10.4%	-23.5%	-10.1%	-23.5%	-8.9%
Large Car	-25.0%	-17.3%	-24.8%	-17.1%	-24.4%	-16.5%	-24.2%	-16.3%	-23.5%	-15.9%
Small MPV	-25.9%	-14.1%	-25.7%	-13.9%	-24.7%	-12.5%	-24.5%	-12.3%	-24.9%	-10.9%
Large MPV	-27.5%	-17.2%	-27.3%	-17.0%	-26.8%	-16.3%	-26.7%	-16.0%	-27.0%	-14.7%
Truck	-37.1%	-22.3%	-37.0%	-22.1%	-36.6%	-21.5%	-36.1%	-21.4%	-36.2%	-19.9%

Note:

CWR = target percent reduction in vehicle curb weight.
Actual reduction will be less if it would require applying more than 20 percent mass reduction to glider.
*NMC622 cathode.

Table 5.118 Estimated Direct Manufacturing Costs in MY2025 for EV200 Battery Packs

EV200* (450k/yr)	0% CWR		2% CWR		7.5% CWR		10% CWR		20% CWR	
EV150 in FRM (2008 baseline)										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$ 8,080	$ 177	$ 8,048	$ 178	$ 8,048	$ 178	$ 8,048	$ 178	$ 8,048	$ 178
Standard Car	$ 9,753	$ 174	$ 9,714	$ 174	$ 9,714	$ 174	$ 9,714	$ 174	$ 9,714	$ 174
Large Car	$ 11,120	$ 167	$ 11,073	$ 167	$ 11,073	$ 167	$ 11,073	$ 167	$ 11,073	$ 167
Small MPV	$ 10,109	$ 171	$ 10,109	$ 171	$ 10,109	$ 171	$ 10,109	$ 171	$ 10,109	$ 171
Large MPV	$ 12,114	$ 162	$ 12,112	$ 162	$ 12,112	$ 162	$ 12,112	$ 162	$ 12,112	$ 162
Truck	$ 13,878	$ 161	$ 13,818	$ 161	$ 13,759	$ 161	$ 13,759	$ 161	$ 13,759	$ 161
EV200 in Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$6,712	$156	$6,675	$157	$6,588	$160	$6,572	$161	$6,588	$160
Standard Car	$7,394	$140	$7,351	$141	$7,246	$143	$7,224	$144	$7,224	$144
Large Car	$8,851	$133	$8,797	$134	$8,743	$134	$8,743	$134	$8,743	$134
Small MPV	$7,734	$138	$7,688	$139	$7,555	$141	$7,555	$141	$7,555	$141
Large MPV	$9,160	$127	$9,101	$128	$8,966	$130	$8,966	$130	$8,966	$130
Truck	$9,795	$119	$9,732	$120	$9,579	$122	$9,515	$123	$9,515	$123
Change from FRM (including change from EV150 to EV200)										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	-16.9%	-11.8%	-17.1%	-11.4%	-18.1%	-9.9%	-18.3%	-9.5%	-18.1%	-9.9%
Standard Car	-24.2%	-19.4%	-24.3%	-19.0%	-25.4%	-17.7%	-25.6%	-17.5%	-25.6%	-17.5%
Large Car	-20.4%	-20.4%	-20.6%	-20.1%	-21.0%	-19.6%	-21.0%	-19.6%	-21.0%	-19.6%
Small MPV	-23.5%	-19.5%	-23.9%	-19.0%	-25.3%	-18.0%	-25.3%	-18.0%	-25.3%	-18.0%
Large MPV	-24.4%	-21.6%	-24.9%	-21.2%	-26.0%	-20.0%	-26.0%	-20.0%	-26.0%	-20.0%
Truck	-29.4%	-25.7%	-29.6%	-25.4%	-30.4%	-24.4%	-30.8%	-24.0%	-30.8%	-24.0%

Note:

CWR = target percent reduction in vehicle curb weight.
Actual reduction will be less if it would require applying more than 20 percent mass reduction to glider.
*NMC622 cathode.

Table 5.119 Estimated Direct Manufacturing Costs in MY2025 for PHEV20 Battery Packs

PHEV20* (450k/yr)	0% CWR		2% CWR		7.5% CWR		10% CWR		20% CWR	
FRM (2008 baseline)										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$ 2,531	$ 364	$ 2,517	$ 364	$ 2,469	$ 370	$ 2,447	$ 371	$ 2,431	$ 373
Standard Car	$ 2,962	$ 347	$ 2,938	$ 348	$ 2,835	$ 345	$ 2,808	$ 346	$ 2,784	$ 347
Large Car	$ 3,734	$ 368	$ 3,696	$ 369	$ 3,592	$ 369	$ 3,546	$ 368	$ 3,510	$ 369
Small MPV	$ 2,835	$ 316	$ 2,813	$ 317	$ 2,754	$ 319	$ 2,730	$ 320	$ 2,703	$ 323
Large MPV	$ 3,424	$ 300	$ 3,393	$ 301	$ 3,309	$ 302	$ 3,274	$ 303	$ 3,244	$ 303
Truck	$ 3,874	$ 295	$ 3,834	$ 295	$ 3,732	$ 295	$ 3,681	$ 297	$ 3,671	$ 296
Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$2,463	$382	$2,454	$385	$2,433	$394	$2,424	$397	$2,420	$399
Standard Car	$2,690	$340	$2,678	$342	$2,649	$349	$2,638	$352	$2,638	$352
Large Car	$3,157	$316	$3,136	$318	$3,080	$321	$3,070	$322	$3,070	$322
Small MPV	$2,737	$325	$2,727	$328	$2,699	$335	$2,688	$337	$2,683	$339
Large MPV	$3,025	$279	$3,008	$281	$2,962	$285	$2,942	$287	$2,937	$288
Truck	$3,190	$259	$3,169	$261	$3,115	$264	$3,103	$265	$3,103	$265
Change from FRM										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	-2.7%	4.9%	-2.5%	5.8%	-1.4%	6.5%	-0.9%	7.1%	-0.5%	7.0%
Standard Car	-9.2%	-1.9%	-8.9%	-1.6%	-6.6%	1.1%	-6.0%	1.7%	-5.2%	1.4%
Large Car	-15.4%	-14.2%	-15.1%	-13.8%	-14.3%	-12.8%	-13.4%	-12.4%	-12.5%	-12.6%
Small MPV	-3.4%	3.1%	-3.1%	3.6%	-2.0%	4.9%	-1.5%	5.5%	-0.7%	5.1%
Large MPV	-11.6%	-7.0%	-11.4%	-6.7%	-10.5%	-5.6%	-10.1%	-5.2%	-9.5%	-5.0%
Truck	-17.6%	-12.0%	-17.3%	-11.6%	-16.5%	-10.6%	-15.7%	-10.8%	-15.5%	-10.5%

Note:

CWR = target percent reduction in vehicle curb weight.
Actual reduction will be less if it would require applying more than 20 percent mass reduction to glider.
*Blended LMO-NMC cathode.

Table 5.120 Estimated Direct Manufacturing Costs in MY2025 for PHEV40 Battery Packs

PHEV40* (450k/yr)	0% CWR		2% CWR		7.5% CWR		10% CWR		20% CWR	
FRM (2008 baseline)										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$ 3,644	$ 262	$ 3,619	$ 262	$ 3,542	$ 264	$ 3,542	$ 264	$ 3,542	$ 264
Standard Car	$ 4,390	$ 257	$ 4,343	$ 257	$ 4,228	$ 258	$ 4,228	$ 258	$ 4,228	$ 258
Large Car	$ 6,006	$ 296	$ 5,921	$ 295	$ 5,671	$ 291	$ 5,671	$ 291	$ 5,671	$ 291
Small MPV	$ 4,247	$ 236	$ 4,207	$ 237	$ 4,101	$ 238	$ 4,100	$ 237	$ 4,100	$ 237
Large MPV	$ 5,269	$ 231	$ 5,212	$ 231	$ 5,065	$ 231	$ 5,065	$ 231	$ 5,065	$ 231
Truck	$ 6,122	$ 233	$ 6,050	$ 233	$ 5,900	$ 232	$ 5,900	$ 232	$ 5,900	$ 232
Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$3,130	$260	$3,111	$262	$3,077	$264	$3,078	$264	$3,077	$264
Standard Car	$3,705	$251	$3,599	$246	$3,559	$247	$3,559	$247	$3,559	$247
Large Car	$5,528	$295	$5,550	$296	$5,552	$296	$5,550	$296	$5,552	$296
Small MPV	$3,661	$233	$3,635	$234	$3,579	$236	$3,579	$236	$3,579	$236
Large MPV	$4,620	$229	$4,622	$231	$4,574	$232	$4,574	$232	$4,574	$232
Truck	$5,073	$221	$5,026	$221	$4,999	$222	$4,999	$222	$4,999	$222
Change from FRM										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	-14.1%	-0.8%	-14.0%	-0.1%	-13.1%	-0.1%	-13.1%	-0.1%	-13.1%	-0.1%
Standard Car	-15.6%	-2.4%	-17.1%	-4.1%	-15.8%	-4.2%	-15.8%	-4.2%	-15.8%	-4.2%
Large Car	-8.0%	-0.5%	-6.3%	0.2%	-2.1%	1.7%	-2.1%	1.7%	-2.1%	1.7%
Small MPV	-13.8%	-1.4%	-13.6%	-1.1%	-12.7%	-0.5%	-12.7%	-0.5%	-12.7%	-0.5%
Large MPV	-12.3%	-1.1%	-11.3%	0.0%	-9.7%	0.2%	-9.7%	0.2%	-9.7%	0.2%
Truck	-17.1%	-5.1%	-16.9%	-4.8%	-15.3%	-4.5%	-15.3%	-4.5%	-15.3%	-4.5%

Note:

CWR = target percent reduction in vehicle curb weight.
Actual reduction will be less if it would require applying more than 20 percent mass reduction to glider.
*NMC622 cathode.

Table 5.121 Estimated Direct Manufacturing Costs in MY2017 for strong HEV Battery Packs

STRONG HEV* (450k/yr)	0% CWR		2% CWR		7.5% CWR		10% CWR		20% CWR	
FRM (2008 baseline)										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$ 726	$ 896	$ 722	$ 909	$ 712	$ 950	$ 708	$ 970	$ 700	$ 1,008
Standard Car	$ 801	$ 804	$ 796	$ 815	$ 783	$ 849	$ 777	$ 866	$ 765	$ 901
Large Car	$ 938	$ 809	$ 929	$ 817	$ 909	$ 848	$ 900	$ 862	$ 882	$ 894
Small MPV	$ 779	$ 747	$ 775	$ 758	$ 762	$ 790	$ 757	$ 806	$ 746	$ 839
Large MPV	$ 876	$ 682	$ 870	$ 691	$ 853	$ 718	$ 846	$ 731	$ 830	$ 760
Truck	$ 1,010	$ 676	$ 1,003	$ 685	$ 983	$ 711	$ 974	$ 724	$ 957	$ 747
Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$ 984	$ 1,216	$ 980	$ 1,236	$ 971	$ 1,297	$ 966	$1,326	$ 958	$ 1,383
Standard Car	$ 1,051	$ 1,057	$ 1,046	$ 1,074	$ 1,033	$ 1,123	$ 1,027	$1,148	$ 1,016	$ 1,198
Large Car	$ 1,197	$ 976	$ 1,188	$ 988	$ 1,168	$ 1,029	$ 1,158	$1,050	$ 1,140	$ 1,093
Small MPV	$ 1,033	$ 984	$ 1,029	$ 1,000	$ 1,017	$ 1,047	$ 1,011	$1,070	$ 1,001	$ 1,118
Large MPV	$ 1,123	$ 855	$ 1,117	$ 868	$ 1,100	$ 907	$ 1,093	$ 925	$ 1,078	$ 966
Truck	$ 1,194	$ 792	$ 1,187	$ 803	$ 1,167	$ 836	$ 1,158	$ 853	$ 1,142	$ 882
Change from FRM										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	35.6%	35.8%	35.8%	36.0%	36.3%	36.5%	36.6%	36.7%	37.0%	37.2%
Standard Car	31.2%	31.5%	31.4%	31.7%	32.0%	32.2%	32.3%	32.5%	32.8%	33.0%
Large Car	27.7%	20.7%	27.9%	20.9%	28.4%	21.5%	28.7%	21.7%	29.2%	22.2%
Small MPV	32.6%	31.7%	32.8%	31.9%	33.4%	32.5%	33.6%	32.7%	34.2%	33.3%
Large MPV	28.2%	25.5%	28.4%	25.7%	29.0%	26.3%	29.2%	26.5%	29.8%	27.1%
Truck	18.3%	17.1%	18.4%	17.2%	18.7%	17.5%	18.8%	17.7%	19.3%	18.2%

Note:

CWR = target percent reduction in vehicle curb weight.
Actual reduction will be less if it would require applying more than 20 percent mass reduction to glider.
*Blended LMO-NMC cathode.

5.3.4.3.7.6 Discussion of Battery Cost Projections

In Section 5.2.4.4.9 (Evaluation of 2012 FRM Battery Cost Projections), the agencies reviewed the 2020-2022 cell-level costs projected by GM for its LG-supplied cells for the Chevy Bolt EV, and converted them to estimated pack-level costs per gross kWh. These estimated costs were shown to appear generally lower than the pack-level costs for EV150 that were generated by the 2012 FRM analysis. Figure 5.114 extends this comparison to the pack-level costs for EV200 projected by this Draft TAR analysis. Although these Draft TAR projected costs are significantly lower than the costs projected in the 2012 FRM analysis, they appear consistent with and in many cases appear to remain conservative with respect to the trend established by the GM/LG pack-converted cost estimates.

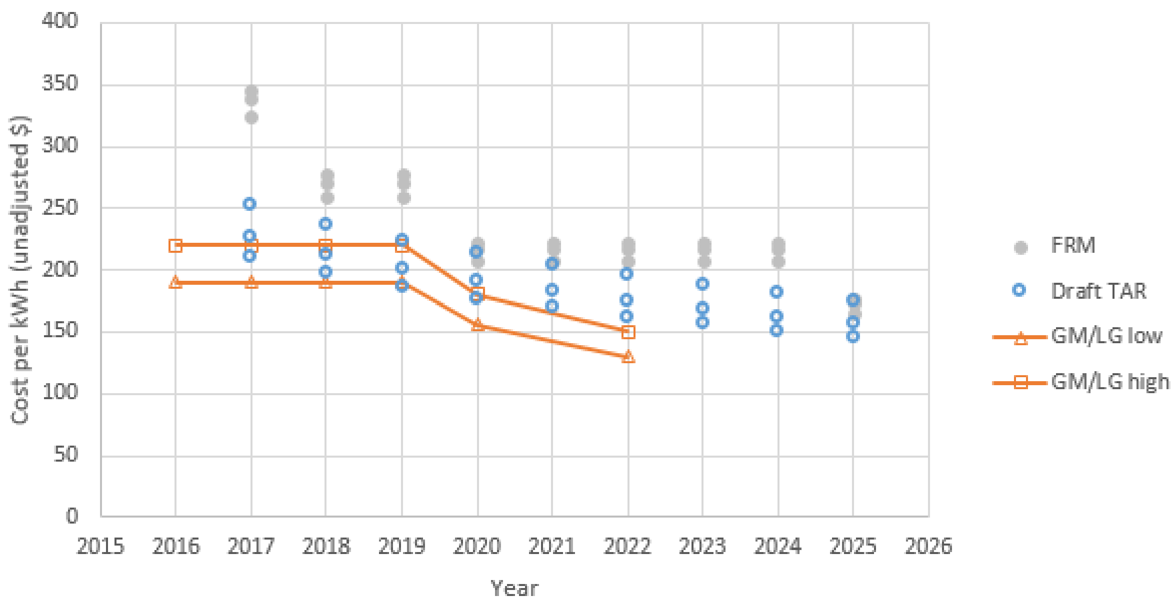


Figure 5.114 Comparison of Estimated Pack-Converted GM/LG Costs to 2012 FRM EV150 and Draft TAR EV200 Projections

As discussed in Section 5.2.4.4.9, comparisons of the GM/LG costs to those of the 2012 FRM and Draft TAR analyses are subject to some uncertainty. However, comparison on this basis to the 2012 FRM projections suggests that those projections may have been conservative with respect to trends in battery cost that have occurred since the FRM. This outcome suggests that EPA's battery costing methodology, with the updates and refinements discussed previously, is an appropriate basis on which to derive updated projections for this Draft GHG Assessment. As suggested throughout this analysis, it should be noted that battery costs have many drivers, and future cost projections derived by any methodology are subject to significant uncertainties.

5.3.4.3.7.7 Battery Pack Costs Used in OMEGA

Table 5.122 Linear Regressions of Strong Hybrid Battery System Direct Manufacturing Costs vs Net Mass Reduction Applicable in MY2017 (2013$)

Vehicle Class	Strong HEV
Small car	-$176x+$984
Standard car	-$235x+$1,051
Large car	-$379x+$1,196
Small MPV	-$217x+$1,033
Large MPV	-$299x+$1,123
Truck	-$365x+$1,194

Note: "x" in the equations represents the net weight reduction as a percentage.

Table 5.123 Linear Regressions of Battery Electric Battery System Direct Manufacturing Costs vs Net Mass Reduction Applicable in MY2025 (2013$)

Vehicle Class	PHEV20	PHEV40	EV75	EV100	EV200
Small car	-$403x+$2,463	-$891x+$3,130	-$885x+$3,960	-$1,121x+$4,534	-$1,628x+$6,710
Standard car	-$518x+$2,689	-$2,607x+$3,685	-$1,123x+$4,414	-$1,319x+$5,306	-$2,063x+$7,394
Large car	-$1,039x+$3,157	-$28,870x+$5,337	-$2,702x+$5,807	-$2,823x+$6,475	-$2,630x+$8,851
Small MPV	-$502x+$2,737	-$1,293x+$3,661	-$1,136x+$4,515	-$1,064x+$5,407	-$2,315x+$7,734
Large MPV	n/a	n/a	n/a	n/a	n/a
Truck	n/a	n/a	n/a	n/a	n/a

Note: "x" in the equations represents the net weight reduction as a percentage.

Table 5.124 Costs for MHEV48V Battery (dollar values in 2013$)

Vehicle Class	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
All	DMC	$306	31	$306	$277	$258	$244	$234	$225	$218	$212	$206
All	IC	High1	2024	$172	$170	$169	$168	$168	$167	$167	$166	$102
All	TC			$478	$447	$427	$413	$401	$392	$384	$378	$309

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.125 Costs for Strong Hybrid Batteries (dollar values in 2013$)

Vehicle Class	WRtech	WRnet	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	10	5	DMC	$975	31	$975	$883	$823	$779	$745	$717	$694	$674	$657
SmCar	15	10	DMC	$966	31	$966	$875	$815	$772	$738	$711	$688	$668	$651
SmCar	20	15	DMC	$957	31	$957	$867	$808	$765	$731	$704	$682	$662	$645
StCar	10	5	DMC	$1,039	31	$1,039	$941	$877	$830	$794	$764	$740	$719	$700
StCar	15	10	DMC	$1,027	31	$1,027	$930	$867	$821	$785	$756	$731	$711	$692
StCar	20	15	DMC	$1,015	31	$1,015	$919	$857	$811	$776	$747	$723	$702	$685
LgCar	10	5	DMC	$1,177	31	$1,177	$1,066	$994	$941	$900	$866	$838	$815	$794
LgCar	15	10	DMC	$1,159	31	$1,159	$1,049	$978	$926	$885	$852	$825	$801	$781
LgCar	20	15	DMC	$1,140	31	$1,140	$1,032	$962	$910	$871	$838	$811	$788	$768
SmMPV	10	5	DMC	$1,022	31	$1,022	$925	$862	$816	$781	$752	$728	$707	$689
SmMPV	15	10	DMC	$1,011	31	$1,011	$916	$853	$808	$773	$744	$720	$699	$682
SmMPV	20	15	DMC	$1,000	31	$1,000	$906	$844	$799	$764	$736	$712	$692	$674
LgMPV	10	6	DMC	$1,105	31	$1,105	$1,000	$932	$883	$844	$813	$787	$764	$745
LgMPV	15	11	DMC	$1,090	31	$1,090	$987	$920	$871	$833	$802	$776	$754	$735
LgMPV	20	16	DMC	$1,075	31	$1,075	$973	$907	$859	$821	$791	$765	$744	$725
Truck	10	6	DMC	$1,172	31	$1,172	$1,061	$989	$937	$896	$862	$835	$811	$790
Truck	15	11	DMC	$1,154	31	$1,154	$1,045	$974	$922	$882	$849	$822	$798	$778
Truck	20	16	DMC	$1,136	31	$1,136	$1,028	$958	$907	$868	$836	$809	$786	$766
SmCar	10	5	IC	High1	2024	$549	$544	$540	$537	$535	$533	$531	$530	$327
SmCar	15	10	IC	High1	2024	$545	$539	$535	$532	$530	$528	$527	$525	$324
SmCar	20	15	IC	High1	2024	$540	$534	$530	$527	$525	$523	$522	$520	$321
StCar	10	5	IC	High1	2024	$586	$579	$575	$572	$570	$568	$566	$565	$348
StCar	15	10	IC	High1	2024	$579	$573	$569	$566	$563	$561	$560	$558	$344
StCar	20	15	IC	High1	2024	$572	$566	$562	$559	$557	$555	$553	$552	$340
LgCar	10	5	IC	High1	2024	$664	$656	$652	$648	$646	$643	$642	$640	$394
LgCar	15	10	IC	High1	2024	$653	$646	$641	$638	$635	$633	$631	$630	$388
LgCar	20	15	IC	High1	2024	$642	$635	$631	$627	$625	$623	$621	$620	$382
SmMPV	10	5	IC	High1	2024	$576	$570	$566	$563	$560	$559	$557	$556	$342
SmMPV	15	10	IC	High1	2024	$570	$564	$560	$557	$554	$553	$551	$550	$339
SmMPV	20	15	IC	High1	2024	$564	$558	$554	$551	$548	$547	$545	$544	$335
LgMPV	10	6	IC	High1	2024	$623	$616	$611	$608	$606	$604	$602	$601	$370
LgMPV	15	11	IC	High1	2024	$614	$608	$603	$600	$598	$596	$594	$592	$365
LgMPV	20	16	IC	High1	2024	$606	$599	$595	$592	$589	$587	$586	$584	$360
Truck	10	6	IC	High1	2024	$661	$654	$649	$645	$643	$641	$639	$637	$393
Truck	15	11	IC	High1	2024	$650	$643	$639	$635	$633	$631	$629	$627	$387
Truck	20	16	IC	High1	2024	$640	$633	$629	$625	$623	$621	$619	$617	$381
SmCar	10	5	TC			$1,524	$1,426	$1,362	$1,316	$1,279	$1,250	$1,226	$1,204	$984
SmCar	15	10	TC			$1,511	$1,413	$1,350	$1,304	$1,268	$1,239	$1,214	$1,194	$975
SmCar	20	15	TC			$1,497	$1,401	$1,338	$1,292	$1,256	$1,228	$1,203	$1,183	$966
StCar	10	5	TC			$1,625	$1,520	$1,452	$1,402	$1,363	$1,332	$1,306	$1,284	$1,048
StCar	15	10	TC			$1,606	$1,503	$1,435	$1,386	$1,348	$1,317	$1,291	$1,269	$1,037
StCar	20	15	TC			$1,588	$1,486	$1,419	$1,370	$1,333	$1,302	$1,276	$1,255	$1,025
LgCar	10	5	TC			$1,841	$1,723	$1,645	$1,589	$1,545	$1,510	$1,480	$1,455	$1,188
LgCar	15	10	TC			$1,811	$1,695	$1,619	$1,563	$1,520	$1,485	$1,456	$1,431	$1,169
LgCar	20	15	TC			$1,782	$1,667	$1,592	$1,538	$1,496	$1,461	$1,432	$1,408	$1,150
SmMPV	10	5	TC			$1,598	$1,495	$1,428	$1,379	$1,341	$1,310	$1,285	$1,263	$1,031
SmMPV	15	10	TC			$1,581	$1,479	$1,413	$1,365	$1,327	$1,296	$1,271	$1,249	$1,020
SmMPV	20	15	TC			$1,564	$1,463	$1,398	$1,350	$1,313	$1,283	$1,257	$1,236	$1,009
LgMPV	10	6	TC			$1,727	$1,616	$1,544	$1,491	$1,450	$1,416	$1,389	$1,365	$1,115
LgMPV	15	11	TC			$1,704	$1,594	$1,523	$1,471	$1,430	$1,397	$1,370	$1,346	$1,100
LgMPV	20	16	TC			$1,681	$1,572	$1,502	$1,450	$1,411	$1,378	$1,351	$1,328	$1,085
Truck	10	6	TC			$1,833	$1,715	$1,638	$1,582	$1,538	$1,503	$1,474	$1,448	$1,183
Truck	15	11	TC			$1,804	$1,688	$1,612	$1,557	$1,514	$1,480	$1,451	$1,426	$1,165
Truck	20	16	TC			$1,776	$1,661	$1,587	$1,533	$1,490	$1,456	$1,428	$1,403	$1,146

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.126 Costs for 20 Mile Plug-in Hybrid Batteries (dollar values in 2013$)

Vehicle Class	WRtech	WRnet	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	15	6	DMC	$2,439	26	$3,933	$3,691	$3,490	$3,319	$3,172	$3,043	$2,929	$2,827	$2,735
SmCar	20	11	DMC	$2,419	26	$3,901	$3,661	$3,461	$3,292	$3,146	$3,018	$2,904	$2,803	$2,712
StCar	15	6	DMC	$2,658	26	$4,287	$4,023	$3,804	$3,618	$3,457	$3,317	$3,192	$3,081	$2,981
StCar	20	11	DMC	$2,632	26	$4,246	$3,984	$3,767	$3,582	$3,423	$3,284	$3,161	$3,051	$2,952
LgCar	15	5	DMC	$3,105	26	$5,008	$4,700	$4,444	$4,226	$4,038	$3,874	$3,729	$3,599	$3,482
LgCar	20	10	DMC	$3,053	26	$4,924	$4,621	$4,369	$4,155	$3,971	$3,809	$3,667	$3,539	$3,424
SmMPV	15	6	DMC	$2,707	26	$4,366	$4,097	$3,874	$3,684	$3,521	$3,377	$3,251	$3,138	$3,036
SmMPV	20	11	DMC	$2,682	26	$4,326	$4,059	$3,838	$3,650	$3,488	$3,346	$3,221	$3,109	$3,008
LgMPV	15	4	DMC	$2,991	26	$4,825	$4,527	$4,281	$4,071	$3,890	$3,732	$3,592	$3,467	$3,355
LgMPV	20	9	DMC	$2,949	26	$4,756	$4,463	$4,220	$4,013	$3,835	$3,679	$3,541	$3,418	$3,307
Truck	15	6	DMC	$3,131	26	$5,050	$4,739	$4,480	$4,261	$4,072	$3,906	$3,760	$3,629	$3,511
Truck	20	11	DMC	$3,082	26	$4,971	$4,665	$4,410	$4,194	$4,008	$3,845	$3,701	$3,572	$3,456
SmCar	15	6	IC	High2	2024	$1,988	$1,970	$1,955	$1,943	$1,932	$1,922	$1,914	$1,906	$1,226
SmCar	20	11	IC	High2	2024	$1,972	$1,954	$1,939	$1,927	$1,916	$1,906	$1,898	$1,891	$1,215
StCar	15	6	IC	High2	2024	$2,167	$2,147	$2,131	$2,117	$2,106	$2,095	$2,086	$2,078	$1,336
StCar	20	11	IC	High2	2024	$2,146	$2,126	$2,110	$2,097	$2,085	$2,075	$2,066	$2,058	$1,323
LgCar	15	5	IC	High2	2024	$2,531	$2,508	$2,490	$2,474	$2,460	$2,448	$2,437	$2,427	$1,560
LgCar	20	10	IC	High2	2024	$2,489	$2,466	$2,448	$2,432	$2,419	$2,407	$2,396	$2,387	$1,534
SmMPV	15	6	IC	High2	2024	$2,207	$2,187	$2,170	$2,156	$2,144	$2,134	$2,124	$2,116	$1,360
SmMPV	20	11	IC	High2	2024	$2,186	$2,166	$2,150	$2,136	$2,124	$2,114	$2,105	$2,096	$1,348
LgMPV	15	4	IC	High2	2024	$2,438	$2,416	$2,398	$2,383	$2,370	$2,358	$2,348	$2,338	$1,503
LgMPV	20	9	IC	High2	2024	$2,404	$2,382	$2,364	$2,349	$2,336	$2,324	$2,314	$2,305	$1,482
Truck	15	6	IC	High2	2024	$2,552	$2,529	$2,510	$2,494	$2,480	$2,468	$2,457	$2,448	$1,573
Truck	20	11	IC	High2	2024	$2,512	$2,490	$2,471	$2,455	$2,441	$2,429	$2,419	$2,409	$1,549
SmCar	15	6	TC			$5,921	$5,661	$5,445	$5,262	$5,104	$4,965	$4,843	$4,733	$3,961
SmCar	20	11	TC			$5,872	$5,614	$5,400	$5,218	$5,061	$4,924	$4,803	$4,694	$3,928
StCar	15	6	TC			$6,454	$6,171	$5,935	$5,735	$5,563	$5,412	$5,278	$5,159	$4,317
StCar	20	11	TC			$6,391	$6,110	$5,877	$5,679	$5,509	$5,359	$5,227	$5,109	$4,275
LgCar	15	5	TC			$7,539	$7,208	$6,933	$6,700	$6,498	$6,322	$6,166	$6,027	$5,043
LgCar	20	10	TC			$7,413	$7,088	$6,817	$6,588	$6,389	$6,216	$6,063	$5,926	$4,958
SmMPV	15	6	TC			$6,573	$6,284	$6,044	$5,841	$5,665	$5,511	$5,375	$5,254	$4,396
SmMPV	20	11	TC			$6,512	$6,226	$5,988	$5,786	$5,612	$5,460	$5,325	$5,205	$4,355
LgMPV	15	4	TC			$7,263	$6,944	$6,679	$6,454	$6,260	$6,090	$5,940	$5,806	$4,858
LgMPV	20	9	TC			$7,160	$6,845	$6,584	$6,362	$6,171	$6,004	$5,855	$5,723	$4,789
Truck	15	6	TC			$7,602	$7,268	$6,991	$6,755	$6,552	$6,374	$6,217	$6,077	$5,085
Truck	20	11	TC			$7,483	$7,154	$6,881	$6,649	$6,449	$6,274	$6,120	$5,981	$5,005

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.127 Costs for 40 Mile Plug-in Hybrid Batteries (dollar values in 2013$)

Vehicle Class	WR tech	WR net	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	20	6	DMC	$3,076	26	$4,962	$4,656	$4,402	$4,187	$4,001	$3,838	$3,694	$3,566	$3,450
StCar	20	5	DMC	$3,554	26	$5,733	$5,380	$5,086	$4,838	$4,623	$4,435	$4,268	$4,120	$3,986
LgCar	20	3	DMC	$4,471	26	$7,211	$6,767	$6,398	$6,085	$5,815	$5,578	$5,369	$5,182	$5,014
SmMPV	20	7	DMC	$3,570	26	$5,759	$5,404	$5,110	$4,860	$4,644	$4,455	$4,288	$4,139	$4,004
LgMPV	20	0	DMC	$4,629	26	$7,467	$7,007	$6,625	$6,300	$6,021	$5,776	$5,559	$5,366	$5,192
Truck	20	5	DMC	$4,960	26	$7,999	$7,507	$7,097	$6,750	$6,450	$6,188	$5,956	$5,749	$5,562
SmCar	20	6	IC	High2	2024	$2,508	$2,485	$2,466	$2,450	$2,437	$2,425	$2,414	$2,405	$1,546
StCar	20	5	IC	High2	2024	$2,897	$2,871	$2,850	$2,831	$2,816	$2,802	$2,790	$2,779	$1,786
LgCar	20	3	IC	High2	2024	$3,645	$3,612	$3,585	$3,562	$3,542	$3,524	$3,509	$3,495	$2,247
SmMPV	20	7	IC	High2	2024	$2,911	$2,884	$2,863	$2,844	$2,828	$2,815	$2,802	$2,791	$1,794
LgMPV	20	0	IC	High2	2024	$3,774	$3,740	$3,712	$3,688	$3,667	$3,649	$3,633	$3,619	$2,326
Truck	20	5	IC	High2	2024	$4,043	$4,007	$3,976	$3,951	$3,929	$3,909	$3,892	$3,877	$2,492
SmCar	20	6	TC			$7,469	$7,141	$6,868	$6,637	$6,437	$6,263	$6,108	$5,970	$4,996
StCar	20	5	TC			$8,630	$8,251	$7,936	$7,669	$7,438	$7,237	$7,058	$6,898	$5,772
LgCar	20	3	TC			$10,856	$10,379	$9,983	$9,647	$9,357	$9,103	$8,878	$8,678	$7,261
SmMPV	20	7	TC			$8,670	$8,289	$7,972	$7,704	$7,472	$7,269	$7,090	$6,930	$5,799
LgMPV	20	0	TC			$11,240	$10,746	$10,336	$9,988	$9,688	$9,425	$9,192	$8,985	$7,518
Truck	20	5	TC			$12,042	$11,513	$11,074	$10,701	$10,379	$10,097	$9,848	$9,626	$8,054

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.128 Costs for 75 Mile BEV Batteries (dollar values in 2013$)

Vehicle Class	WR tech	WR net	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	10	10	DMC	$3,872	26	$6,245	$5,860	$5,541	$5,270	$5,036	$4,831	$4,650	$4,488	$4,342
SmCar	15	15	DMC	$3,827	26	$6,173	$5,793	$5,477	$5,209	$4,978	$4,776	$4,596	$4,437	$4,292
SmCar	20	20	DMC	$3,783	26	$6,102	$5,726	$5,414	$5,149	$4,920	$4,720	$4,543	$4,385	$4,243
StCar	10	10	DMC	$4,301	26	$6,938	$6,511	$6,156	$5,854	$5,594	$5,367	$5,166	$4,986	$4,824
StCar	15	15	DMC	$4,245	26	$6,847	$6,426	$6,075	$5,778	$5,521	$5,297	$5,098	$4,921	$4,761
StCar	20	20	DMC	$4,189	26	$6,757	$6,341	$5,995	$5,702	$5,448	$5,227	$5,031	$4,856	$4,698
LgCar	10	10	DMC	$5,536	26	$8,930	$8,380	$7,923	$7,535	$7,200	$6,908	$6,649	$6,417	$6,209
LgCar	15	15	DMC	$5,401	26	$8,712	$8,175	$7,729	$7,351	$7,025	$6,739	$6,486	$6,261	$6,057
LgCar	20	20	DMC	$5,266	26	$8,494	$7,971	$7,536	$7,167	$6,849	$6,571	$6,324	$6,104	$5,906
SmMPV	10	10	DMC	$4,401	26	$7,099	$6,661	$6,298	$5,990	$5,724	$5,491	$5,285	$5,101	$4,936
SmMPV	15	15	DMC	$4,344	26	$7,007	$6,576	$6,217	$5,913	$5,650	$5,420	$5,217	$5,036	$4,872
SmMPV	20	20	DMC	$4,288	26	$6,916	$6,490	$6,136	$5,835	$5,576	$5,350	$5,149	$4,970	$4,808
LgMPV	10	5	DMC	$5,312	26	$8,568	$8,040	$7,602	$7,230	$6,908	$6,628	$6,379	$6,157	$5,957
LgMPV	15	10	DMC	$5,243	26	$8,457	$7,936	$7,503	$7,136	$6,819	$6,542	$6,296	$6,077	$5,880
LgMPV	20	15	DMC	$5,174	26	$8,346	$7,831	$7,404	$7,042	$6,729	$6,456	$6,214	$5,997	$5,803
Truck	10	10	DMC	$5,638	26	$9,094	$8,534	$8,069	$7,674	$7,333	$7,035	$6,771	$6,536	$6,323
Truck	15	15	DMC	$5,538	26	$8,932	$8,382	$7,925	$7,537	$7,202	$6,910	$6,651	$6,419	$6,211
Truck	20	20	DMC	$5,437	26	$8,770	$8,230	$7,781	$7,400	$7,072	$6,784	$6,530	$6,303	$6,098
SmCar	10	10	IC	High2	2024	$3,156	$3,128	$3,104	$3,084	$3,067	$3,052	$3,039	$3,027	$1,946
SmCar	15	15	IC	High2	2024	$3,120	$3,092	$3,069	$3,049	$3,032	$3,017	$3,004	$2,992	$1,923
SmCar	20	20	IC	High2	2024	$3,084	$3,056	$3,033	$3,014	$2,997	$2,982	$2,969	$2,958	$1,901
StCar	10	10	IC	High2	2024	$3,506	$3,475	$3,449	$3,427	$3,407	$3,391	$3,376	$3,363	$2,162
StCar	15	15	IC	High2	2024	$3,461	$3,430	$3,404	$3,382	$3,363	$3,346	$3,332	$3,319	$2,133
StCar	20	20	IC	High2	2024	$3,415	$3,384	$3,359	$3,337	$3,318	$3,302	$3,288	$3,275	$2,105
LgCar	10	10	IC	High2	2024	$4,513	$4,473	$4,439	$4,410	$4,386	$4,364	$4,345	$4,328	$2,782
LgCar	15	15	IC	High2	2024	$4,403	$4,363	$4,331	$4,303	$4,279	$4,258	$4,239	$4,222	$2,714
LgCar	20	20	IC	High2	2024	$4,293	$4,254	$4,222	$4,195	$4,172	$4,151	$4,133	$4,117	$2,646

SmMPV	10	10	IC	High2	2024	$3,588	$3,555	$3,529	$3,506	$3,486	$3,469	$3,454	$3,441	$2,212
SmMPV	15	15	IC	High2	2024	$3,541	$3,510	$3,483	$3,461	$3,441	$3,425	$3,410	$3,396	$2,183
SmMPV	20	20	IC	High2	2024	$3,495	$3,464	$3,438	$3,416	$3,396	$3,380	$3,365	$3,352	$2,155
LgMPV	10	5	IC	High2	2024	$4,330	$4,291	$4,259	$4,231	$4,208	$4,187	$4,169	$4,153	$2,669
LgMPV	15	10	IC	High2	2024	$4,274	$4,236	$4,204	$4,177	$4,153	$4,133	$4,115	$4,099	$2,635
LgMPV	20	15	IC	High2	2024	$4,218	$4,180	$4,148	$4,122	$4,099	$4,079	$4,061	$4,045	$2,600
Truck	10	10	IC	High2	2024	$4,596	$4,555	$4,521	$4,492	$4,467	$4,445	$4,425	$4,408	$2,834
Truck	15	15	IC	High2	2024	$4,514	$4,474	$4,440	$4,412	$4,387	$4,365	$4,346	$4,329	$2,783
Truck	20	20	IC	High2	2024	$4,432	$4,393	$4,360	$4,331	$4,307	$4,286	$4,267	$4,251	$2,733
SmCar	10	10	TC			$9,401	$8,988	$8,645	$8,354	$8,103	$7,883	$7,688	$7,515	$6,288
SmCar	15	15	TC			$9,293	$8,885	$8,546	$8,258	$8,010	$7,793	$7,600	$7,429	$6,216
SmCar	20	20	TC			$9,186	$8,782	$8,447	$8,163	$7,917	$7,703	$7,512	$7,343	$6,144
StCar	10	10	TC			$10,444	$9,986	$9,604	$9,281	$9,002	$8,758	$8,542	$8,349	$6,986
StCar	15	15	TC			$10,308	$9,855	$9,479	$9,160	$8,884	$8,643	$8,430	$8,240	$6,895
StCar	20	20	TC			$10,172	$9,725	$9,354	$9,039	$8,767	$8,529	$8,319	$8,131	$6,803
LgCar	10	10	TC			$13,443	$12,852	$12,362	$11,945	$11,586	$11,272	$10,994	$10,745	$8,991
LgCar	15	15	TC			$13,115	$12,539	$12,060	$11,654	$11,303	$10,997	$10,725	$10,483	$8,772
LgCar	20	20	TC			$12,787	$12,225	$11,758	$11,362	$11,021	$10,722	$10,457	$10,221	$8,552
SmMPV	10	10	TC			$10,686	$10,217	$9,827	$9,496	$9,210	$8,961	$8,740	$8,542	$7,148
SmMPV	15	15	TC			$10,549	$10,085	$9,700	$9,374	$9,092	$8,845	$8,627	$8,432	$7,055
SmMPV	20	20	TC			$10,411	$9,953	$9,573	$9,251	$8,973	$8,729	$8,514	$8,322	$6,963
LgMPV	10	5	TC			$12,898	$12,331	$11,860	$11,461	$11,116	$10,815	$10,548	$10,310	$8,627
LgMPV	15	10	TC			$12,731	$12,171	$11,707	$11,312	$10,972	$10,675	$10,411	$10,176	$8,515
LgMPV	20	15	TC			$12,563	$12,011	$11,553	$11,164	$10,828	$10,534	$10,275	$10,042	$8,403
Truck	10	10	TC			$13,691	$13,089	$12,590	$12,166	$11,800	$11,480	$11,196	$10,943	$9,157
Truck	15	15	TC			$13,447	$12,856	$12,365	$11,949	$11,589	$11,275	$10,997	$10,748	$8,994
Truck	20	20	TC			$13,202	$12,622	$12,141	$11,732	$11,379	$11,070	$10,797	$10,553	$8,830

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.129 Costs for 100 Mile BEV Batteries (dollar values in 2013$)

Vehicle Class	WR tech	WR net	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	10	8	DMC	$4,445	26	$7,169	$6,727	$6,360	$6,049	$5,781	$5,546	$5,338	$5,152	$4,985
SmCar	15	13	DMC	$4,389	26	$7,078	$6,642	$6,280	$5,973	$5,708	$5,476	$5,270	$5,087	$4,922
SmCar	20	18	DMC	$4,332	26	$6,988	$6,557	$6,200	$5,897	$5,635	$5,406	$5,203	$5,022	$4,859
StCar	10	7	DMC	$5,214	26	$8,410	$7,892	$7,461	$7,096	$6,781	$6,505	$6,261	$6,044	$5,847
StCar	15	12	DMC	$5,148	26	$8,303	$7,792	$7,367	$7,006	$6,695	$6,423	$6,182	$5,967	$5,773
StCar	20	17	DMC	$5,082	26	$8,197	$7,692	$7,273	$6,917	$6,610	$6,341	$6,103	$5,891	$5,699
LgCar	10	8	DMC	$6,249	26	$10,080	$9,459	$8,943	$8,506	$8,128	$7,798	$7,505	$7,244	$7,009
LgCar	15	13	DMC	$6,108	26	$9,852	$9,245	$8,741	$8,314	$7,944	$7,621	$7,336	$7,080	$6,850
LgCar	20	18	DMC	$5,967	26	$9,625	$9,032	$8,539	$8,121	$7,761	$7,445	$7,166	$6,917	$6,692
SmMPV	10	7	DMC	$5,332	26	$8,601	$8,071	$7,631	$7,257	$6,935	$6,653	$6,404	$6,181	$5,980
SmMPV	15	12	DMC	$5,279	26	$8,515	$7,990	$7,555	$7,185	$6,866	$6,587	$6,340	$6,119	$5,920
SmMPV	20	17	DMC	$5,226	26	$8,429	$7,910	$7,478	$7,112	$6,797	$6,520	$6,276	$6,057	$5,861
LgMPV	10	3	DMC	$6,214	26	$10,024	$9,406	$8,893	$8,458	$8,082	$7,754	$7,463	$7,203	$6,969
LgMPV	15	8	DMC	$6,131	26	$9,888	$9,279	$8,773	$8,344	$7,973	$7,649	$7,362	$7,106	$6,875
LgMPV	20	13	DMC	$6,047	26	$9,753	$9,152	$8,653	$8,230	$7,864	$7,544	$7,261	$7,009	$6,781
Truck	10	7	DMC	$6,540	26	$10,548	$9,899	$9,359	$8,901	$8,506	$8,160	$7,854	$7,580	$7,334
Truck	15	12	DMC	$6,443	26	$10,392	$9,752	$9,220	$8,769	$8,379	$8,039	$7,737	$7,468	$7,226
Truck	20	17	DMC	$6,346	26	$10,235	$9,605	$9,081	$8,637	$8,253	$7,918	$7,621	$7,356	$7,117
SmCar	10	8	IC	High2	2024	$3,623	$3,591	$3,564	$3,541	$3,521	$3,504	$3,488	$3,475	$2,234
SmCar	15	13	IC	High2	2024	$3,577	$3,545	$3,519	$3,496	$3,476	$3,459	$3,444	$3,431	$2,205
SmCar	20	18	IC	High2	2024	$3,532	$3,500	$3,474	$3,451	$3,432	$3,415	$3,400	$3,387	$2,177
StCar	10	7	IC	High2	2024	$4,250	$4,212	$4,180	$4,153	$4,130	$4,110	$4,092	$4,076	$2,620
StCar	15	12	IC	High2	2024	$4,196	$4,159	$4,127	$4,101	$4,078	$4,058	$4,040	$4,024	$2,587
StCar	20	17	IC	High2	2024	$4,143	$4,105	$4,075	$4,048	$4,026	$4,006	$3,988	$3,973	$2,554
LgCar	10	8	IC	High2	2024	$5,094	$5,049	$5,011	$4,978	$4,951	$4,926	$4,905	$4,886	$3,141
LgCar	15	13	IC	High2	2024	$4,979	$4,935	$4,897	$4,866	$4,839	$4,815	$4,794	$4,775	$3,070

LgCar	20	18	IC	High2	2024	$4,864	$4,821	$4,784	$4,754	$4,727	$4,704	$4,683	$4,665	$2,999
SmMPV	10	7	IC	High2	2024	$4,347	$4,308	$4,275	$4,248	$4,224	$4,203	$4,185	$4,168	$2,680
SmMPV	15	12	IC	High2	2024	$4,303	$4,265	$4,233	$4,205	$4,182	$4,161	$4,143	$4,127	$2,653
SmMPV	20	17	IC	High2	2024	$4,260	$4,222	$4,190	$4,163	$4,140	$4,119	$4,101	$4,085	$2,626
LgMPV	10	3	IC	High2	2024	$5,066	$5,020	$4,983	$4,951	$4,923	$4,899	$4,877	$4,858	$3,123
LgMPV	15	8	IC	High2	2024	$4,997	$4,953	$4,915	$4,884	$4,856	$4,833	$4,811	$4,793	$3,081
LgMPV	20	13	IC	High2	2024	$4,929	$4,885	$4,848	$4,817	$4,790	$4,766	$4,746	$4,727	$3,039
Truck	10	7	IC	High2	2024	$5,331	$5,283	$5,243	$5,210	$5,181	$5,155	$5,133	$5,112	$3,287
Truck	15	12	IC	High2	2024	$5,252	$5,205	$5,166	$5,132	$5,104	$5,079	$5,056	$5,037	$3,238
Truck	20	17	IC	High2	2024	$5,173	$5,126	$5,088	$5,055	$5,027	$5,002	$4,980	$4,961	$3,189
SmCar	10	8	TC			$10,792	$10,318	$9,924	$9,590	$9,301	$9,049	$8,826	$8,626	$7,218
SmCar	15	13	TC			$10,656	$10,188	$9,799	$9,469	$9,184	$8,935	$8,714	$8,518	$7,127
SmCar	20	18	TC			$10,520	$10,057	$9,674	$9,348	$9,067	$8,821	$8,603	$8,409	$7,036
StCar	10	7	TC			$12,660	$12,104	$11,642	$11,250	$10,911	$10,615	$10,353	$10,119	$8,468
StCar	15	12	TC			$12,500	$11,951	$11,494	$11,107	$10,773	$10,481	$10,222	$9,991	$8,360
StCar	20	17	TC			$12,339	$11,797	$11,347	$10,965	$10,635	$10,347	$10,091	$9,863	$8,253
LgCar	10	8	TC			$15,174	$14,508	$13,954	$13,484	$13,079	$12,724	$12,410	$12,129	$10,149
LgCar	15	13	TC			$14,832	$14,180	$13,639	$13,180	$12,783	$12,436	$12,130	$11,855	$9,920
LgCar	20	18	TC			$14,489	$13,852	$13,324	$12,875	$12,488	$12,149	$11,849	$11,581	$9,691
SmMPV	10	7	TC			$12,947	$12,378	$11,906	$11,505	$11,159	$10,856	$10,588	$10,349	$8,660
SmMPV	15	12	TC			$12,818	$12,255	$11,787	$11,390	$11,048	$10,748	$10,483	$10,246	$8,573
SmMPV	20	17	TC			$12,689	$12,131	$11,668	$11,275	$10,936	$10,640	$10,377	$10,143	$8,487
LgMPV	10	3	TC			$15,089	$14,426	$13,876	$13,409	$13,005	$12,653	$12,340	$12,061	$10,092
LgMPV	15	8	TC			$14,886	$14,232	$13,688	$13,227	$12,830	$12,482	$12,174	$11,899	$9,956
LgMPV	20	13	TC			$14,682	$14,037	$13,501	$13,046	$12,654	$12,311	$12,007	$11,736	$9,820
Truck	10	7	TC			$15,879	$15,182	$14,602	$14,111	$13,686	$13,315	$12,986	$12,693	$10,621
Truck	15	12	TC			$15,644	$14,957	$14,386	$13,901	$13,483	$13,117	$12,794	$12,505	$10,463
Truck	20	17	TC			$15,408	$14,731	$14,169	$13,692	$13,280	$12,920	$12,601	$12,316	$10,306

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.130 Costs for 200 Mile BEV Batteries (dollar values in 2013$)

Vehicle Class	WR tech	WR net	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	20	8	DMC	$6,580	26	$10,613	$9,959	$9,416	$8,955	$8,558	$8,210	$7,902	$7,627	$7,379
StCar	20	8	DMC	$7,229	26	$11,660	$10,942	$10,345	$9,839	$9,402	$9,020	$8,681	$8,379	$8,107
LgCar	20	10	DMC	$8,588	26	$13,852	$12,998	$12,290	$11,688	$11,169	$10,715	$10,313	$9,954	$9,631
SmMPV	20	8	DMC	$7,549	26	$12,176	$11,426	$10,803	$10,274	$9,818	$9,419	$9,065	$8,750	$8,466
LgMPV	20	4	DMC	$9,057	26	$14,608	$13,709	$12,961	$12,327	$11,779	$11,301	$10,877	$10,498	$10,157
Truck	20	8	DMC	$9,564	26	$15,426	$14,476	$13,686	$13,017	$12,438	$11,933	$11,485	$11,086	$10,726
SmCar	20	8	IC	High2	2024	$5,364	$5,316	$5,276	$5,242	$5,212	$5,187	$5,164	$5,144	$3,307
StCar	20	8	IC	High2	2024	$5,893	$5,840	$5,796	$5,759	$5,726	$5,698	$5,673	$5,651	$3,633
LgCar	20	10	IC	High2	2024	$7,000	$6,938	$6,885	$6,841	$6,803	$6,770	$6,740	$6,714	$4,316
SmMPV	20	8	IC	High2	2024	$6,153	$6,098	$6,052	$6,013	$5,980	$5,950	$5,924	$5,901	$3,794
LgMPV	20	4	IC	High2	2024	$7,383	$7,317	$7,262	$7,215	$7,175	$7,139	$7,108	$7,080	$4,552
Truck	20	8	IC	High2	2024	$7,796	$7,726	$7,668	$7,619	$7,576	$7,539	$7,506	$7,476	$4,806
SmCar	20	8	TC			$15,977	$15,275	$14,692	$14,197	$13,770	$13,397	$13,066	$12,771	$10,686
StCar	20	8	TC			$17,553	$16,781	$16,141	$15,597	$15,128	$14,718	$14,355	$14,030	$11,740
LgCar	20	10	TC			$20,852	$19,936	$19,175	$18,529	$17,972	$17,485	$17,053	$16,668	$13,947
SmMPV	20	8	TC			$18,329	$17,524	$16,855	$16,287	$15,797	$15,369	$14,990	$14,651	$12,259
LgMPV	20	4	TC			$21,991	$21,025	$20,223	$19,542	$18,954	$18,440	$17,985	$17,579	$14,709
Truck	20	8	TC			$23,222	$22,202	$21,354	$20,635	$20,015	$19,472	$18,991	$18,562	$15,532

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.3.4.3.7.8 Electrified Vehicle Costs Used In OMEGA (Battery + Non-battery Items)

Costs presented in the tables that follow sum the battery, non-battery and, where applicable, the in-home charger related costs for mild, strong and plug-in hybrids and full battery electric vehicles.

Table 5.131 Full System Costs for 48V Mild Hybrids (2013$)

Vehicle Class	WRtech	WRnet	Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	5	1.5	TC	$1,045	$1,007	$939	$919	$902	$888	$876	$865	$792
StCar	5	2	TC	$1,045	$1,007	$939	$919	$902	$888	$876	$865	$792
LgCar	5	2.5	TC	$1,045	$1,007	$939	$919	$902	$888	$876	$865	$792
SmMPV	5	2.5	TC	$1,045	$1,007	$939	$919	$902	$888	$876	$865	$792
LgMPV	5	2.5	TC	$1,045	$1,007	$939	$919	$902	$888	$876	$865	$792
Truck	5	3	TC	$1,045	$1,007	$939	$919	$902	$888	$876	$865	$792

Note: TC=total costs.

Table 5.132 Full System Costs for Strong Hybrids (2013$)

Vehicle Class	WRtech	WRnet	Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	10	5	TC	$4,088	$3,963	$3,499	$3,431	$3,374	$3,325	$3,283	$3,244	$3,008
SmCar	15	10	TC	$4,054	$3,930	$3,470	$3,402	$3,346	$3,297	$3,255	$3,217	$2,983
SmCar	20	15	TC	$4,020	$3,897	$3,441	$3,373	$3,318	$3,270	$3,228	$3,190	$2,958
StCar	10	5	TC	$4,459	$4,325	$3,815	$3,741	$3,679	$3,627	$3,580	$3,539	$3,286
StCar	15	10	TC	$4,410	$4,278	$3,773	$3,700	$3,639	$3,587	$3,541	$3,501	$3,250
StCar	20	15	TC	$4,362	$4,231	$3,732	$3,659	$3,599	$3,548	$3,502	$3,462	$3,215
LgCar	10	5	TC	$5,142	$4,990	$4,397	$4,313	$4,242	$4,182	$4,129	$4,082	$3,794
LgCar	15	10	TC	$5,059	$4,909	$4,326	$4,243	$4,174	$4,114	$4,062	$4,015	$3,733
LgCar	20	15	TC	$4,975	$4,827	$4,255	$4,173	$4,105	$4,046	$3,995	$3,949	$3,671
SmMPV	10	5	TC	$4,314	$4,183	$3,692	$3,620	$3,560	$3,509	$3,464	$3,424	$3,176
SmMPV	15	10	TC	$4,271	$4,142	$3,656	$3,584	$3,525	$3,474	$3,430	$3,390	$3,144
SmMPV	20	15	TC	$4,229	$4,101	$3,619	$3,549	$3,490	$3,440	$3,396	$3,356	$3,113
LgMPV	10	6	TC	$4,846	$4,703	$4,144	$4,064	$3,998	$3,941	$3,891	$3,847	$3,577
LgMPV	15	11	TC	$4,784	$4,642	$4,090	$4,012	$3,947	$3,891	$3,841	$3,797	$3,531
LgMPV	20	16	TC	$4,721	$4,582	$4,037	$3,959	$3,895	$3,840	$3,791	$3,748	$3,485
Truck	10	6	TC	$5,119	$4,967	$4,377	$4,293	$4,223	$4,163	$4,110	$4,063	$3,777
Truck	15	11	TC	$5,040	$4,891	$4,310	$4,227	$4,158	$4,099	$4,047	$4,001	$3,719
Truck	20	16	TC	$4,962	$4,815	$4,243	$4,161	$4,094	$4,035	$3,984	$3,938	$3,661

Note: TC=total costs.

Table 5.133 Full System Costs for 20 Mile Plug-in Hybrids, Including Charger & Charger Labor (2013$)

Vehicle Class	WRtech	WRnet	Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	15	6	TC	$10,136	$9,840	$9,143	$8,931	$8,746	$8,582	$8,437	$8,305	$7,505
SmCar	20	11	TC	$10,055	$9,763	$9,072	$8,862	$8,678	$8,516	$8,372	$8,241	$7,448
StCar	15	6	TC	$11,115	$10,792	$10,006	$9,773	$9,570	$9,391	$9,231	$9,087	$8,214
StCar	20	11	TC	$11,003	$10,683	$9,907	$9,677	$9,476	$9,299	$9,140	$8,998	$8,133
LgCar	15	5	TC	$13,287	$12,905	$11,909	$11,634	$11,393	$11,180	$10,990	$10,819	$9,798
LgCar	20	10	TC	$13,059	$12,683	$11,708	$11,438	$11,201	$10,992	$10,805	$10,637	$9,633
SmMPV	15	6	TC	$11,095	$10,768	$9,999	$9,764	$9,559	$9,378	$9,217	$9,071	$8,184
SmMPV	20	11	TC	$10,990	$10,666	$9,906	$9,673	$9,471	$9,291	$9,132	$8,988	$8,108
LgMPV	15	4	TC	$12,502	$12,137	$11,231	$10,968	$10,739	$10,537	$10,356	$10,193	$9,211
LgMPV	20	9	TC	$12,329	$11,970	$11,078	$10,819	$10,594	$10,394	$10,216	$10,055	$9,087
Truck	15	6	TC	$13,054	$12,672	$11,720	$11,445	$11,206	$10,994	$10,804	$10,634	$9,606
Truck	20	11	TC	$12,849	$12,473	$11,539	$11,269	$11,033	$10,824	$10,638	$10,470	$9,459

Note: TC=total costs.

Table 5.134 Full System Costs for 40 Mile Plug-in Hybrids, Including Charger & Charger Labor (2013$)

Vehicle Class	WRtech	WRnet	Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	20	6	TC	$12,644	$12,259	$11,391	$11,115	$10,875	$10,662	$10,473	$10,303	$9,260
StCar	20	5	TC	$14,689	$14,242	$13,200	$12,879	$12,600	$12,352	$12,132	$11,933	$10,727
LgCar	20	3	TC	$19,170	$18,600	$17,130	$16,720	$16,362	$16,045	$15,762	$15,506	$13,991
SmMPV	20	7	TC	$14,482	$14,034	$13,035	$12,713	$12,434	$12,187	$11,967	$11,768	$10,554
LgMPV	20	0	TC	$18,425	$17,850	$16,543	$16,130	$15,771	$15,453	$15,170	$14,915	$13,357
Truck	20	5	TC	$19,641	$19,026	$17,625	$17,184	$16,800	$16,460	$16,158	$15,885	$14,220

Note: TC=total costs.

Table 5.135 Full System Costs for 75 Mile BEVs, Including Charger & Charger Labor (2013$)

Vehicle Class	WRtech	WRnet	Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	10	10	TC	$10,905	$10,473	$10,115	$9,812	$9,550	$9,321	$9,119	$8,938	$7,595
SmCar	15	15	TC	$10,787	$10,361	$10,008	$9,709	$9,451	$9,225	$9,025	$8,847	$7,505
SmCar	20	20	TC	$10,669	$10,249	$9,901	$9,606	$9,351	$9,128	$8,932	$8,756	$7,416
StCar	10	10	TC	$12,645	$12,155	$11,748	$11,401	$11,102	$10,840	$10,608	$10,401	$8,877
StCar	15	15	TC	$12,374	$11,892	$11,491	$11,150	$10,856	$10,598	$10,370	$10,166	$8,682
StCar	20	20	TC	$12,103	$11,629	$11,234	$10,899	$10,610	$10,357	$10,133	$9,932	$8,487
LgCar	10	10	TC	$16,820	$16,184	$15,653	$15,202	$14,812	$14,469	$14,166	$13,894	$11,788
LgCar	15	15	TC	$16,214	$15,595	$15,080	$14,642	$14,263	$13,930	$13,636	$13,372	$11,355
LgCar	20	20	TC	$15,607	$15,007	$14,507	$14,081	$13,714	$13,392	$13,106	$12,851	$10,921
SmMPV	10	10	TC	$12,102	$11,622	$11,225	$10,888	$10,598	$10,345	$10,121	$9,921	$8,301
SmMPV	15	15	TC	$11,950	$11,477	$11,086	$10,755	$10,469	$10,220	$10,000	$9,804	$8,183
SmMPV	20	20	TC	$11,797	$11,332	$10,947	$10,621	$10,341	$10,095	$9,879	$9,686	$8,066
LgMPV	10	5	TC	$15,076	$14,479	$13,982	$13,560	$13,196	$12,877	$12,594	$12,341	$10,501
LgMPV	15	10	TC	$14,718	$14,131	$13,643	$13,228	$12,870	$12,556	$12,278	$12,030	$10,242
LgMPV	20	15	TC	$14,361	$13,783	$13,303	$12,895	$12,543	$12,235	$11,963	$11,719	$9,984
Truck	10	10	TC	$15,106	$14,495	$13,987	$13,558	$13,187	$12,864	$12,578	$12,323	$10,310
Truck	15	15	TC	$14,834	$14,236	$13,740	$13,320	$12,958	$12,642	$12,362	$12,113	$10,098
Truck	20	20	TC	$14,562	$13,977	$13,492	$13,082	$12,728	$12,420	$12,147	$11,904	$9,886

Note: TC=total costs.

Table 5.136 Full System Costs for 100 Mile BEVs, Including Charger & Charger Labor (2013$)

Vehicle Class	WRtech	WRnet	Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	10	8	TC	$12,300	$11,807	$11,398	$11,051	$10,752	$10,490	$10,259	$10,052	$8,532
SmCar	15	13	TC	$12,153	$11,667	$11,264	$10,922	$10,627	$10,370	$10,142	$9,938	$8,424
SmCar	20	18	TC	$12,007	$11,528	$11,131	$10,794	$10,503	$10,249	$10,025	$9,824	$8,315
StCar	10	7	TC	$14,941	$14,353	$13,864	$13,448	$13,089	$12,774	$12,496	$12,247	$10,421
StCar	15	12	TC	$14,646	$14,067	$13,585	$13,176	$12,822	$12,513	$12,239	$11,993	$10,210
StCar	20	17	TC	$14,352	$13,781	$13,306	$12,904	$12,556	$12,251	$11,981	$11,740	$9,999
LgCar	10	8	TC	$18,663	$17,949	$17,354	$16,848	$16,410	$16,027	$15,686	$15,382	$13,032
LgCar	15	13	TC	$18,042	$17,346	$16,767	$16,275	$15,849	$15,476	$15,145	$14,848	$12,589
LgCar	20	18	TC	$17,421	$16,744	$16,181	$15,702	$15,287	$14,924	$14,603	$14,315	$12,145
SmMPV	10	7	TC	$14,371	$13,792	$13,311	$12,903	$12,552	$12,246	$11,974	$11,733	$9,828
SmMPV	15	12	TC	$14,228	$13,655	$13,180	$12,778	$12,431	$12,128	$11,861	$11,622	$9,716
SmMPV	20	17	TC	$14,084	$13,518	$13,049	$12,652	$12,310	$12,011	$11,747	$11,511	$9,605
LgMPV	10	3	TC	$17,344	$16,649	$16,072	$15,581	$15,158	$14,787	$14,458	$14,164	$12,025
LgMPV	15	8	TC	$16,950	$16,266	$15,699	$15,216	$14,800	$14,435	$14,112	$13,824	$11,742
LgMPV	20	13	TC	$16,555	$15,884	$15,325	$14,851	$14,442	$14,084	$13,767	$13,483	$11,459
Truck	10	7	TC	$17,312	$16,603	$16,014	$15,515	$15,085	$14,709	$14,377	$14,081	$11,804
Truck	15	12	TC	$17,049	$16,352	$15,774	$15,285	$14,863	$14,495	$14,169	$13,878	$11,597
Truck	20	17	TC	$16,785	$16,101	$15,535	$15,055	$14,641	$14,280	$13,961	$13,676	$11,391

Note: TC=total costs.

Table 5.137 Full System Costs for 200 Mile BEVs, Including Charger & Charger Labor (2013$)

Vehicle Class	WRtech	WRnet	Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
SmCar	20	8	TC	$17,485	$16,764	$16,166	$15,658	$15,221	$14,838	$14,499	$14,197	$12,001
StCar	20	8	TC	$19,808	$19,006	$18,338	$17,771	$17,282	$16,853	$16,473	$16,134	$13,674
LgCar	20	10	TC	$24,232	$23,270	$22,469	$21,788	$21,200	$20,684	$20,227	$19,819	$16,746
SmMPV	20	8	TC	$19,750	$18,934	$18,257	$17,684	$17,189	$16,757	$16,374	$16,033	$13,422
LgMPV	20	4	TC	$24,207	$23,210	$22,381	$21,677	$21,069	$20,537	$20,066	$19,645	$16,612
Truck	20	8	TC	$24,649	$23,618	$22,762	$22,036	$21,410	$20,863	$20,379	$19,947	$16,706

Note: TC=total costs.

5.3.4.4 Aerodynamics: Data and Assumptions for this Assessment

In Section 5.2.5 (Aerodynamics: State of Technology), the agencies reviewed the assumptions associated with two levels of aerodynamic drag reduction technology, Aero 1 and Aero 2. These represented applications of drag reduction technology resulting in a 10 percent and 20 percent reduction in aerodynamic drag, respectively.

That Section also reviewed the findings of several studies including: (a) the 2015 NAS Report; (b) a joint aerodynamics test program between EPA, Transport Canada, and other organizations; a CARB study performed by Control-Tec; and an informal survey of aerodynamic technologies at the 2015 North American International Auto Show (NAIAS).

These studies were seen to generally support the assumptions for cost and effectiveness of Aero 1 and Aero 2 as defined in the 2012 FRM. The findings of the NAS report generally supported the assumptions for Aero 1 and Aero 2 as being applicable to the 2020-2025 time frame. The findings of the Joint Aerodynamics Assessment Program and the Control-Tec analysis also were shown to lend support to the feasibility of the 10 percent and 20 percent effectiveness levels assumed for Aero 1 and Aero 2. The penetration of passive and active aerodynamic technologies as surveyed at the 2015 NAIAS was also shown to demonstrate that manufacturers are already implementing many passive and active aerodynamic technologies in MY2015 vehicles, with significant opportunity remaining to further apply these technologies in a more optimized fashion as vehicles enter redesign cycles in the future.

At this time, EPA is therefore continuing to use the FRM cost and effectiveness assumptions for passive and active aerodynamic technology as a basis for OMEGA runs for this Draft TAR analysis. In Section 5.2, some tradeoffs and interactions among specific aerodynamic technologies were identified that suggest there could be value in refining the specific combinations of technologies that are assumed to make up the Aero1 and Aero2 packages that are applied to vehicles in OMEGA. However, because EPA has not changed the costs associated with specific aerodynamic technologies from those used in the FRM, EPA has not chosen at this time to make such adjustments to the aerodynamic packages. EPA intends to continue analyzing costs and package combinations prior to the draft determination.

Costs associated with aero treatments and technologies are equivalent to those used in the 2012 FRM except for updates to 2013 dollars and use of a new learning curve (curve 24). The aero costs are shown below.

Table 5.138 Costs for Aero Technologies (dollar values in 2013$)

Tech	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
Passive aero	DMC	$43	24	$41	$40	$39	$39	$38	$38	$37	$37	$36
Passive aero	IC	Low2	2018	$10	$10	$8	$8	$8	$8	$8	$8	$8
Passive aero	TC			$51	$50	$48	$47	$46	$46	$45	$45	$44
Active aero	DMC	$128	24	$123	$120	$118	$116	$114	$113	$111	$110	$108
Active aero	IC	Med2	2024	$49	$49	$49	$49	$49	$49	$49	$49	$37
Active aero	TC			$172	$170	$167	$165	$163	$162	$160	$159	$145
Passive+Active	TC			$223	$220	$215	$212	$210	$207	$205	$203	$189

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.3.4.5 Tires: Data and Assumptions for this Assessment

In Section 5.2.6 (Tires: State of Technology), the agencies reviewed the assumptions associated with two levels of low rolling resistance tire technology, LRRT1 and LRRT2. These represented applications of rolling resistance reduction technology corresponding to a 10 percent and 20 percent reduction in rolling resistance, respectively.

That Section reviewed the findings of the 2015 NAS Report, which examined the agencies' 2012 FRM assumptions for feasibility, cost, and effectiveness for LRRT1 and LRRT2. The report concluded that the feasibility and effectiveness projected by the agencies for a 20 percent reduction in rolling resistance in the 2020-2025 time frame appears to be reasonable. With regard to costs, the Committee substantially agreed with the costs projected by the agencies, while noting that the problem of maintaining tread wear and traction requirements while reducing rolling resistance continues to present engineering challenges that could affect tire costs.

The Section also reviewed EPA's activity in following industry developments and trends in application of low rolling resistance technologies to light-duty vehicles, and a project to track trends in rolling resistance of OEM tires through the Control-Tec project. It also reviewed an ongoing joint research program with Transport Canada and other agencies to study the rolling resistance and traction characteristics of low-rolling resistance tires.

At this time, these efforts have suggested that the 2012 FRM estimates of cost and effectiveness for LRRT1 and LRRT2 remain reasonable for the time frame of the rule. EPA is therefore continuing to use the FRM cost and effectiveness assumptions for LRRT1 and LRRT2 as a basis for OMEGA runs for this Draft TAR GHG Assessment.

In the FRM and this Draft TAR GHG Assessment, LRRT1 remains defined as a 10 percent reduction in rolling resistance from a base tire, and is estimated to result in a 1.9 percent effectiveness improvement for all vehicle classes.

Similarly, LRRT2 remains defined as a 20 percent reduction in rolling resistance from a base tire, and is estimated to result in a 3.9 percent effectiveness improvement.

Costs associated with lower rolling resistance tires are equivalent to those used in the 2012 FRM except for updates to 2013 dollars and use of a new learning curve (curve 32 for LRRT2). The LRRT costs are shown below.

Table 5.139 Costs for Lower Rolling Resistance Tires (dollar values in 2013$)

Tech	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
LRRT1	DMC	$6	1	$6	$6	$6	$6	$6	$6	$6	$6	$6
LRRT1	IC	Low2	2018	$1	$1	$1	$1	$1	$1	$1	$1	$1
LRRT1	TC			$7	$7	$7	$7	$7	$7	$7	$7	$7
LRRT2	DMC	$43	32	$56	$53	$51	$49	$48	$47	$45	$44	$43
LRRT2	IC	Low2	2024	$10	$10	$10	$10	$10	$10	$10	$10	$8
LRRT2	TC			$66	$64	$62	$60	$58	$57	$56	$55	$52

Note: DMC=direct manufacturing costs; IC=indirect costs;
TC=total costs; both levels of lower rolling resistance are incremental to today's baseline tires.

5.3.4.6 Mass Reduction: Data and Assumptions for this Assessment

This section describes the specific assumptions for mass reduction cost and effectiveness that are used in this Draft TAR assessment of the GHG standards. These assumptions are based largely on the information presented in Section 5.2, and the agencies' joint assessment of the state of mass reduction technology which highlighted notable applications of mass reduction in production vehicles since the FRM, and the significant amount of research and development into lightweight materials and designs as shown in information in the Appendix.

Section 5.3.4.6.1 describes the mass reduction costs and the cost curve development methodology that are used in the analysis. Two separate cost curves were developed from the studies described in Section 5.2; one that is applied to cars and cross-over utility vehicles that typically have a unibody construction, and another that is applied to light duty trucks that typically have a body-on-frame construction.

Section 5.3.4.6.2 details the methodology for determining how much mass reduction is already present in the MY2014 baseline fleet. This information is then used to assign the appropriate costs for additional mass reduction beyond what has been applied to each vehicle in the baseline.

Section 5.3.4.6.3 describes the assumptions used in the GHG analysis for the effectiveness of mass reduction for reducing emissions.

Section 5.3.4.6.4 contains sample tables of the direct manufacturing cost (DMC), indirect costs (IC), and total costs (TC) for cars (unibody) and trucks (body on frame) over 2017-2025 with learning applied given example baseline percent mass reduction. The analysis utilizes baseline costs adjusted for every 0.5 percent mass reduction

The treatment of mass reduction in the fleet safety analyses is explained in Chapter 8.

5.3.4.6.1 Cost Curves

The Direct Manufacturing Cost (DMC) curve utilized in the 2012 FRM was a linear cost curve starting at $0 for no mass reduction with costs increasing at a constant rate of $4.36/lb for each percent mass reduction (e.g. 10 percent mass reduction = $0.436/lb (or $0.96/kg)), see Figure 5.115. The cost curve was applied to all vehicles uniformly, with the assumption that all vehicles in the MY2008 baseline were starting from a level of zero percent mass reduction.

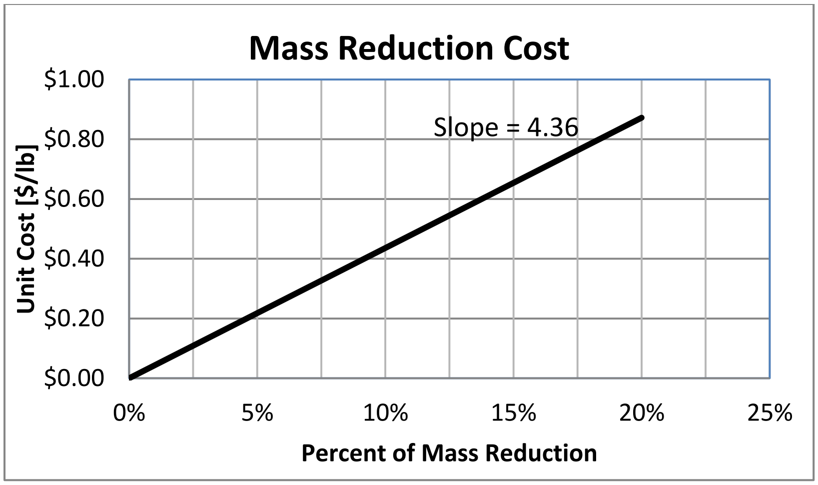


Figure 5.115 2012 FRM Mass Reduction Direct Manufacturing Cost Curve ($/lb)

These FRM costs were based primarily on a number of different component, subsystem and vehicle -level studies. While these studies represented the best information available on mass reduction costs at the time, EPA continues to believe that tear-down and analysis of actual vehicle components are the best way to derive technology cost estimates. For mass reduction in particular, the most cost-effective management of vehicle mass will likely involve a holistic approach to vehicle design which takes into consideration not only the primary opportunities for mass reduction, but also all secondary mass reduction opportunities. CAE analyses to evaluate crash, NVH and dynamic factors are also very important in determining material, grade, gauge and geometry of BIW and other components. For this draft TAR, the FRM costs have been updated in two important ways. First, the costs used in in this assessment were directly informed by several of holistic full vehicle tear-down studies described in Section 5.2. Second, this assessment uses one cost curve for cars and cross-over utility vehicles (CUVs), and a different cost curve for light-duty trucks, as appropriate for vehicles with fundamentally different design and usage characteristics. Within EPA's application of technology packages, the Car/CUV curve is applied to Vehicle Types 1-7 and 13 which are defined as the non-towing vehicles and typically unibody construction. The light duty truck curve is applied to Vehicle Types 8-12 and 14-19 which are defined as towing vehicles, and are typically body-on-frame vehicles. An explanation of the Vehicle Types can be found in Chapter 12.

The baseline model year in the FRM was MY2008 and the vast majority of vehicles at that time were developed without the significant incentives for mass reduction, or the metals and approaches that have been created as a result of, the current GHG and CAFE standards, and therefore form a reasonable basis from which to measure future mass reduction. The vehicle and component designs typical of MY2008-2010 era vehicles are assumed to represent the “null” technology for mass reduction, consistent with the definition of a null technology definition for powertrain, aero, tire, etc. as described in Section 5.3.1.1.

The GHG analysis for the Draft TAR uses a MY2014 baseline fleet, so that when determining the cost of mass reduction in this draft TAR, EPA recognizes it is important to account for any mass reduction that has been applied beyond the “null” mass reduction level typical of MY2008 era vehicles. Since the emissions reducing benefits of mass reduction aren't realized unless the overall curb weight decreases, mass reduction technology for this Draft TAR is defined to be equivalent to a reduction in curb weight, with some additional adjustments described in 5.3.4.6.2. The mass reduction application to electrified vehicles accounts for the additional weight of electrical components as described in 5.3.4.3.7.1. This methodology for accounting for mass reduction in electrified vehicles is the same as that used for the FRM.

The car and CUV costs for this Draft TAR were developed as described in the following section based on the tear-down studies of the MY2011 Honda Accord, and the MY2010 Toyota Venza, conducted by NHTSA and EPA respectively. These two vehicles represent designs which have primarily steel structures, and component design and materials typical of MY2008-2010 era cars and CUVs.

The truck costs for this Draft TAR are also described in the following section and are based on two light duty pickup truck studies. Both studies focused on the Chevrolet Silverado 1500, which is a steel intensive truck design. One study utilized a MY2011 model which was introduced for MY2007, and is representative of MY2008-2010 vintage light-duty trucks. The second study utilized a MY2014 model which was redesigned and slightly lighter than the MY2011 version. The methodology described here considered both LDT study results to develop a MY2008 applicable cost curve. Light-duty trucks, and pickup-trucks in particular, have a number of unique characteristics which influence the potential solutions for achieving mass reduction. The use of a body-on-frame design in which the bed and cab are separately mounted to a frame that provides the main load bearing structure for towing, hauling, and crash performance. Because of these unique load requirements, the opportunity to achieve secondary mass reduction may be less than other passenger vehicles since the overall vehicle and subsystem designs will still need to meet vehicle functional objectives under these unique load conditions.

Overall, EPA believes these new Car/CUV and LDT cost curves are more representative than the FRM's linear curve of direct manufacturing costs for applying mass. The holistic vehicle studies provide a more comprehensive evaluation of the opportunity for mass reduction as they take into account all vehicle systems (e.g. body, interior, suspension, engine, drivetrain) as well as the potential for secondary mass reduction (e.g. decrease the size of powertrain and suspension components as loads are reduced) In addition, vehicle functional objectives are also considered through CAE modeling and simulation (material grade and gauge, NVH characteristics, vehicle acceleration, crashworthiness). In addition, the results in each study show that while high levels of mass reduction may increase costs, there are also opportunities for cost savings, especially at lower levels of mass reduction. These findings are consistent with statements from industry, including suppliers and several OEMs. An article released by the Center for Automotive Research (CAR) in February 2016 illustrates this point as it states "The figure below [Figure 5] illustrates a generic cost curve for lightweighting that is broadly supported."[571]

Figure 7: General Auto Manufacturer Cost Curve to Lightweight Vehicles

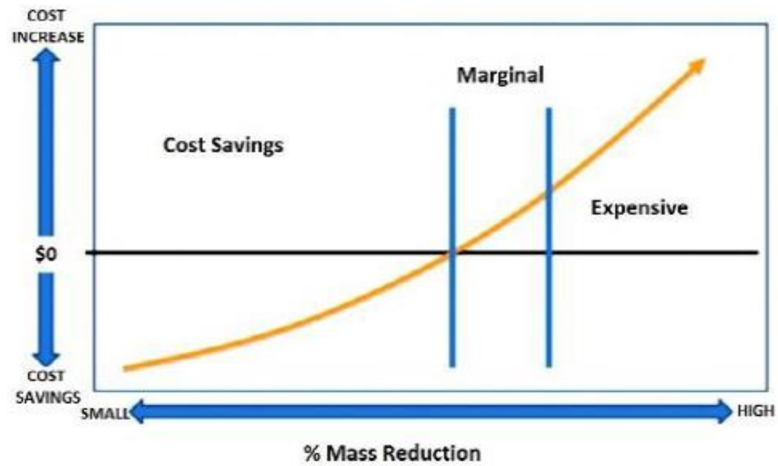


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Figure 5.116 CAR Figure for "General Auto Manufacturer Cost Curve to Lightweight Vehicles"

It should be noted that while the costs used in this assessment are applied broadly across the fleet, EPA recognizes that each particular vehicle will present specific opportunities for mass reduction that are in some cases are more cost-effective, and in other cases less cost-effective than were available on the vehicles selected for the tear-down studies. However, it is important to note that the cost curves are intended to be representative of mass reduction applied to typical MY2008-2010 vehicles, with subsequent adjustments for any additional mass reduction present in MY2014 baseline. Also note that the cost curves represent component and system mass reductions that are entirely applied towards a reduction in vehicle curb weight, as opposed to offsetting mass increases from the addition of content and features.

5.3.4.6.1.1 Cost Curve for Cars and CUVs

The cost curve for Cars/CUVs developed for this Draft TAR described below represents an estimate of the Direct Manufacturing Cost (DMC) for mass reduction technologies that are expected to be broadly available in 2020. Total Costs, which are made up of both DMCs and Indirect Costs (ICs), are also presented in this section for completeness, although the details of calculating ICs are provided separately. Additionally, learning is applied to mass reduction consistent with the other technologies in this assessment to account for changes in costs over time. More detail on the methods for calculating indirect costs and learning is provided in Section 5.3.4.6.4.

Car/CUV DMC Curve Generation

The Car/CUV direct manufacturing cost curve is based on EPA's midsize CUV study based on the Venza, and NHTSA's passenger car study based on the Accord. This section describes the development of the Car/CUV DMC curve. Four related topics for the resultant passenger car/CUV cost curve are also discussed. First is a discussion of the potential concerns for the cost savings in the cost curve from a 2008 era vehicle. Second, a cost curve adjustment methodology is described such that vehicles with an acknowledged baseline mass reduction percentage will have higher costs for additional mass reduction. Third, this section addresses additional technology points (such as aluminum BIW) and whether extension of the current cost curve can represent these points. Lastly, the complete cost curve is shown with DMC, Indirect cost (IC) and resultant Total Cost (TC).

Development of the Car/CUV DMC curve for use in EPA modeling is completed in the following steps outlined in Table 5.140.

Table 5.140 Car/CUV DMC Development

STEP	TASK
1	Begin with the cost curves for the Passenger Car and the Midsize CUV lightweighting studies (both of which are of the 2008 design era).
2	Update the individual curves given OEM, peer review feedback and other considerations.
3	Translate the Passenger Car DMC cost curve to use a similar methodology as the Midsize CUV curve.
4	Average the new Passenger Car and Midsize CUV curves using the best fit line for each curve.

STEP 1: The 2012 NHTSA Passenger Car[LLL] and EPA Midsize CUV[572] study cost curves are shown in Figure 5.117.

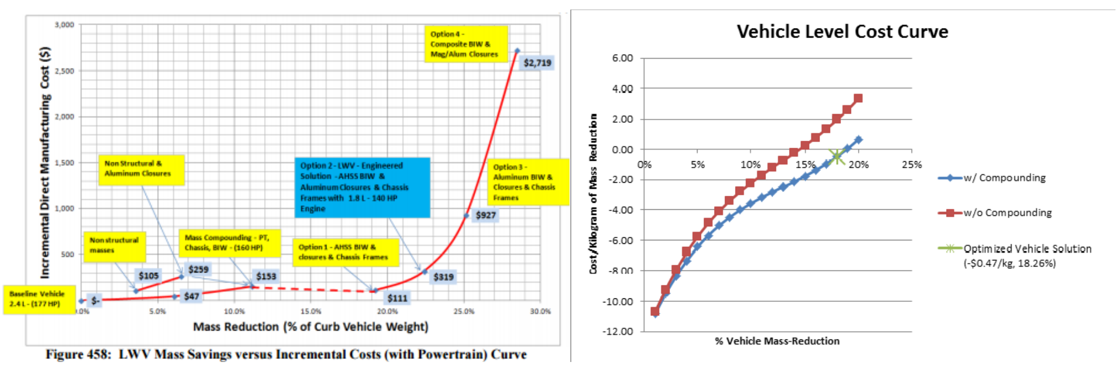


Figure 5.117 2012 NHTSA Passenger Car and EPA Midsize CUV Lightweighting Study Cost Curves

STEP 2: Both cost curves in Figure 5.117 were updated since 2012. The cost curve from the 2012 Midsize CUV study[572] was adjusted based on peer review, OEM feedback and other considerations specific to the report. The resultant cost curve for a MY2008-2010 era midsize CUV is shown in Figure 5.118. The final $/kg and percent mass reduction results for the whole vehicle direct manufacturing cost for the HSS BIW and aluminum closure point is $0.50/kg and 17.6 percent mass reduction for the Midsize CUV.

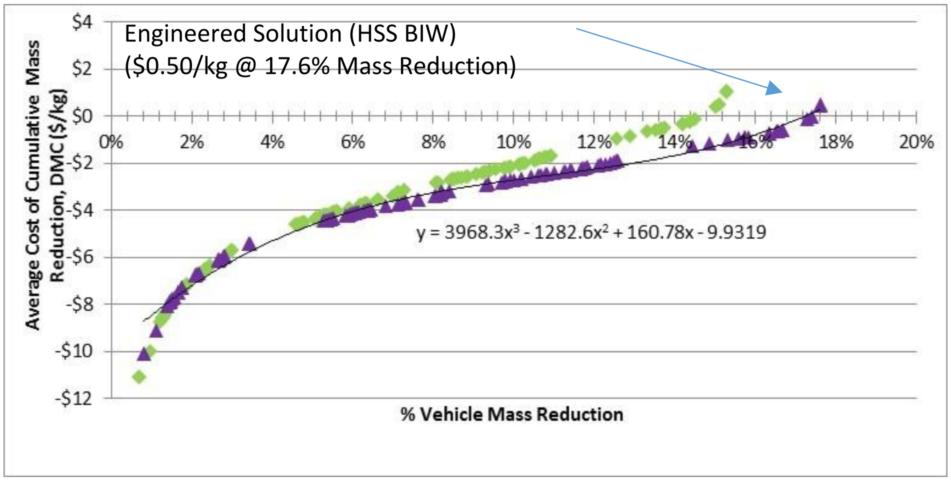


Figure 5.118 EPA Updated Midsize CUV Direct Manufacturing Cost Curve from Midsize CUV Study

NHTSA's 2012 passenger car cost curve Engineered Solution point has been updated two times. Figure 5.119 shows the point LWV1.1 which is the updated engineered solution point achieved through analysis of Honda's comments[573]. The point LWV1.2 is the updated engineered solution point and includes the updates from NHTSA's analysis of Honda's comments as well as re-analyzed BIW for the IIHS small overlap crash. Design changes to the BIW result in some additional mass and cost. The analysis and NHTSA's updated cost curves are presented in their report published in February 2016.[574]

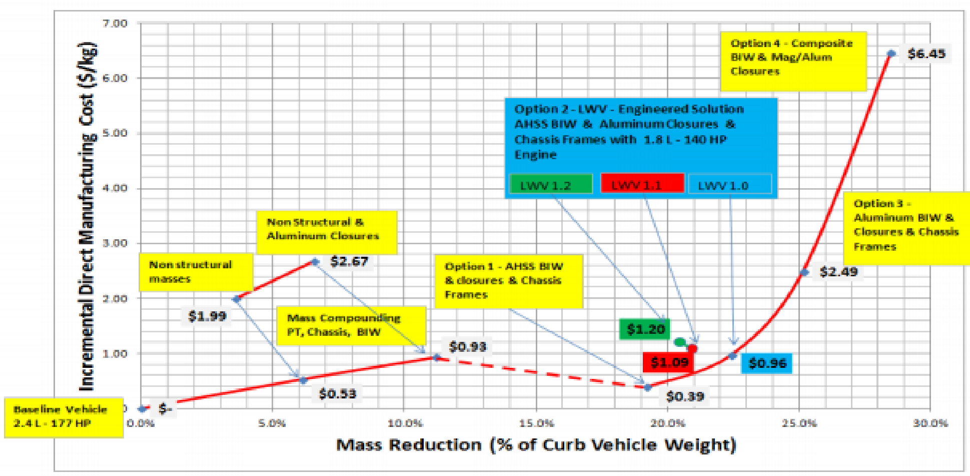


Figure 5.119 NHTSA Updated Passenger Car Direct Manufacturing Cost Curve from Passenger Car Study[EEE,574]

STEP 3: For this analysis, the NHTSA passenger car cost curve was translated using a similar methodology to the EPA midsize CUV cost curve so that the two curves represent the same basis and can be averaged. Review of Figure 5.118 (EPA) and Figure 5.119 (NHTSA) reveals that

[EEE] LWV 1.2 contains the IIHS small overlap design solution and mass add of 6.9kg and $26.88. LWV 1.1 only addresses NHTSA's responses to Honda's comments.

two different methodologies were utilized to create these curves. Figure 5.118 is a cost curve represented of one vehicle solution which includes one set of mass reduction technology ideas focused on using an AHSS BIW and a number of aluminum components. Figure 5.119 is based on several whole vehicle solutions including 1) AHSS BIW and closures, 2) AHSS BIW and Aluminum closures and chassis frame, 3) Aluminum BIW, closures and chassis frame, 4) Composite BIW and Mag/Al closures. The detailed work in the study is based on the AHSS BIW and Aluminum Closures and Chassis frame point and the remaining are estimates.

Details on the differences in the study approaches and methodologies used to generate the original 2012 passenger car and CUV curves are presented in Table 5.141.

Table 5.141 Methodology Differences Between Original 2012 Car and CUV Mass Reduction Studies

	NHTSA (Passenger Car Study)	EPA (Midsize CUV: Phase 2 Low Dev Study)
COSTS and TIMEFRAME	Costs are representative of 2017. Vehicle of MY2011 (similar to 2008)	Costs are representative of 2020. Vehicle of MY2010 (similar to 2008)
TECHNOLOGY IDENTIFICATION	-Study examined a number of components, material choices and mfg techniques. -Several components using new materials were redesigned. -Powertrain mass reduction confined to downsizing from Civic to avoid engine efficiency technologies (powertrain component MR beyond scope).	-Study examined each component within the vehicle for mass reduction possibilities. -A few non-established technologies were adopted with the expectation research would make them, or similar technologies, available in the 2020-2025 timeframe. -Reference some technologies, such as wheels, utilized in Phase 1 study on Midsize CUV.[575]
BIW	Material replacement, computer optimization of load paths and material grade and gauge.	Material replacement, grade and gauge optimization
BIW SAFETY CRASH/NVH inCAE	-Include NVH, FMVSS and other crash tests, in design, grade and gauge decisions. -Mass add due to IIHS small overlap included in updated study with BIW changes applied in vehicle solution point.	-Include NVH, FMVSS and other crash tests in grade and gauge decisions. - No IIHS small overlap in design -Utilized NHTSA mass add and cost findings in baseline safety credits, not cost curve.
ORDERING OF PRIMARY MR TECHNOLOGIES for COST CURVE	-Some technologies and related MR grouped into two points. -Glider technologies used as primary (glider=vehicle-powertrain)	-Ordered in lowest $/kg and then cumulatively added for $/kg over %MR. -Only grouped ideas as required for implementation feasibility.
INCORPORATION OF SECONDARY MASS SAVINGS (SMS)	-SMS for two intermediate points (for body, chassis and powertrain MR) determined using factors to primary. -Full SMS applied to only individual vehicle solution points. -SMS is inherent in the powertrain downsizing (Civic components adopted into the solution for several system components, ex: engine).	-Study examined a number of major components that could be made smaller due to a lighter vehicle at the main solution point. -SMS was ratio'd at each level of mass reduction from 100% SMS at solution point back toward zero percent mass reduction. -SMS based in downsizing components.
COST CURVE EXPRESSION	-Curve is a connection of vehicle solution estimates for several material focused solutions. Rigorous analysis (CAE analysis etc.) performed for AHSS BIW + Al intensive point only. -DMC curve included two points for grouped glider technologies (non-structure and non-structure with aluminum closures) with system technologies and SMS included in whole vehicle solution.	-The cost curve was created through the cumulative addition of best value primary mass reduction components, up through aluminum closures, and resulted in a continuous curve for the AHSS BIW and aluminum intensive solution. -Compounded curve includes primary + secondary percent mass red and $/kg.

To create a similar cost curve as shown in Figure 5.118, several steps must be taken. This is achieved through an understanding of the methodology for Figure 5.118, referencing Figure 5.119 and using the descriptions and data in the 2012 NHTSA lightweighting report.

a) Evaluate the data used to create the Engineered Solution, at the AHSS BIW and Aluminum Closures and Chassis Frame point, in Figure 5.119 and separate into primary and secondary technologies. See Table 5.142. The mass save and costs were adjusted for the NHTSA response to Honda's comments. (The IIHS mass add was not included in this curve for the mass add in EPA's analysis is used in the MY2014 baseline calculations for safety credit and applied to all passenger cars and the applicable CUV's/SUV's).

b) Create the primary cost curve. The primary non-compounded cost curve, such as that shown in the green/top curve of Figure 5.118, represents cumulatively added mass reduction and costs for individual primary mass reduction technologies for the AHSS BIW and Aluminum intensive vehicle solution. These primary technologies can be adopted without concern of the resultant mass of the vehicle.

c) Determine the secondary mass and cost savings at the Engineered Solution point. Secondary mass and cost reduction technologies are determined and applied for a number of components, including the chassis and powertrain that could be redesigned to reflect the reduction in load associated with a reduced vehicle curb weight.

d) Create the compounded cost curve. Ratio the secondary mass and cost savings from the Engineered Solution point across the percent mass reduction from the primary cost curve. In Figure 5.118 this is shown as the purple/bottom curve. This effectively shifts the cost curve down and to the right. The translated curve in Figure 5.120 shows that NHTSA's approach for only applying secondary mass at points greater than 10 percent was maintained.

e) Create best fit curves to the data to be used in averaging.

Table 5.142 Designation of Primary and Secondary Mass reduction for 2012 NHTSA Accord-based Passenger Car Study

System	MR Technology/List of System Components	Primary	Secondary
Body	AHSS	*	*
Hood	Aluminum	*	
Radiator	Radiator Hoses Radiator Support Fan system Expansion Bottle	*	*
Front Bumper	AHSS	*	
Rear Bumper	AHSS	*	
Deck lid	Stamped Al	*	
Fenders	Stamped Al	*	
Front Door Frame	Stamped Al	*	
Rear Door Frame	Stamped Al	*	
Front Suspension	Lower Control Arm (AHSS) Steering Knuckles (Al) Stabilizer Bar (AHSS) Engine Cradle (Al) Other Material Change and Downsize	*	*
Interior Systems	Trim (Mucell) Front Seat(mg base) Rear Seat (composite back) Instrument Panel (mag)	*	
HVAC	Mucell	*	*

	Downsize to Civic		
Electrical	Wiring and wiring harness (Al/copper) Headlamps Tail Lamps	*	
Rear Suspension	K Frame Suspension Arms Bearing Hub Stabilizer Bar Other	*	*
Wheels & Tires	Wheels (AHSS) Tires Spare Wheel and Tire Car Jack	*	*
Engine	Downsize (Civic)		*
Transmission	Downsize	*	*
Drive Shafts	Downsize from Civic		*
Fuel System	Downsize Fuel Tank		*
Exhaust	Exhaust on Body Exhaust on Engine Heat Shields Downsize from Civic		*
Brake System	Front Calipers Rear Calipers Pads (Front) Pads (Rear) Brake Discs (front) Brake Discs (rear) ABS system Vacuum Pump Emergency Brake	*	*
Steering	Steering shaft assembly Steering rack Power steering Downsize to Civic		*
Battery	Downsize		*
Fuel	Less fuel used with smaller tank		*
Insulation - NVH	Add in 3.2kg at $10 - 3M Thinsulate, Quietblend		

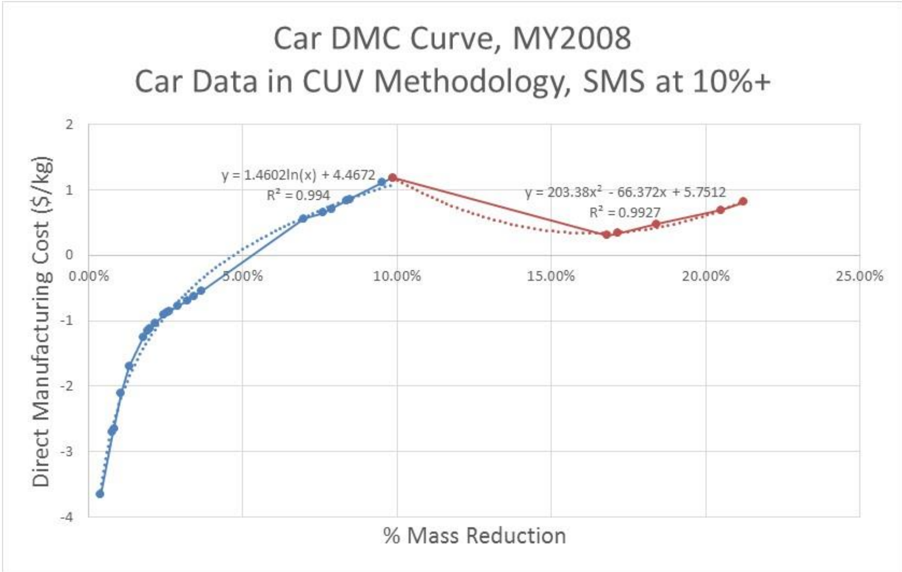


Figure 5.120 Car DMC Curve from Car Data shown in CUV Methodology ($/kg vs %MR), Engineered Solution AHSS BIW & Aluminum Closures and Chassis Frames

One notable difference between Figure 5.118 and Figure 5.120 is the place of the cost save mass reduction and the amount of cost increase mass reduction offset by these savings. The CUV curve, Figure 5.118, has notable mass savings in the primary (green/top) curve due to the number and cost estimates for the primary technologies. The Car curve, Figure 5.120, has notable mass savings in the secondary mass (as noted by the negative slope to the Engineered Solution point) due to the notable number of downsized technologies. Regardless of the specific technologies used to make the DMC curve, the curves reflect two different ways that mass reduction may be implemented on 2008 era vehicles.

STEP 4: To combine the two 2008 era DMC curves (Car and CUV) into a single Car/CUV curve, the best fit equations for the cost curves in Figure 5.118 and Figure 5.120 were determined and averaged together. The result is shown in Figure 5.121. This specific curve is utilized in the application of mass reduction for vehicles with a MY2014 baseline percent mass reduction of zero. Vehicles with a MY2014 baseline percent mass reduction above zero will have an adjusted cost curve applied. Calculation of the MY2014 baseline percent mass reduction is discussed in Section 5.3.4.6.2. Adjustment of the curve for vehicles with MY2014 baseline percent mass reduction is discussed in Section 5.3.4.6.2 as well as in "Cost Curve Adjusted for Baseline Mass Reduction Percent" further on in this discussion. The FRM linear cost curve is also included in the figure and it is noted that the new cost curve lies below the FRM cost curve.

Another factor in regards to costs for mass reduction is the improvement in fuel efficiency. EPA's analysis includes an increase in fuel efficiency of 5.2 percent for all vehicles in the 2020-2025 timeframe. Others have estimated the improvement as being 6 percent to 8 percent and the recent presentation by IBIS Associates, Inc. at the 2016 DOE Annual Merit Review[576] listed that up to 7 percent improvement in fuel efficiency for every 10 percent reduction in vehicle mass. If EPA's estimate is too low then other technologies will have to be adopted in order to make up this difference and in essence raising EPA's cost estimate for overall compliance with the standards.

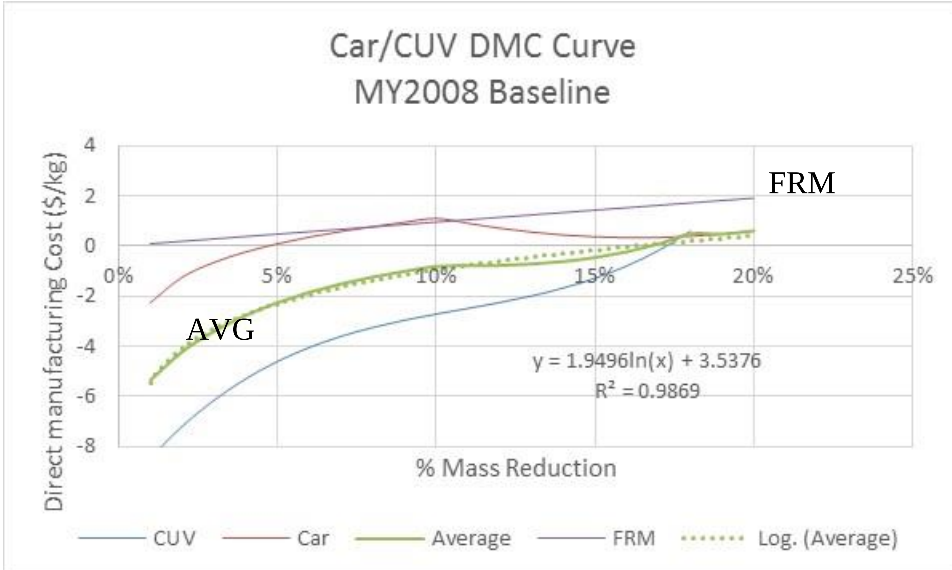


Figure 5.121 DMC Curve for 2008 Era Car/CUV (2013$/kg v %MR) - HSS BIW, Al intensive

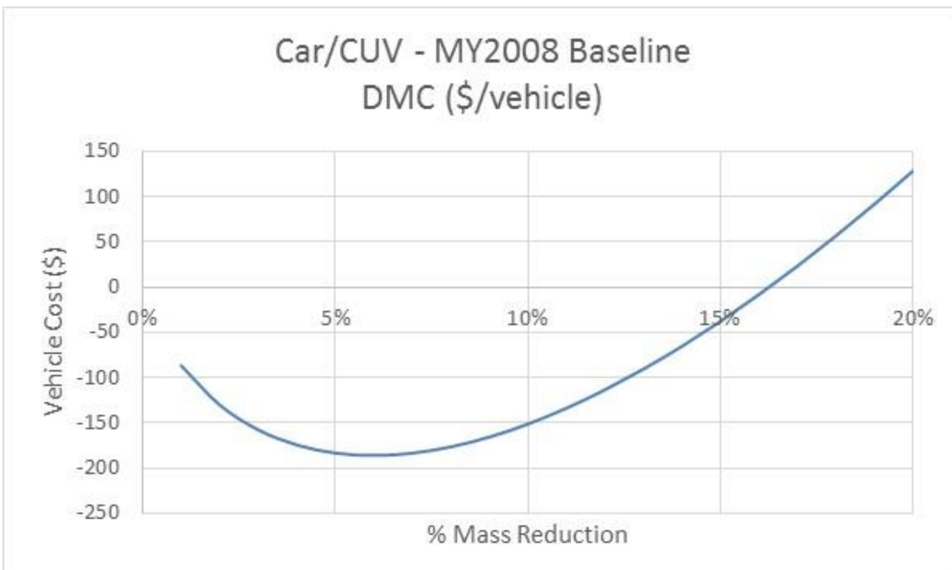


Figure 5.122 DMC Curve for 2008 Era Car/CUV (2013$/vehicle for a 3000 pound vehicle) -AHSS BIW, Al Intensive

The DMC curve for Car/CUV, Figure 5.121, shows cost savings when starting from a 2008 era vehicle design. Other resources acknowledge mass reduction at cost savings including the diagram by CAR in Figure 5.116. Several other documents also acknowledge some cost neutral mass reduction. These include the presentation by IBIS Associates, Inc. at the 2016 DOE

Annual Merit Review[576] , and the 2015 NAS study on the costs for mass reduction for passenger cars and light duty trucks.[492,FFF] Answers to several questions on this topic are listed below.

1. What types of technologies/approaches result in a mass reduction and a cost savings?

Table 5.143 Technologies/Approaches that Result in a Mass Reduction and a DMC Savings

Approach	Technology	Supporting Notes
DMC Savings and Mass Reduction	Design Part Integration and Optimization	Enhanced by improvements in CAE tools (Ex: airbag housing)
	Material and Component Design Optimization	Redesign a component for less mass of an existing material (Ex: scalloped edges in BIW)
	Material Processing	Ex: Mucell
	Design and Processing	Ex: Hollow Tube
Secondary Mass	Identification and Modification of components for Secondary Mass Savings	Use less of a material due to less load stresses (Ex: downsized engine, brakes)

2. Have OEM's expressed the ability to achieve mass reduction at a cost savings?

Information from an October 2015 GM investor presentation addressed the issue of cost savings for adopting mass reduction in 2016 vehicle releases. The Malibu and Camaro are on their second redesign since 2008 and the Cruze on its first since 2008. Using 2008 and 2016 curb weight values, from edmunds.com and A2Mac1, mass reductions of 4.4 to 12.1 percent[577] over 2008 MY are estimated, as shown in Table 5.144.

Figure 5.123 GM Investment Conference Call "Vehicles with More Efficiency at Better Margins"

FFF The 2015 NAS study includes a 'min' curve for the DMC for passenger car which reflects 6.5 percent mass reduction at a cost neutral, and includes 40 percent secondary mass for passenger cars at $1.00/kg cost save and 25 percent secondary mass for light duty trucks at $1.00/kg cost save, at points of 10 percent primary mass reduction or more.

Table 5.144 Estimate of Percent Change in Mass Reduction Compared to 2008 Estimates

Vehicle	Curb Weight 2008	Curb Weight 2014	2014 % MR Change (CW only)	2016 Curb Weight Dec Est	Est CW 2016	Est %MR 2016 over 2008
Malibu	3415-3649	3393-3660	-0.6% to +0.3%	300	3093-3388	-9.4 to -7.9
Cruze	3000	3118	+4%	250	2868	-4.4
Camaro	3780-3860	3719-3820	-1.6% to -1.0%	400	3319-3420	-12.1 to -11.4

*source of information: edmunds.com/A2Mac1

Cost Curve Adjusted for Baseline Mass Reduction Percent

Since the 2012 FRM, some manufacturers have reduced the curb weight of some of their vehicles, modified the design to allow compliance with new FMVSS and IIHS safety requirements and increased vehicle footprint. The Draft TAR uses a MY2014 baseline for which a baseline percent mass reduction per vehicle is calculated. The percent mass reduction is based on a change in curb weight in MY2014 from MY2008 (along with an allowance for safety compliance and vehicle footprint increase), and not the amount of mass reduction technology applied. The reason for this is that the mass reduction technologies are not always evident by the eye in the vehicle and the benefits of mass reduction are not achieved unless the overall vehicle is lighter. The detailed methodology for estimating the amount of mass reduction already present in a MY2014 vehicle is presented in Section 5.3.4.6.2.

The methodology for identifying and assigning baseline mass reduction is reflected in the calculations for the higher future cost for mass reduction and a potential decrease in the total additional mass reduction that can be applied to any given vehicle. Figure 5.124 and Figure 5.125 show the results of the DMC curve of a MY2014 vehicle with 5 percent mass reduction applied since MY2008. The original maximum DMC save of $200 (for a vehicle with zero percent MY2014 baseline mass reduction) is removed and the net zero cost mass reduction at 16 percent is also eliminated. The overall mass reduction potential, given the AHSS BIW and Aluminum intensive solution, has been reduced from 20 percent to 15 percent.

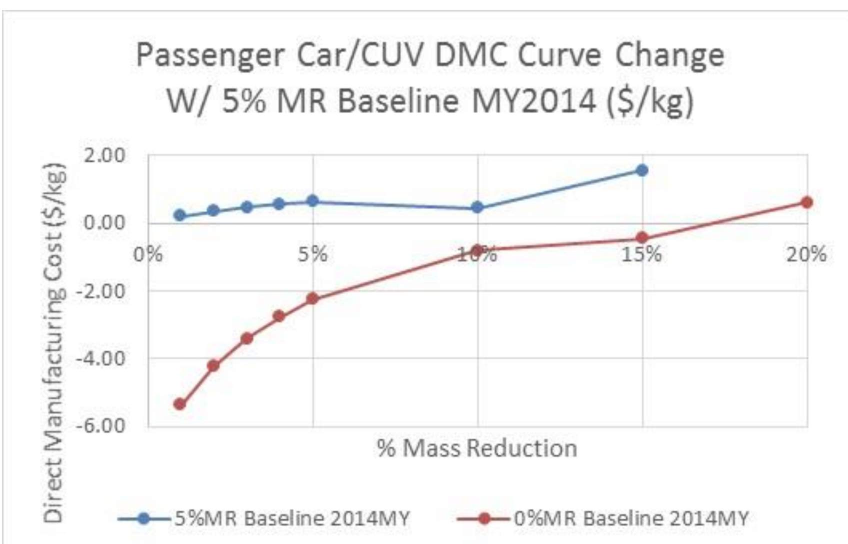


Figure 5.124 DMC Curve Adjusted for Car/CUV with 5 Percent Baseline Mass Reduction for MY2014 ($/kg)

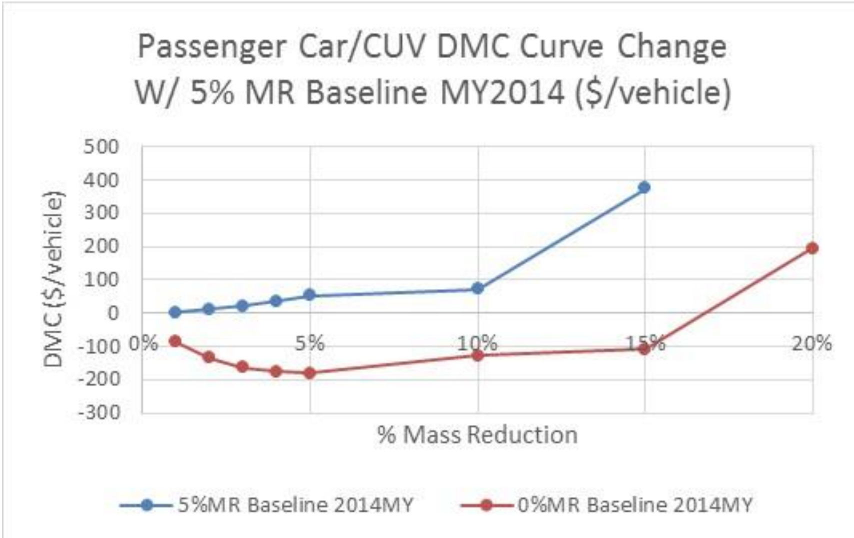


Figure 5.125 DMC Curve Adjusted for Car/CUV with 5 percent Baseline Mass Reduction for MY2014 ($/veh)

Total Costs for Car/CUV Mass Reduction

As described in Section 5.3.2.2.2, this assessment adopts a methodology for estimating the indirect costs of mass reduction based on separating direct manufacturing costs according to whether the components are purchased supplier parts, or OEM-produced. The OEM's markup on supplier produced components is expected to be less than the markup on an OEM produced component since the supplier markups are included in the OEM piece price to the supplier.

Figure 5.126 and Figure 5.127 show the resultant DMC cost curve, ICM curve and Total Cost curve for those vehicles designated to be assigned the passenger car cost curve for mass reduction based on MY2008. This curve is based on a vehicle with no baseline mass reduction differences noted between MY2008 and MY2014. If a vehicle were to have a baseline mass reduction noted for MY2014 then the Total Costs would increase due to the Direct Manufacturing Cost increases.

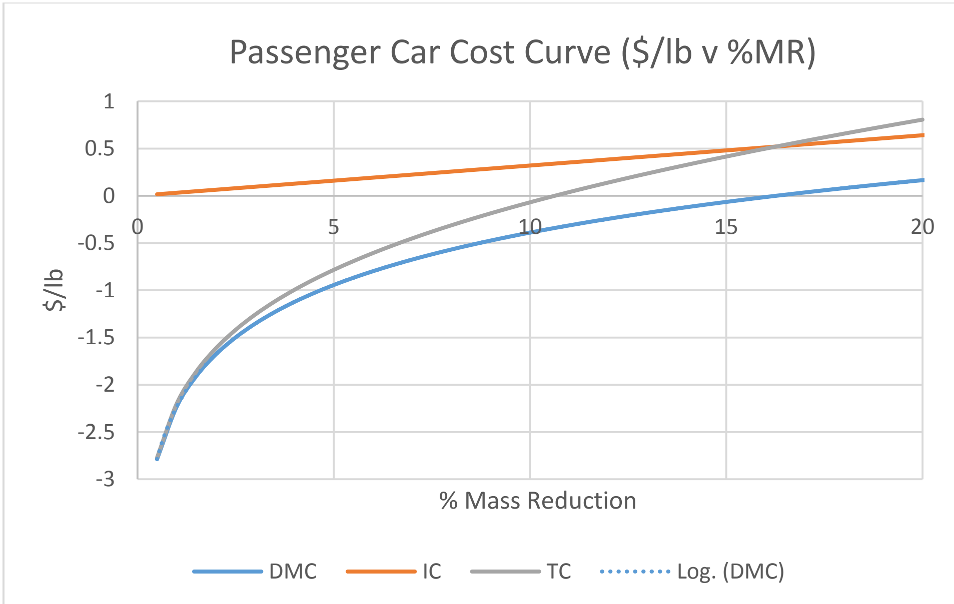


Figure 5.126 Resultant Passenger Car Cost Curve (2013$/lb, 3000 pound vehicle shown)

Note: DMC, IC using ICMs and Total Cost, MY2008 with 0 percent Baseline MR, applicable in MY2020 with learning effects determined by learning curve 30 (see Section 5.3.2.1.4)).

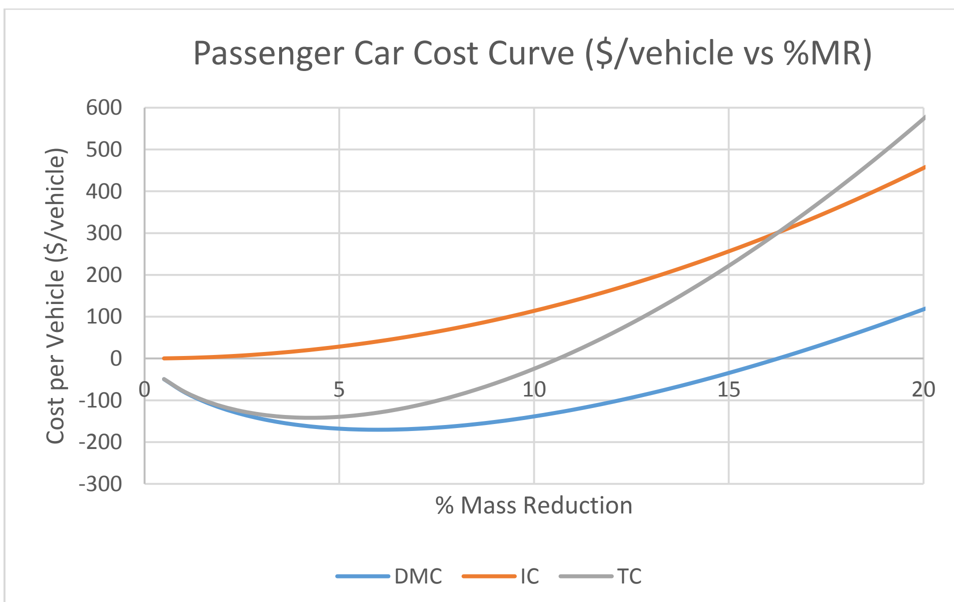


Figure 5.127 Resultant Passenger Car Cost Curve (2013$/vehicle, 3000 pound vehicle shown)

Note: DMC, IC using ICMs and Total Cost, MY2008 with 0 percent Baseline MR, applicable in MY2020 with learning effects determined by learning curve 30 (see Section 5.3.2.1.4)).

Comparison of Data for Lightweight Car/CUV with Aluminum BIW

In order to assess the opportunity to reduce the mass of passenger cars and CUV's beyond what was considered in the cost curves discussed, the EPA reviewed alternatives for all aluminum body-in-white. The alternatives presented here are not reflected in the draft TAR cost curves, but are included to recognize that EPA does not expect a significant inflection upward in cost with mass reduction beyond what has been considered in the draft TAR analysis of 2008 era vehicles. The solution points from the lightweight studies for the TAR contain AHSS BIW and aluminum intensive components correspond to mass reduction levels of 17.6 percent and just over 20 percent for the CUV and passenger car holistic vehicle studies respectively. In addition to the Aluminum BIW discussed below, the feasibility of achieving higher levels of mass reduction was shown in the work by DOE/Ford/Magna in which 23.5 percent mass reduction was achieved relative to a MY2013 Fusion[GGG] for the Mach 1 design, as described in Section 5.2. The overall BIW design was multi-material with 64 percent aluminum, 29 percent steel and 7 percent hot stamping. A number of vehicles were built and crashed, including IIHS ODB, with acceptable results and several notes for further improvement in the BIW design to CAE predictive correlation were noted. Costing was not a part of this project, however the SAE paper states "multi-material automotive bodies can achieve weight reduction with cost effective performance." [578]

Several additional design solutions at higher levels of mass reduction with all aluminum BIW were developed using the Venza and Accord-based studies as starting points, as shown in Figure 5.128, along with an extrapolation of the best fit Car/CUV cost curve from Figure 5.121.

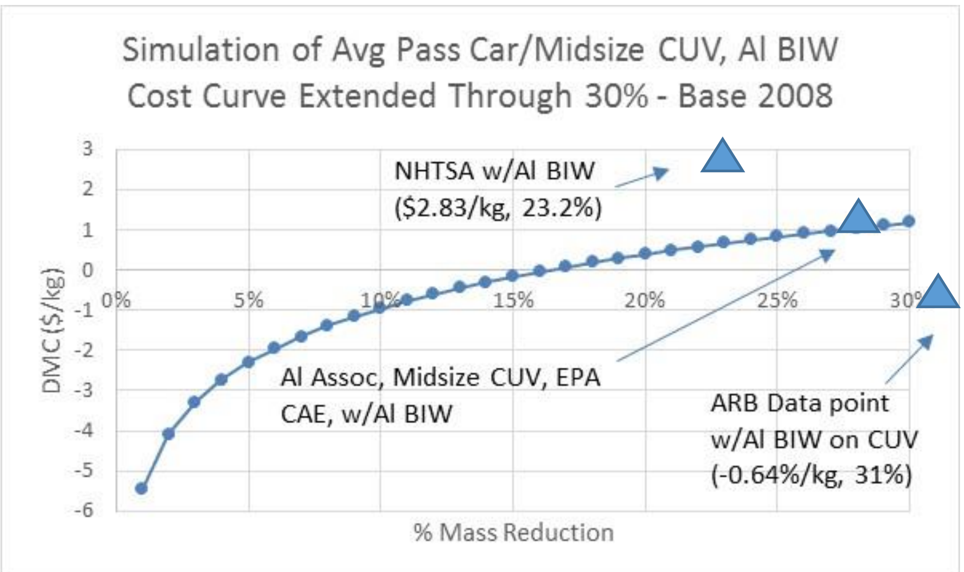


Figure 5.128 Car/CUV DMC Curve Extended to Points with Aluminum BIW

[GGG] The MY2013 Fusion was one redesign beyond the 2008 era Fusion. The base vehicle is approximately 250 lbs heavier and the top trim is approximately 100 lbs heavier in 2013 compared to 2008. The 2013 Fusion is approximately 2.80sq ft larger in footprint compared to the 2008 era Fusion and slightly taller and wider overall. Several safety features were also included. (https://en.wikipedia.org/wiki/Ford_Fusion_(Americas))

Figure 5.129 shows two points for the CUV aluminum intensive solution. One point is from the ARB-sponsored study by Lotus Engineering[579] and one point is from the Aluminum Association study through EDAG.[580] The ARB full vehicle data point with optimized BIW design and reduction of BIW components is 531kg (31 percent) mass reduction at -$0.64/kg. The Aluminum Association study of an all-aluminum BIW, based on material replacement into the CAE model from the original U.S. EPA Midsize CUV study, resulted in a total vehicle solution of $1.12/kg at a total of 476kg (27.8 percent) mass reduced. NHTSA studied the aluminum intensive vehicle design for the passenger car (based on the MY2011 Accord) and the result is a point at $2.83/kg for 23.2 percent.

Table 5.145 shows the detailed results of the studies. The cost/kg estimate for the NHTSA estimated point are likely overestimated given the recent reduction in the commodity price for aluminum and comments in the 2001 JOM source document used for the cost estimate indicates that costs have very likely decreased since this work was completed.[HHH581] Similarities are seen in the mass reduction results between the two aluminum intensive projects for the Midsize CUV (Lotus Engineering and EDAG) and these include the total BIW/closure/bumper total mass reduction which is only 6kg apart (201.7kg v 207.7kg respectively). The differences between the two projects include the BIW designs used and the resultant estimated costs. The EDAG study used the existing BIW design and the materials of aluminum alloy sheet, extrusion and casting. The Lotus Engineering solution also utilized the different aluminum components while optimizing component aggregation as only 169 components were used in the BIW compared to the original 419 and significant savings with the new manufacturing processes were assumed.

Table 5.145 Three Aluminum Intensive Vehicle Design Summary - DMC ($), %MR and $/kg

Aluminum BIW, Closures, Chassis	2012 ARB/Lotus (midsize CUV-1711kg)		2012 Al Assoc/EDAG (midsize CUV -1711kg)		2012 NHTSA/Electricore/ EDAG (Pass Car-1480kg)	
	Mass save (kg)	Cost ($)	Mass save (kg)	Cost ($)	Mass save (kg)	Cost ($)
BIW	140.7	239	162.2	780	113	782
Closures/Fenders	59	-381	43.2	106	44	153.7
Bumpers	2	9	2.3	8.6	-	-
TOTAL	201.7	-133	207.7	894.6	157	935.7
Total Vehicle	530	-342	464*	+520*	343.6	971.9
$/kg	-$0.64/kg		$1.12/kg		$2.83/kg	

Note: *adjusted for changes in the EPA baseline Midsize CUV cost curve into which the aluminum BIW was placed

Future Work for Proposed Determination

EPA recognizes that mass reduction technology will play an important role in meeting the 2022~2025 MY standards. The agency will continue to monitor and research developments in material development, material substitution approaches, design optimization and manufacturing.

[HHH] Investigation into the supporting documentation for the analysis revealed that the information was taken from a 2001 article in the Journal of Minerals, Metals and Materials Society. The article states "In fact, design developments by Audi already have resulted in significant cost reductions between its first- and second-generation vehicles. These have come about through parts consolidation, process substitutions, and part simplification."

EPA plans to revisit the assessment of overall mass reduction costs and the evaluation of mass reduction in the baseline fleet for the proposed determination.

5.3.4.6.1.2 Cost Curve for Light Duty Trucks

The cost curve for light-duty trucks developed for this assessment as described below represents an estimate of the Direct Manufacturing Cost (DMC) for mass reduction technologies that are expected to be broadly available in 2020. Total costs, which are made up of both DMCs and Indirect Costs (ICs), are also presented herein. More detail on the methods for calculating indirect costs and learning for mass reduction are provided in Section 5.3.2.

Light Duty Truck DMC Curve Generation

The LDT direct manufacturing cost curve was created through combining the results of the EPA MY2011 base LDT and NHTSA MY2014[III] base LDT lightweighting studies which are outlined in Section 5.2. Development of the LDT DMC curve for use in EPA modeling is completed in the following steps outlined in Table 5.146. This section also includes discussion of the complete LDT cost curve with Direct Manufacturing Cost (DMC), Indirect cost (IC) and resultant Total Cost (TC).

Table 5.146 LDT DMC Curve Development

STEP	TASK
1	Begin with the MY2011 and MY2014 Light Duty Truck cost curves (the vehicles are of different design eras)
2	Translate the NHTSA LDT DMC cost curve to use a similar methodology as the EPA LDT DMC cost curve
3	Average the two LDT curves using the best fit line for each curve. Account for difference in eras between the two studies.

STEP 1: The cost curve for the Car/CUV was based on two 2008 era vehicles and hence represents the technology of lightweighting on 2008 era vehicles. The MY2011 Silverado 1500 design and the MY2014 Silverado 1500 are from two different design eras. The MY2011 Silverado 1500 is a 2008 design era vehicle. The MY2014 Silverado 1500 is the next redesign and has been redesigned with safety compliance[JJJ], some lightweighting and slightly larger size. All of these features will come into play later on in the LDT cost curve development process described herein. The curb weight difference between the MY2011 and MY2014 light duty truck study vehicles is 22kg as shown in Table 5.147.

Table 5.147 Comparison of MY2011 and MY2014 Crew Cab Silverado 1500[582]

	MY2011 Silverado 1500	My2014 Silverado 1500^
Cabin Design	Crew Cab	Crew Cab
2x4, 4x4	4x4	4x4
Truck Bed Length	5.8 ft	5.8 ft

[III] The final report for the MY2014LDT was not available in time for this Draft TAR analysis. The Proposed Determination will contain an updated analyses given the final mass reduction and cost information from the final MY2014 LDT lightweighting study.

[JJJ] The safety design features in the MY2014 Silverado include higher compliance to the IIHS small overlap crash test as well as compliance with FMVSS crash tests that came in during the 2008 and 2014 timeframe.

Engine	5.3L V8 FFV (315hp)	5.3L V6 (355hp)
Transmission	4 speed	6 speed
Wheelbase	143.5 inches	143.5 inches
Track Width	68 in front, 67 in rear	68.7-68.9 in front, 67.6-67.9 in rear
Curb Weight*	2454kg	2432kg
*The curb weights were from the EPA and NHTSA light duty truck lightweighting studies. The mass decrease for these two trucks is 22kg. ^The 2014 LDT incorporates materials to address the safety standards that came into effect between 2012 and 2014. The 2014 LDT is also slightly larger		

The two light duty truck DMC curves are reviewed to assure the two cost curves utilize a similar methodology.

The EPA light duty truck direct manufacturing cost curve is shown in Figure 5.129 and is based on EPA's light duty truck light-weighting study (MY2011 Silverado 1500). The lightweight design is aluminum intensive combined with an AHSS frame. The DMC curve was created using the similar cost curve methodology in the EPA Midsize CUV study. EPA's methodology is to a) cumulatively add all of the primary mass reduction technologies (not dependent on vehicle mass for optimization) and costs (green/top curve), b) add an NVH allotment component by ratio across all mass save steps, and c) determine secondary mass at primary solution point and ratio secondary mass savings across the primary mass curve to create the compounded curve (purple/bottom curve). The original engineered solution point to the study was 20.8 percent mass reduction at $4.35/kg. The cost curve on the MY2011 LDT result was modified with a re-evaluation of the NVH allotment to 15kg from 50kg, both at $3/kg, based on new NVH technology. The resultant cost curve is shown in Figure 5.129 with an engineered solution point of 22 percent mass reduction at $3.92/kg direct manufacturing cost. The MY2011 LDT was the same design cycle as the MY2008 LDT[582].

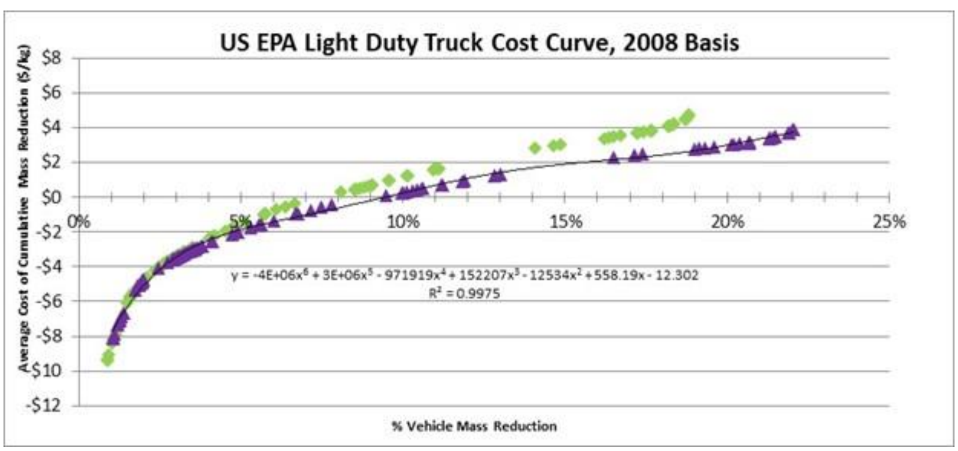


Figure 5.129 U.S. EPA Light Duty Pickup Truck Direct Manufacturing Cost Curve, MY2008 Design[583]

The NHTSA light duty truck direct manufacturing cost curve is shown in Figure 5.130 and is calculated by NHTSA based on the data from the May/June pre-peer review version light duty truck light-weighting study (MY2014 Silverado 1500).[KKK] NHTSA's cost curve methodology

[KKK] The NHTSA LDT final report was not available in time for this Draft TAR analysis.

changed from that used in development of the cost curve for the passenger car. The initial curve was created by a) cumulatively add mass and cost of primary technologies (from glider) and then b) apply downsized components (non-glider) at the main vehicle solution point (Aluminum Intensive and AHSS frame (noted as 'AHSS+Al Solution (LWV)')) and c) connect the end of the cumulatively added technologies to the vehicle solution point with a straight. The cumulative add of the primary (glider) technology ends at approximately 12.5 percent. The solution point, located at 17.5 percent, includes non-glider technologies (engine, transmission, exhaust, etc.) and any other secondary components optimized for maximum mass reduction for the solution point. The costs are assumed to increase linearly from the 12.5 percent point to the 17.5 percent point. Additional technologies from the Aluminum Solution and the CFRP Solution are applied to achieve a total of 20 percent mass reduction from the MY2014 LDT design. Unlike the passenger car cost curve, the cumulative cost curve does take into account some of the secondary mass reduction opportunities to account for different powertrain options and platform sharing. Any changes to NHTSA's interpretation of the data/cost curve in the final light duty truck lightweighting study will be incorporated for the Proposed Determination.

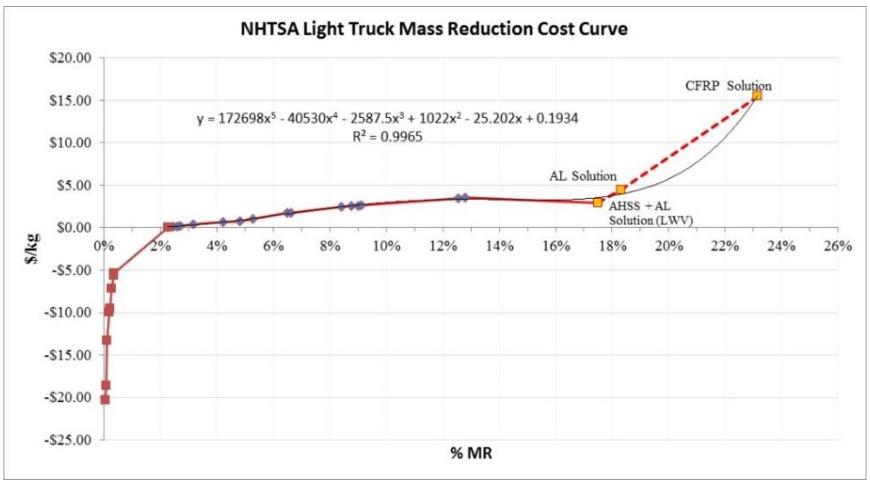


Figure 5.130 NHTSA Light Duty Truck Direct Manufacturing Cost Curves, MY2014 Design[LLL]

STEP 2: Translate the NHTSA LDT DMC curve to use a similar methodology as the EPA LDT DMC curve. The cost curves from the EPA MY2011 LDT study and NHTSA interpreted curve from the MY2014 LDT study data were similar in methodology however differences still remain. Table 5.148 contains a comparison of the two cost curve methodologies. For determination of the final cost curve for the light duty truck, the cost curve for the MY2014 based study is recalculated using the MY2011 cost study methodology.

[LLL] See Section 5.2 for NHTSA light duty truck lightweighting study.

Table 5.148 Light Duty Truck Study Cost Curve Methodology Comparison

Topic	EPA (Peer Reviewed MY2011 LDT Study)	NHTSA (NHTSA Curve from Data of the Pre-Peer Review MY2014 LDT study)
COSTS and TIMEFRAME	Costs are representative of 2020 LDT of MY2011 Design (similar to 2008)	Costs are representative of 2017 LDT of MY2014 Design (new design)
TECHNOLOGY IDENTIFICATION	A large number of individual vehicle components including engine, trans.	A number of components and adoption of systems from lighter vehicles (engine, etc.).
BIW/FRAME	Material replacement, material grade and gauge optimization.	Material replacement, computer optimization of load paths, grade and gauge optimization for AHSS frame with Al intensive design only
BIW/FRAME SAFETY CRASH/NVH in CAE	-Include NVH, FMVSS, etc. crash results -IIHS small overlap evaluated in study by Transport Canada in which base LDT crash used for CAE development and solution developed in CAE for mass add determination	-Include NVH, FMVSS, etc. crash results -IIHS small overlap based on observation of F150 IIHS crash results, applied to Silverado 1500
Base Vehicle Comply with IIHS Small Overlap	Poor rating likely - review of crash results of MY2013 Silverado 1500	Marginal according to IIHS website
ORDERING OF PRIMARY MR TECHNOLOGIES FOR COST CURVE	-All technologies with primary mass reduction ordered lowest to highest $/kg -Only grouped ideas as required for implementation feasibility.	-Glider technologies for AHSS frame/Al intensive solution used as primary tech -Technologies ordered in lowest to highest $/kg order and cumulatively summed -Whole vehicle solution and technologies for other materials plotted and used to achieve 20 percent
NVH (noise)	Originally 50kg at $150* (adjusted 15kg and $45)	Incorporated in vehicle load path design Additional ~3kg at $10.69
INCORPORATION OF SECONDARY MASS SAVINGS (SMS)	-Study examined a number of major components that could be made smaller due to a lighter vehicle at the main solution point. -SMS based on downsizing -SMS ratio'd at each level of mass reduction from 100% SMS at solution point back toward zero percent mass reduction.	-Applied at solution points only -Inferred in line connecting end of primary cumulative curve and vehicle solution for AHSS Frame/Al Intensive solution point -Inferred in points up to 20 percent mass reduction
Cost Curve Expression	- Cumulative addition of best value primary mass reduction components, up through aluminum closures, and resulted in a continuous curve for the AHSS BIW and aluminum intensive solution. -Compounded curve includes primary + secondary percent mass red and $/kg.	-Cumulative add glider technologies for AHSS frame with Al intensive solution - SMS at solution point -Additional aluminum and CFRP technologies used to reach 20 percent mass reduction

Note:
* Learned in 2015 through the DOE/Ford/Magna cosponsored Mach1/Mach2 SAE papers

In order to combine cost curves, it is important that the two cost curves are considered in the same methodology since the exact same technologies were not evaluated. The NHTSA cost curve shows additional technologies beyond the main solution point, of AHSS+Al (LWV) Solution, to achieve 20 percent mass reduction from the MY2014 basis. The following analysis will show how these technologies are not required for the combined cost curve to achieve 20 percent mass reduction on a 2008 era basis. The following steps were performed to translate the NTHSA resultant study findings for the AHSS+Al Solution (LWV) into the EPA LDT cost curve methodology.

a) Evaluate the data used to create the AHSS+Al Solution (LWV) point and assure all technologies are separated into their primary and secondary components, see Table 5.149.[MMM]

b) Create the primary cost curve. The primary non-compounded cost curve, such as that shown in the green/top curve of Figure 5.129, represents cumulatively added mass reduction and costs for individual primary mass reduction technologies for the LWV solution. These primary technologies can be adopted without concern of the resultant mass of the vehicle.

c) Determine the secondary mass and cost savings at the AHSS+Al Solution (LWV) point. Secondary mass and cost reduction technologies are determined and applied for a number of components, including the chassis and powertrain that could be redesigned to reflect the reduction in load associated with a reduced vehicle curb weight.

d) Create the compounded cost curve. Ratio the secondary mass and cost savings from the AHSS+Al Solution (LWV) point across the percent mass reduction from the primary cost curve. In Figure 5.129 this is shown as the purple/bottom curve. The translated curve in Figure 5.131, although not evident, does contain the NHTSA's approach for only applying secondary mass at points greater than 10 percent was maintained. The secondary mass and cost savings were offset by the mass reduction technology at that point. Figure 5.132 is an expression of the curve in $/vehicle v. percent mass reduction.

e) Create best fit curves to the data for use in averaging.

[MMM] Figure 5.130 became available in the May/June 2016 timeframe and will be updated when the final report becomes available. The cost curve for the EPA mass reduction modeling was completed prior to the availability of this final curve from the May/June timeframe.

Table 5.149 Re-Designation of Secondary Technologies Listed in NHTSA Light Duty Truck Lightweighting Report

System	Technology	Primary	Secondary
Cab	Aluminum	*	
FESM (per vehicle)	Aluminum	*	
Radiator Support Structure	Al & Cast Magnesium	*	
Front Bumper	AHSS		*
Rear Bumper	AHSS		*
Chassis Frame	AHSS		*
Towing Hitch	AHSS		*
Front Suspension	Lower Control Arm (Al to AHSS) Others downsized	*	*
Rear Suspension	Leaf spring: 1 steel +2FGRP Others downsized	*	*
Wheels & Tires[NNN]	eVOLVE Rims	*	
Engine	Downsize		*
Transmission	Rear Diff Housing to Al Other Downsize	*	*
Drive Shafts	Downsize		*
Fuel System	Downsize fuel tank		*
Exhaust	Downsize		*
Brake System[OOO]	Keep Iron Discs - Master Cyl DS - front discs DS -Front calipers (to Al) and DS -Front Pads DS - Rear Discs DS - Rear Calipers (to Al and DS) -Rear pads DS -Park Brake to EPB -Caliper Supports DS	*	*
Water Cooling	Downsize		*
Battery	Downsize		*
Fuel	Less fuel used with smaller tank		*

[NNN] The material for the wheels were changed, but the size remained the same - hence primary mass reduction change.

[OOO] The brakes contained several technology changes. Some changes were material/design and these are primary changes, downsizing of components are secondary and since there was some of both in the work then the mass reduction for brakes falls into both categories.

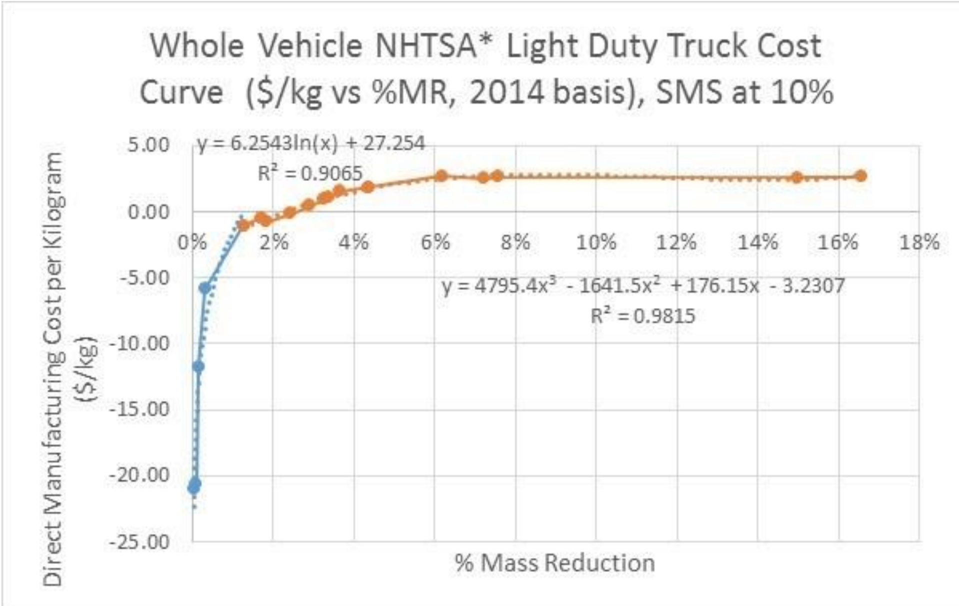


Figure 5.131 NHTSA Light Duty Truck (MY2014) Data Points in EPA Cost Curve Methodology ($/kg v %MR) for Aluminum Intensive with AHSS Frame

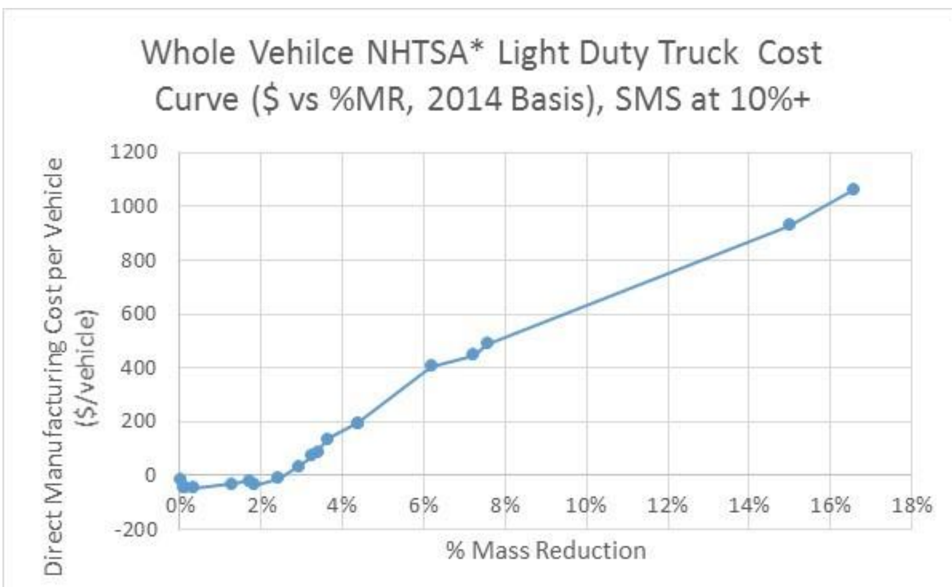


Figure 5.132 NHTSA Light Duty Truck (MY2014) Data Points in EPA Cost Curve Methodology ($/vehicle v %MR)

Comparing the best fit curve calculated results from Figure 5.131 with NHTSA's cost curve presented in Figure 5.130, it is observed that the calculated $/kg at the 17.5 percent mass reduction point is $3.02/kg with EPA's analysis of the LDT data while the NTHSA cost curve best fit curve result is $3.55/kg. The differences are likely due to the offset of the best fit curve offset at this point in Figure 5.130 and partially due to the preliminary nature of the data available from NHTSA's light duty truck study at the time of EPA's calculation of the translated cost curve. Both curves show the same amount of mass reduction at a cost save which is approximately two percent. A direct comparison between the EPA and NHTSA results cannot yet be made due to the fact that the curves represent different vehicle design years. Additional cost curve manipulation must occur before the cost curves can be averaged.

STEP 3: To average the two LDT DMC curves using the best fit line for each curve, the differences in eras between the two studies must first be addressed. As done in EPA modeling, the 2008 era cost curve is adjusted for differences in curb weight (with factors for safety and footprint) to match the 2014 era vehicle. The difference in curb weight is found in Table 5.147 and is noted as 22kg. Adjustments for safety, such as mass add to comply with new 2010-2014 FMVSS standards and IIHS small overlap are credited to the MY2014 vehicle, along with adjustment for larger footprint and are performed per steps outlined in 5.3.4.6.2.1. The total mass difference between the MY2011 LDT and MY2014 LDT is 22kg (curb weight)+11.6kg (FMVSS safety allowance) + 22kg (IIHS small overlap allowance) 7.9kg (footprint calculation) which equals 63.5kg or 2.6 percent of the MY2011 LDT. All of the mass reduction ideas in the cost curve within the 2.6 percent are cost save ideas and as a result the resultant cost curve increases in $/kg for these ideas are not available to offset cost increase ideas. The resultant EPA LDT cost curve to represent a MY2014 vehicle is illustrated in Figure 5.133.

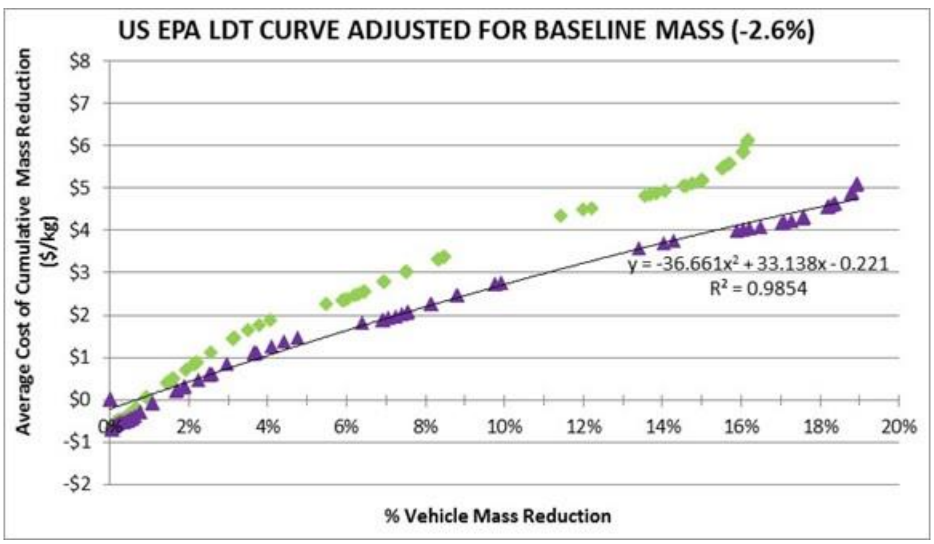


Figure 5.133 EPA Adjusted MY2011 LDT Cost Curve for 2014 LDT Design (-2.6%)

The two MY2014 based direct manufacturing cost curves for the Aluminum with AHSS frame solution, represented by the best fit line for each cost curve, as shown in Figure 5.131 (NHTSA*=data by EPA) and Figure 5.133 (EPA), are then averaged together. The result cost curve is shown in Figure 5.134. The dip in the NHTSA curve is due to the application of secondary mass savings at points of 10 percent mass reduction and greater.

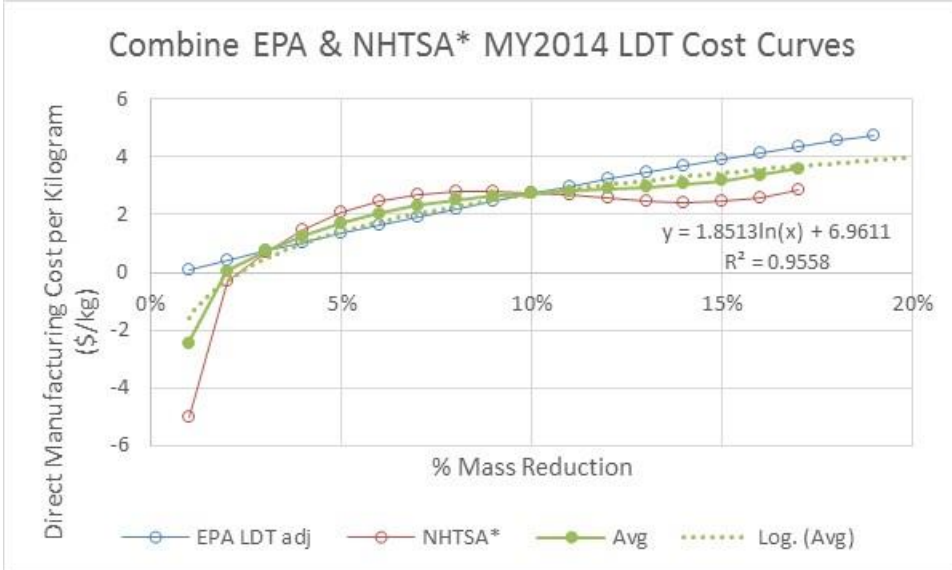


Figure 5.134 Combined Direct Manufacturing Cost Curve using EPA LDT and NHTSA LDT

The average curve shown in Figure 5.134 is specific to the example for the MY 2014 LDT. To create a cost curve which can be applicable to all vehicles with various MY2014 percent baseline mass reduction, the cost curve in Figure 5.134 must be brought back to a 2008 era base. EPA uses 2008 era base cost curves in its passenger car/midsize CUV curve and making the LDT curve a 2008 era base will be consistent. The MY2014 base DMC curve is converted back to MY2008[PPP] by adding in the removed points from the EPA LDT cost curve (0-2.6 percent and all cost save) and the resultant curve is shown in Figure 5.135 with costs per vehicle shown in Figure 5.136. Note that the overall cost is reduced due to the initial points being all cost save items.[QQQ]

The DMC cost curve shown in Figure 5.135 is applied as-is for vehicles with no mass reduction identified in their MY2014 baseline. For LDT with a MY2014 baseline mass reduction noted, such as the 2.6 percent noted on the MY2014 Silverado 1500, the cost curve will be adjusted with the same methodology as used to form the EPA MY2011 LDT curve to a MY2014 LDT curve, previously described. This methodology results in further mass reduction technologies being more expensive on vehicles that incorporate mass reduction technologies that result in a change in curb weight from their previous design. This methodology also results in a reduction in the maximum mass reduction percentage that can be applied as noted if comparing Figure 5.135 and Figure 5.134.

[PPP] The MY2011 Silverado 1500 is of the same design cycle as the MY2008 Silverado 1500.

[QQQ] For EPA's analysis, the LDT DMC cost curve is being applied to all vehicles designated as a truck and this include some SUV's and CUV's which meet the truck definition and may be unibody in design.

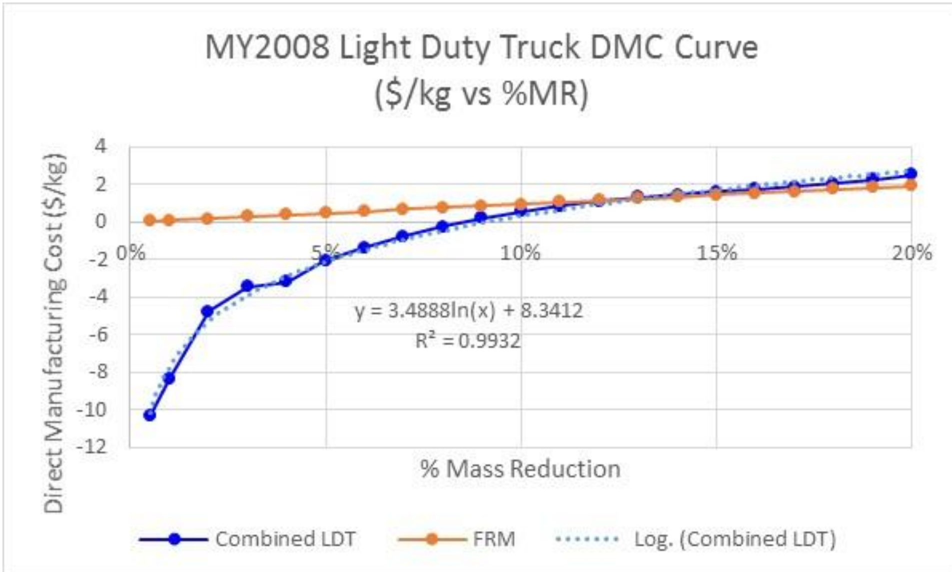


Figure 5.135 Direct Manufacturing Cost Curve for 2008 Era Light Duty Trucks (2013$/kg vs %MR)

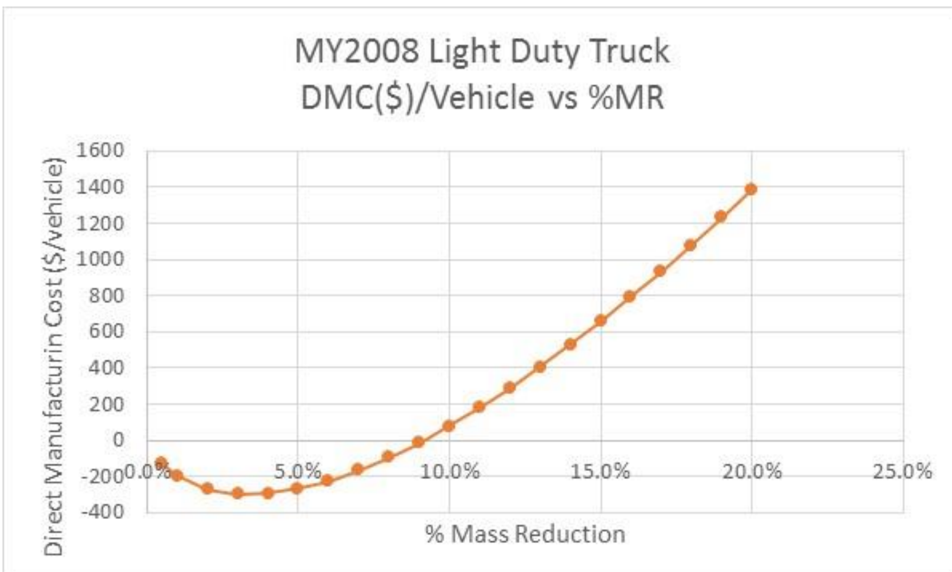


Figure 5.136 MY2008 Light Duty Truck DMC (2013$/Vehicle for a 6000 pound truck) vs Mass Reduction

Total Costs for Light Duty Truck Mass Reduction

As described in Section 5.3.2.2.2, this assessment adopts a methodology for estimating the indirect costs of mass reduction based on separating direct manufacturing costs according to whether the components are purchased supplier parts, or OEM-produced. The OEM's markup on supplier produced components is expected to be less than the markup on an OEM produced component since the supplier markups are included in the OEM piece price to the supplier.

Figure 5.137 and Figure 5.138 show the resultant DMC cost curve, ICM curve and Total Cost curve for those vehicles designated to be assigned the light duty truck cost curve for mass reduction based on MY2008. These curves are based on a vehicle with no baseline mass reduction differences noted between MY2008 and MY2014. If a vehicle were to have a baseline mass reduction noted for MY2014 then the Total Costs would increase due to the Direct Manufacturing Cost increases.

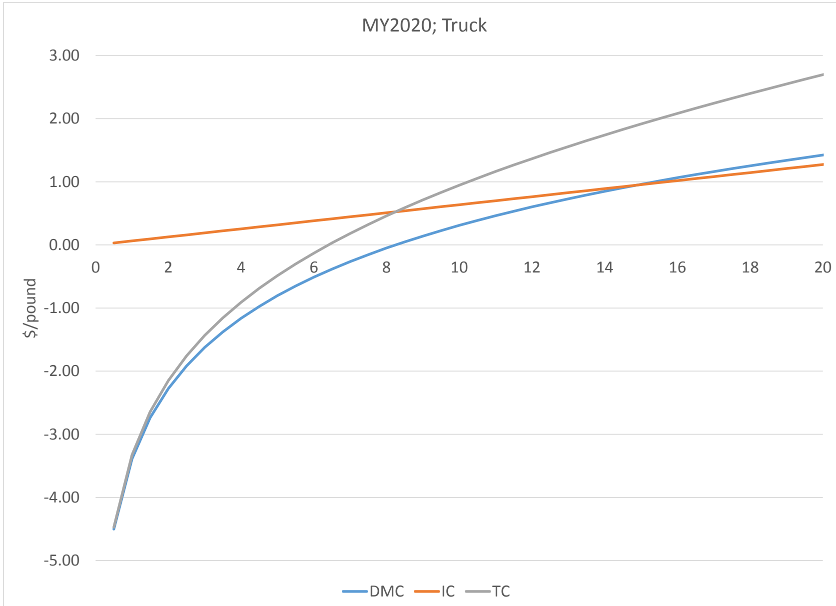


Figure 5.137 Resultant Light duty Truck Cost Curve (2013$/lb, 6000 pound vehicle shown)

Note: DMC, IC using ICMs and Total Cost, MY2008 with 0 percent Baseline MR, applicable in MY2020 with learning effects determined by learning curve 30 (see Section 5.3.2.1.4))

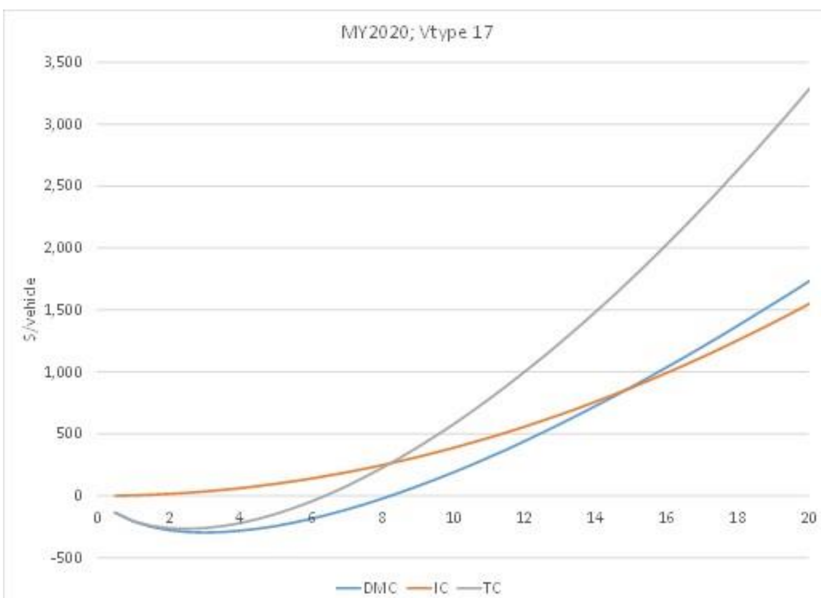


Figure 5.138 Resultant Light Duty Truck Cost Curve (2013$/vehicle, 6000 pound vehicle shown)

Note: DMC, IC using ICMs and Total Cost, MY2008 with 0 percent Baseline MR, applicable in MY2020 with learning effects determined by learning curve 30 (see Section5.3.2.1.4))

Future Work for Proposed Determination

EPA recognizes that mass reduction technology will play an important role in meeting the 2022~2025 MY standards. The agency will continue to monitor and research developments in material development, material substitution approaches, design optimization and manufacturing. EPA plans to incorporate NHTSA's final LDT DMC curve technology points as well as revisit the assessment of overall mass reduction costs and the evaluation of mass reduction in the baseline fleet for the proposed determination.

5.3.4.6.2 Mass Reduction in the Baseline MY2014 Fleet

The baseline fleet methodology for this Draft TAR has been updated from the FRM for model year and for starting percent mass reduction as shown in Table 5.150. For the FRM, the MY2008 fleet was the baseline fleet and it was assumed that each vehicle in the baseline had zero mass reduction[RRR] irrespective of any differences in vehicle type, the use of lightweight materials, or overall vehicle design and implementation. Each vehicle was also assumed to have the same maximum potential for additional mass reduction.

For the Draft TAR, mass reduction continues to be defined as a decrease in curb weight. This definition provides a direct relationship between the level of mass reduction, the cost, and the benefits achieved. As shown in Table 5.150, the Draft TAR is updated to a MY2014 baseline and is adjusting the incremental costs and the maximum mass reduction potential on the percent mass reduction that is calculated in the MY2014 baseline. This updated approach has important implications for cost estimation since mass reduction becomes increasingly more expensive at higher levels.

Table 5.150 Draft TAR Mass Reduction Baseline Revisions

TOPIC	FRM	Draft TAR
Baseline MY	2008	2014
Percent Mass Reduction	0 percent - all vehicles	-Vehicle specific: MY2014-MY2008 curb weight difference plus MY2014 footprint and safety mass adjustments. -OR Vehicle Specific: OEM lightweighting trend from current vehicles with MY2008/MY2014 models applied to new 2014 models. -Calculations use 0.5 increments percent mass reduction
Potential Maximum Mass Reduction	Same for all vehicles	Differs depending on MY2014 baseline calculated percent mass reduction. (Max= 20 percent - MY2014 baseline percent)
Mass Reduction Cost	Same for all vehicle	Cost curve costs are modified depending on MY2014 baseline calculated percent mass reduction.

After evaluating a variety of alternatives, EPA estimated mass reduction for each vehicle in the MY2014 baseline fleet relative to the corresponding MY2008 vehicle. If a vehicle did not have a MY2008 counterpart then the sales weighted average percent mass reduction over the

[RRR] In terms of dollars per kilogram curb weight reduction.

OEM's nameplate product line is used to represent the expectation of the amount of mass reduction technology within the vehicle. This consumer-oriented "lineage" approach is similar to model-level comparison, although with additional consideration for models newly introduced or renamed after MY2008. The following sections describe the calculations in more detail.

The methodology considers AWD/4WD v 2WD differences as well as 2014 mass increases due to new safety requirements and changes in footprint over 2008. Limitations to this analysis include 1) no adjustment for engine size differences between trim levels, 2) no adjustment for hybrid or EV trim levels (typically smaller volume and high mpg), and 3) mass additions due to future potential safety regulations.

5.3.4.6.2.1 Vehicles with MY2008 and MY2014 Production

Vehicle baseline percent mass reduction was determined by subtracting the MY2014 curb weight (with adjustments) from the MY2008 curb weight (with adjustments). The base curb weight data for MY2008 was taken directly from the data used in the Light Duty GHG 2017-2025 FRM. The MY2014 curb weight data was adopted from information in the ARB sponsored study Control Tec study[584], which assembled the baseline from EPA test vehicle weight data and other sources.

The following paragraphs describe the methodology utilized in the creation of the MY2014 baseline database.

1. Sales weight the 2008 models and related trim levels - per vehicle

When sales weighting the curb weight of several trim levels within a vehicle model in two different years (2008 and 2014), in order to gain a more accurate picture of change in curb weight due to mass reduction technology, one needs to ensure that unique vehicle characteristics do not influence the overall vehicle sales weighted mass in either year. One vehicle attribute that would influence trim level mass is 4WD/AWD v 2WD. A mass allotment is added to 2WD vehicles and then the trim levels are sales weighted within the respective years.

a. Adjust the 2008 curb weight for 4WD/AWD v 2WD variations.

A report funded by Transport Canada with Pilot Systems included the evaluation of mass differences in AWD v 2WD on three different vehicles. The mass amount was determined through a review of three different AWD systems - Jeep Cherokee, Ford Fusion and VW Tiguan. The mass differences were 135kg, 72kg, and 78kg respectively for an average of 95kg or 209lbs. A value of 200lbs was used to provide an adjustment to minimize the influence of this vehicle characterization difference in the baseline sales weighted curb weight.[585]

b. Sales weight the 2008 vehicle trim levels per vehicle.

2. Sales weight the 2014 models and related trim levels - per vehicle adjusting for footprint and safety

The same AWD/4WD v 2WD adjustment is made on the 2014 vehicle trim levels. Vehicle trim levels are then sales weighted. Prior to calculating the final MY2014 baseline mass reduction allotments, adjustments to the MY2014 curb weight were made to account for footprint, which is a change in vehicle characteristics that influence CAFE and GHG target levels, and MY2008-MY2014 increased FMVSS and IIHS crash requirements.

a. Adjust the 2014 curb weight for 4WD/AWD v 2WD (as with 2008). Same mass difference is utilized as for 2008 models.

b. Sales weight the 2014 vehicle trim levels per vehicle.

c. Adjust the 2014 curb weight data for footprint increase

Footprint is allowed to increase from 2008 to 2014 without penalty and as a result a kg/square foot credit was applied to footprint differences between the 2008 and 2014 vehicles. The main idea behind this action is that if vehicles remain at a similar curb weight but increased in size then they did incorporate mass reduction technology to offset the increased footprint.

The methodology used to determine the footprint mass credit (mass/sqft) is as follows:

1) Identify the portions of the vehicle that would be affected by an increase in footprint area (passenger compartment back seat leg room).

2) Gather mass data from a number of vehicles, using the A2Mac1 database (mass) for BIW, glass, and interior masses. Choose vehicles which span the 6 vehicles classes (small car, standard car, large car, small SUV, large SUV and truck).

3) Gather footprint data on the same vehicles.

4) Determine the mass/sqft by dividing the total mass of these components per vehicle by the total vehicle footprint. The resultant average mass/area per vehicle class is shown in Table 5.151.

Table 5.151 Footprint Density per Vehicle Class (lb/sqft and kg/sqft)

Avg FP Density	Small	Midsize	Large	Pickups	Small MPV	Large MPV/Truck
lb/sqft	18.56	20.07	21.13	11.88	20.72	23.56
kg/sqft	8.43	9.12	9.60	5.40	9.42	10.71

The averages in Table 5.151 were applied to all respective vehicles for which it was determined there was an increase in footprint in 2014 compared to 2008. Table 5.152 shows the application of the average kg/sqft mass credit to the Acura MDX and RDX, which are designated Large MPV/Truck.

1) Determine if the vehicle footprint did increase from 2008 to 2014. The vehicle footprint and footprint of related trim levels, if applicable, were sales weighted for both 2008 and 2014 and the 2008 model footprint average was subtracted from the 2014 model footprint average. A positive number meant an increase in overall footprint ("Delta FP"). (Note: if vehicles changed names in 2014 compared to 2008 then this was noted and the vehicles still compared with each other)

2) Determine the mass increase by multiplying the change in footprint by the footprint adjustment in the appropriate vehicle class from Table 5.151.

3) Add the mass credit to the original Delta CW for a new change in mass reduction.

4) Recalculate the adjusted curb weight percentage

For example, Table 5.152 shows that the adjustment factor for the Acura MDX and RDX, is 10.71 kg/sqft, as from , for they are both considered Large MPV/Truck. Based on the change in square feet and the footprint density factor for large MPV's, the credit for mass reduction in the MDX and RDX are 3.2kg and 13.9kg respectively and the overall % curb weight changes 0.2 percent and 0.8 percent respectively.

Table 5.152 Examples of Mass Footprint Adjustment (single vehicle)

Make	Model	LineageID	MY	Delta CW (kg)	**Delta CW %**	Delta FP (sqft)	FP Density (kg/sqft)	Adj FP (kg)	Adj CW (kg)	**Adj CW%**
Acura	MDX	2	2008							
Acura	MDX	2	2014	-238	**-11.5%**	0.3	10.71	3.2	-241	**-11.7%**
Acura	RDX	3	2008							
Acura	RDX	3	2014	-94.1	**-5.3%**	1.3	10.71	13.9	-108	**-6.1%**

Footprint changes were not accounted for between trim variants. Examples include light duty trucks with different cab designs and box lengths,

d) Adjust the 2014 curb weight data for mass credit for safety (FMVSS and IIHS)

Several NHTSA safety regulations have come into effect between 2008 and 2014. Table 5.153 lists the specific FMVSS test as well as the estimated car and light truck mass increase. The amount of mass increase for the NHTSA/FMVSS safety regulations was determined from information from NHTSA's 'Corporate Average Fuel Economy for MY2017-2025 Passenger Cars and Light Trucks' Final Regulatory Impact Analysis document[586].

One IIHS Top Safety Pick requirement, the Small Overlap, was published in 2012 and came into full effect with the MY2014. Table 5.153 lists the mass credit estimates for the IIHS small overlap which EPA also applied to all 2014 MY vehicles for simplicity of analysis reflecting the assumption that each vehicle will be redesigned to achieve this goal before 2021MY. The mass credit for the IIHS small overlap test on 20 percent lightweight vehicles was determined by two agency studies for which a good/acceptable rating was the goal. One study was funded by NHTSA, the updated light weight passenger car study[587,] and a second by Transport Canada[588] as a follow-up study to EPA's light duty pickup light-weighting study along with one peer review comment to the study. The light weight passenger car credit was found to be a range from 6.3-9.6kg for subcompact to minivans respectively. The lightweight light duty pickup truck (aluminum intensive) mass reduction mass increase was determined to be 22kg.

Each vehicle's MY2014 baseline curb weight is credited with the total safety mass estimate.

Table 5.153 Additional Safety Mass Added for 2014 Vehicles

ESTIMATED VEHICLE WEIGHT IMPACT OF FMVSS SAFETY REGULATIONS and IIHS Small Overlap (kg)			
Final Rules by FMVSS No.	Passenger Cars Added Weight (kg)	Light Trucks Added Weight (kg)	Compliance Dates
214 Side Pole	5.64	5.25	Sept 2009-2012
216 Roof Crush	5.28	5.28	Sept 2012-2015
226 Ejection Mitigation	0.91	1.07	Sept 2013-2017
Final Rules Subtotal	**11.83kg**	**11.6kg**	
IIHS small overlap On ~20% lightweight vehicle	6.9kg	22 kg	2012/2014 for Top Safety
Total Mass Increase Est*	**18.73kg**	**33.6kg**	

Note: All pass cars and some SUV's fall into the passenger car category. Some SUV's fall into the light duty truck classification. It is also understood that some of the IIHS small overlap mass add may be duplicated in the roof crush NHTSA design adjustments.

A reality check on these mass increases for light duty pickup trucks can be seen in the comparison of the MY2011 Silverado 1500 cabin mass (207.2 kg) compared to the MY2014 Silverado 1500 cabin mass (242.6 kg) which were measured in the EPA and NHTSA respective light duty pickup truck light-weighting studies. This is a difference of 35.4kg and is the result of the addition of a door ring and other improvements which the AHSS components provide. Although this evaluation is on an AHSS cabin design from a mild steel cabin design, the mass increase supports the overall mass increase, in Table 5.153, which is based on the optimized solution for an aluminum truck design. The F150 was redesigned for MY2015, however the mass increase for the IIHS small overlap was not known since it was incorporated into the overall vehicle redesign.

For the passenger car, there are some vehicle designs which currently meet the IIHS small overlap and are not yet designed to meet the IIHS small overlap.

3. Calculate the Resultant Curb Weight Difference between MY2008 and MY2014

With mass credits for change in footprint and safety determined for the MY2014 vehicles, then adjusted weight reduction amounts can be calculated as shown in Table 5.154. For example, the Acura MDX which had a curb weight difference of 11.5 percent is noted to now have a 13.3 percent difference in curb weight given credits for increased footprint and safety.

This amount of percent mass reduction will then be applied as a baseline mass reduction for the particular vehicle and if additional mass reduction technology is to be applied to the vehicle then the mass reduction cost curve will be recalculated prior to mass reduction technology application. In this way, the EPA has attempted to quantify the amount of mass reduction a manufacturer may have already implemented in the baseline fleet and the associated cost of increasing the amount of mass reduction form the baseline. This will be covered in more detail further in this section. The vehicles that were found to have an increase in curb weight or had no change in curb weight from 2008 to 2014, after being adjusted for footprint and safety mass increase, had no adjustment to the mass reduction cost curve.

Table 5.154 Examples of Safety Mass Reduction Allotted and Weight Reduction Change (single vehicle)

Vehicle Make	Footprint Category/Safety Category	Model Year	Weight Reduction based on change in curb weight (kg)	Weight Reduction (%)	Change in footprint	Add Mass Savings from Footprint Increase/ Safety	Weight Reductio n (%)
Acura MDX	Large SUV/Truck	2014	238	11.5%	0.3	(238+0.3*10.71+11.6+22)/ 2067	13.3%
GM Cadillac CTS	Med Car/Pass Car	2014	112	6.4%	0.275	(112+0.275*9.12+11.83+6.9)/ 1755	7.6%
Land Rover Range Rover	Large SUV/Al intensive Truck	2014	354	14%	2.63	(354+2.63*10.71+11.6+22)/ 2500	16.6%
Chevy Cruze (Cobalt 2008)	Compact/Small	2014	98	3.0%	2.67	(98+8.43*2.67+11.83+6.9)/ 1417	9.8%

Note: The numbers in the table are for example only.

5.3.4.6.2.2 MY2014 Vehicles without MY2008 Counterparts

A review of the MY2014 baseline vehicle models in the MY2008 baseline database reveal that about half of the models did not have a match in MY2008 by which to determine a mass reduction change (percent change in curb weight). For these vehicles, a methodology was determined to create estimates of MY2014 baseline percent mass reduction. The adjustment for safety as listed in the previous section was applied.

For each vehicle and respective OEM nameplate group, the percent mass reductions from the group of OEM nameplate vehicles with MY2008-MY2014 comparisons would be sales weighted together to obtain a general mass reduction trend for that nameplate. This average sales weighted value would then be applied to the new MY2014 vehicles that did not have MY2008 comparisons. It was observed that the majority of vehicles that fall under this category did not incorporate significant mass reduction and so applying the OEM trend towards mass reduction was an appropriate approximate.

Additional work will be to review the applicability of this methodology as well as apply baseline percent mass reduction for those vehicles which incorporated lightweight technologies in MY2008 and MY2014 and as a result may not have the correct percent mass reduction assigned to them to represent their current state of technology adoption. Such vehicles include those which were known to be aluminum intensive or carbon fiber intensive in 2008 and 2014 and the OEM did not have other vehicles on which to determine an appropriate sales weighted evaluation, such as Lotus, Tesla, and BMWi3/i8. The majority of these vehicles are low volume and/or already far exceed the 2025 standards.

5.3.4.6.2.3 MY2014 Cost Curve Adjustments Due to Vehicle Baseline MY2014-MY2008 Curb Weight Differences

The NAS committee noted in the 2015 report that "It is generally acknowledged that the cost to reduce mass increases for each additional unit of mass eliminated on a vehicle."[492] EPA agrees that this is the case, however also notes that in order that the benefits of mass reduction be achieved, the actual curb weight of the vehicle must actually decrease. As a result the calculation for the MY2014 baseline percent mass reduction (compared to 2008MY) is calculated through comparison of the curb weight and application of several mass reduction credits.[SSS]

The MY2014 vehicles found to be heavier, or the same, than their MY2008 counterparts will start in the cost curve as-is with zero percent mass reduction. Modifications to the cost curve are made for those vehicles with resultant curb weight decreases for the MY2014, compared to MY2008 counterparts, and hence assumes that mass reduction technologies have been adopted to achieve reduced curb weight. The removal of mass reduction technology starts with the cost saving technologies and as a result the remaining points on the cost curve increase from their original position. While the percent baseline mass reduction is determined on a vehicle specific basis (in 0.5%MR increments), the amount of cost curve adjustment ($/vehicle) used in EPA modeling is based on a vehicle type basis. Specifically, each vehicle type (1-19) has a set sales weighted curb weight for all vehicles within that type based on the vehicle curb weight and sales information within the type.

Figure 5.139 and Figure 5.140 illustrate the change in the EPA passenger car cost curve and the overall Direct Manufacturing Cost estimates for a MY2014 baseline vehicle (vehicle type 5 (1916kg)) that has 5 percent lighter mass (curb weight plus MR credits) than the MY2008. The $/kg results are the same across all vehicle types to which the Car/CUV DMC curve is applied. The overall $/vehicle vary depending on vehicle type and related curb weight.

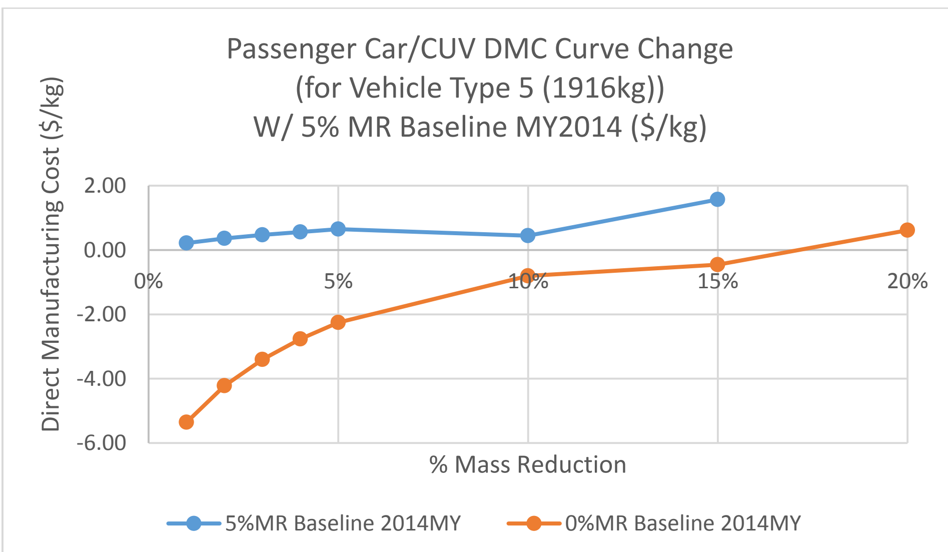


Figure 5.139 Car/CUV DMC ($/kg) Curve for MY2014 Vehicle with 5 Percent Lower Curb Weight Than MY2008 (Vehicle Type 5)

SSS This section has described certain credits given to MY2014 vehicles for increased footprint and safety mass increases that lowers the curb weight of the MY2014 vehicle in these calculations.

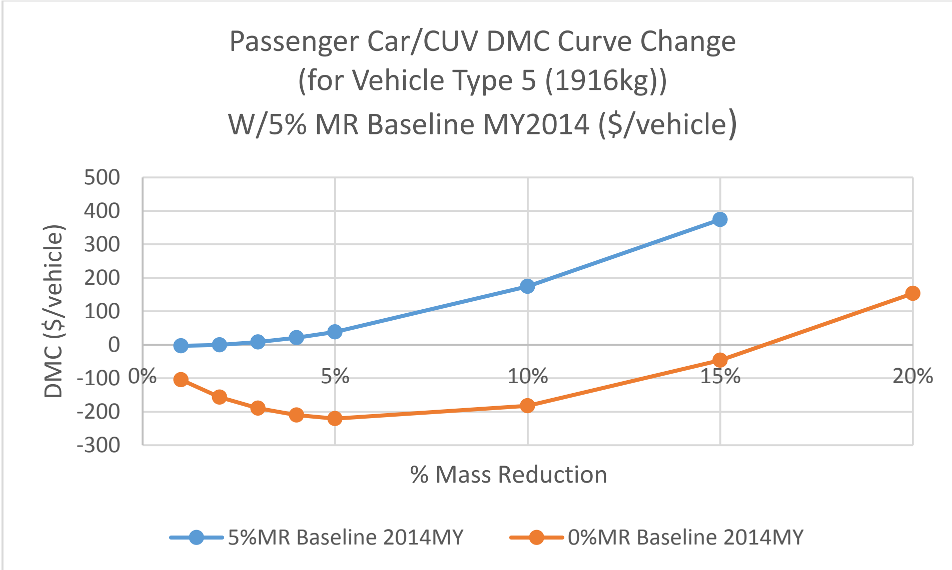


Figure 5.140 Total Car/CUV DMC ($/vehicle) Curve for MY2014 Vehicle with 5 Percent Lower Curb Weight Than MY2008 (Vehicle Type 5 of 1916kg)

Table 5.155 shows the calculations for calculating the new $/kg for adding 5 percent additional mass reduction on top of a passenger vehicle (EPA vehicle type 5) that already has 5 percent baseline mass reduction. In Table 5.155, the example is based on a vehicle type 5 with a sales weighted curb weight of 1916kg (4215lb). Results are that the additional 5 percent mass reduction costs $0.40/kg or an increase of $38.32 (DMC, 2013$ in 2020). As noted previously, this increase ($/vehicle) is applied across all vehicle type 5 that happen to have 5 percent baseline mass reduction, regardless of the specific curb weight of the particular vehicle.

Table 5.155 Example of Calculations for Adjusting Car/CUV DMC Curve for 5 Percent Baseline Mass Reduction

Vehicle has 5%MR and Applying Additional 10%. Vehicle type 5 curb weight is 1916kg. $/kg points on Original DMC Curve: 10%= -0.95/kg, 5%= -2.3/kg		
Calculation Step	Mass Reduced (kg) =%MR*vehicle mass	$ Difference =$/kg*mass reduced
Point of max mass reduction (ex: 10%)	.10*1916 =192 kg	-$0.95 *192= -$182.40
Point of allotted curb weight mass reduction (ex: 5%)	.05*1916 =95.8 kg	-$2.3/kg *95.8= -$220.34
Subtract the original (5%) from the total (10%)	192-95.8=95.8kg	(-$182.40)- (-$220.34) =$37.94
Calculate the new $/kg for the additional 5%MR	$37.94/95.8kg=+$0.40/kg	
$/vehicle for additional 5%	0.40*(1916*0.05)=**$38.32**	

The EPA modeling does not apply mass reduction to passenger cars with individual curb weights of 3197lbs or below. The maximum amount of mass reduction is also limited to not allow a passenger vehicle to go below 3197lbs and so this limits a large number of vehicles (in vehicle types 1-7 and 13) to either 2, 5, or 10 percent maximum mass reduction. The maximum amount of 20 percent mass reduction is allowed on passenger car vehicle type 5 (large car) whose sales weighted curb weight is large enough such that the 20 percent mass reduction would not go below 3197lbs.[TTT,UUU] The light duty truck DMC curve is applied to vehicle types 8-12 and 14-19 (towing vehicles) and the maximum percent mass reduction (20 percent) is allowed to be applied without any lower bound cutoff. These vehicle types cover midsize to large SUV's and all size light duty pickup trucks.

5.3.4.6.2.4 Safety Regulation Mass Increase Estimate Post MY2014

For the Proposed Determination analyses, a consideration of future potential and final regulation mass reduction offsets will be considered for the 2022-2025 standards. Table 5.156 shows that a range of 7.08-9.51 kg mass increase from potential/future final rules for passenger cars and light duty trucks is estimated. Due to the timeline required for NHTSA to progress from study to full implementation, it is estimated that the NHTSA oblique test may be incorporated sometime on or after 2022 so the mass increase is a consideration for the 2022-2025 mass reduction feasibility.

Table 5.156 Future Safety Regulation Reference. Mass Increase Expectations[VVV]

POTENTIAL RULES	Passenger Cars Added Weight (kg)		Light Trucks Added Weight (kg)	
	Min	Max	Min	Max
Pedestrian Protection	?		?	
Forward Collision Warning (with Dynamic Brake Support and Crash Imminent Braking), Lane Departure Warning	0.29	2.72	0.29	2.72
Oblique	5.0		5.0	
Part 563 EDR	0.04		0.04	
V2V	1.56		1.56	
Final Potential Rules Subtotal	6.89	9.32	6.89	9.32
Final Rule: 111 Rear Cameras May 2016-2018	*0.19*		*0.15*	
TOTAL	*7.08*	*9.51*	*7.08*	*9.51*
Automatic Emergency Braking by 2022/2025 Announced 3/17/2016	*?*	*?*	*?*	*?*

[TTT] If there was not a mass cutoff for application of mass reduction then the results from the baseline calculations for the MY2008 v MY2014 vehicle data show that approximately 50 percent of the more than 1400 passenger car vehicle listing in the modeling, representing 54 percent of the volume within the passenger car modeling, has a lighter curb weight in MY2014. Within the 50 percent of passenger car vehicle listings in the modeling, the majority are within the 0-5 percent range and a few span the 5-20 percent range. The remaining vehicles are either the same or heavier than the 2008 era design vehicles.

[UUU] When all passenger car and light duty truck vehicles are weighted together the overall mass change is 0.4 percent or near neutral. This result is in line with the overall mass pattern within the 2014 Trends report[UUU] which shows a near neutral change in regards to vehicle mass for 2014/2015 model years. When the vehicles are sales weighted average all together, and those with curb weight increases are set to zero, the overall mass reduction decrease is 1.9 percent.

[VVV] Based on “Estimated Vehicle Weight Impact of Safety Regulations - Potential Rulemakings" (reference: SAE Government Industry Conference January 2015). Lane departure warning included in previous table on safety mass increase.

The estimate of 5kg mass increase for the potential NHTSA oblique test is increased based on the estimate that the vehicles currently comply with IIHS small overlap and that there will be a small additional mass increase due to the uniqueness of the oblique test[WWW]. It is also understood that restraint modifications to the seat belt and air bag timing may likely be required. NHTSA is evaluating this at the time of the writing of the Draft TAR and should have a decision by the time of the Proposed Determination.

5.3.4.6.3 *Effectiveness of Mass Reduction*

In the FRM EPA estimated mass reduction related fuel economy improvement to be 5.1 percent for every 10 percent reduction in mass. This included application of secondary mass reduction (which considered downsizing of the engine, brake, transmission, suspension, etc.) at every percent mass reduction.[XXX] This methodology recognizes that a manufacturer does not have a single threshold which results in right-sizing the engine, but rather designs the vehicle as a system.

For the Draft TAR, EPA performed effectiveness analyses for the standard car class using the ALPHA model and engine maps representing MY2014 and newer engines. Results showed the effectiveness for mass reduction is a linear equation based on the engine baseline out CO_2 emissions. As a result an effectiveness of 5.2 percent is utilized for both cars and trucks. For Discussion of the Alpha model see Section 5.3.3.2.2.

5.3.4.6.4 *Mass Reduction Costs used in OMEGA*

The tables below show an excerpt of the mass reduction costs used in OMEGA. There are 8 tables that follow, with the first four showing mass reduction costs at 5 percent, then 10 percent, then 15 percent then 20 percent mass reduction for the 8 vehicle types that use the car cost curve. The next four tables show mass reduction costs at 5 percent, then 10 percent, then 15 percent then 20 percent mass reduction for the 11 vehicle types that use the truck cost curve. The direct manufacturing costs (DMC), indirect costs (IC, using ICMs) and the total costs (TC) are shown along with the sales weighted average curb weight of all vehicles mapped into the indicated vehicle types, the complexity levels used for indirect costs and the learning curve factor used as discussed in Section 5.3.2.

The cost for additional mass reduction increases with increasing MY2014 baseline mass reduction. The MY2014 baseline percent mass reduction is determined for each vehicle model (sales weighted for trim with adjustments for AWD/2WD, adjustments for safety and footprint changes) and noted on a 0.5 percent mass reduction increment basis. Since the cost curves are developed with the greatest cost save/kg mass reduction ideas listed first, which are then cumulatively added, the calculations for removing the baseline mass reduction percentage is performed beginning with the lowest cost save portion of the curve. As a result the additional mass reduction technology costs increase with increasing MY2014 baseline mass reduction.

[WWW] The mass increase for the IIHS small overlap crash test was accounted for in the MY2014 baseline curb weight.

[XXX] This is assumed to be the outcome in 2025 and not necessarily in the transition years. EPA has observed that in 2016 some OEM's have engine models with 0.1L or 0.2L difference between them and so OEM's are able to be successful in their engine downsize-vehicle matching.

Table 5.157 Costs for 5 Percent Mass Reduction for Non-towing (Car curve) Vehicle Types (2013$)

Vehicle Type	Cost type	DMC: CurbWt IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	DMC	2629	30	-$150	-$145	-$141	-$137	-$134	-$131	-$129	-$126	-$124
2	DMC	3131	30	-$178	-$172	-$168	-$163	-$160	-$156	-$153	-$150	-$148
3	DMC	3557	30	-$202	-$196	-$190	-$186	-$181	-$177	-$174	-$171	-$168
4	DMC	3495	30	-$199	-$193	-$187	-$182	-$178	-$174	-$171	-$168	-$165
5	DMC	4215	30	-$240	-$232	-$226	-$220	-$215	-$210	-$206	-$202	-$199
6	DMC	3967	30	-$226	-$219	-$212	-$207	-$202	-$198	-$194	-$191	-$187
7	DMC	3494	30	-$199	-$193	-$187	-$182	-$178	-$174	-$171	-$168	-$165
13	DMC	3767	30	-$214	-$208	-$202	-$196	-$192	-$188	-$184	-$181	-$178
1	IC	Low2	2024	$26	$26	$26	$26	$26	$26	$26	$26	$21
2	IC	Low2	2024	$31	$31	$31	$31	$31	$31	$31	$31	$25
3	IC	Low2	2024	$35	$35	$35	$35	$35	$35	$35	$35	$28
4	IC	Low2	2024	$35	$35	$35	$35	$35	$35	$35	$35	$28
5	IC	Low2	2024	$42	$42	$42	$42	$42	$42	$42	$42	$34
6	IC	Low2	2024	$39	$39	$39	$39	$39	$39	$39	$39	$32
7	IC	Low2	2024	$35	$35	$35	$35	$35	$35	$35	$35	$28
13	IC	Low2	2024	$37	$37	$37	$37	$37	$37	$37	$37	$30
1	TC			-$124	-$119	-$115	-$111	-$108	-$105	-$102	-$100	-$103
2	TC			-$147	-$141	-$136	-$132	-$128	-$125	-$122	-$119	-$123
3	TC			-$167	-$161	-$155	-$150	-$146	-$142	-$139	-$136	-$139
4	TC			-$164	-$158	-$152	-$148	-$143	-$140	-$136	-$133	-$137
5	TC			-$198	-$190	-$184	-$178	-$173	-$168	-$164	-$161	-$165
6	TC			-$186	-$179	-$173	-$168	-$163	-$159	-$155	-$151	-$156
7	TC			-$164	-$158	-$152	-$148	-$143	-$140	-$136	-$133	-$137
13	TC			-$177	-$170	-$164	-$159	-$155	-$151	-$147	-$144	-$148

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

Table 5.158 Costs for 10 Percent Mass Reduction for Non-towing (Car curve) Vehicle Types (2013$)

Vehicle Type	Cost type	DMC: CurbWt IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	DMC	2629	30	-$123	-$119	-$116	-$113	-$111	-$108	-$106	-$104	-$102
2	DMC	3131	30	-$147	-$142	-$138	-$135	-$132	-$129	-$126	-$124	-$122
3	DMC	3557	30	-$167	-$162	-$157	-$153	-$150	-$146	-$144	-$141	-$139
4	DMC	3495	30	-$164	-$159	-$154	-$150	-$147	-$144	-$141	-$139	-$136
5	DMC	4215	30	-$198	-$192	-$186	-$181	-$177	-$173	-$170	-$167	-$164
6	DMC	3967	30	-$186	-$180	-$175	-$171	-$167	-$163	-$160	-$157	-$155
7	DMC	3494	30	-$164	-$159	-$154	-$150	-$147	-$144	-$141	-$138	-$136
13	DMC	3767	30	-$177	-$171	-$166	-$162	-$158	-$155	-$152	-$149	-$147
1	IC	Low2	2024	$104	$104	$104	$104	$104	$104	$104	$104	$84
2	IC	Low2	2024	$124	$124	$124	$124	$124	$124	$124	$124	$100
3	IC	Low2	2024	$141	$141	$141	$141	$141	$141	$141	$141	$114
4	IC	Low2	2024	$139	$139	$139	$139	$139	$139	$139	$139	$112
5	IC	Low2	2024	$167	$167	$167	$167	$167	$167	$167	$167	$135
6	IC	Low2	2024	$158	$158	$158	$158	$158	$158	$158	$158	$127
7	IC	Low2	2024	$139	$139	$139	$139	$139	$139	$139	$139	$112
13	IC	Low2	2024	$150	$150	$150	$150	$150	$150	$150	$150	$121
1	TC			-$19	-$15	-$12	-$9	-$6	-$4	-$2	$0	-$18
2	TC			-$23	-$18	-$14	-$10	-$7	-$5	-$2	$0	-$22
3	TC			-$26	-$20	-$16	-$12	-$8	-$5	-$2	$0	-$25
4	TC			-$25	-$20	-$16	-$12	-$8	-$5	-$2	$0	-$24
5	TC			-$31	-$24	-$19	-$14	-$10	-$6	-$3	$0	-$29
6	TC			-$29	-$23	-$18	-$13	-$9	-$6	-$3	$0	-$27
7	TC			-$25	-$20	-$16	-$12	-$8	-$5	-$2	$0	-$24
13	TC			-$27	-$22	-$17	-$13	-$9	-$5	-$2	$0	-$26

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

Table 5.159 Costs for 15 Percent Mass Reduction for Non-towing (Car curve) Vehicle Types (2013$)

Vehicle Type	Cost type	DMC: CurbWt IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	DMC	2629	30	-$31	-$30	-$29	-$28	-$28	-$27	-$27	-$26	-$26
2	DMC	3131	30	-$37	-$36	-$35	-$34	-$33	-$32	-$32	-$31	-$31
3	DMC	3557	30	-$42	-$40	-$39	-$38	-$37	-$37	-$36	-$35	-$35
4	DMC	3495	30	-$41	-$40	-$39	-$38	-$37	-$36	-$35	-$35	-$34
5	DMC	4215	30	-$50	-$48	-$47	-$45	-$44	-$43	-$43	-$42	-$41
6	DMC	3967	30	-$47	-$45	-$44	-$43	-$42	-$41	-$40	-$39	-$39
7	DMC	3494	30	-$41	-$40	-$39	-$38	-$37	-$36	-$35	-$35	-$34
13	DMC	3767	30	-$44	-$43	-$42	-$41	-$40	-$39	-$38	-$37	-$37
1	IC	Med2	2024	$235	$235	$235	$235	$235	$235	$235	$235	$189
2	IC	Med2	2024	$280	$280	$280	$280	$280	$280	$280	$280	$226
3	IC	Med2	2024	$318	$318	$318	$318	$318	$318	$318	$318	$256
4	IC	Med2	2024	$312	$312	$312	$312	$312	$312	$312	$312	$252
5	IC	Med2	2024	$377	$377	$377	$377	$377	$377	$377	$377	$304
6	IC	Med2	2024	$354	$354	$354	$354	$354	$354	$354	$354	$286
7	IC	Med2	2024	$312	$312	$312	$312	$312	$312	$312	$312	$252
13	IC	Med2	2024	$337	$337	$337	$337	$337	$337	$337	$337	$271
1	TC			$204	$205	$206	$207	$207	$208	$208	$209	$164
2	TC			$243	$244	$245	$246	$247	$247	$248	$249	$195
3	TC			$276	$277	$278	$279	$280	$281	$282	$283	$222
4	TC			$271	$273	$274	$275	$276	$276	$277	$278	$218
5	TC			$327	$329	$330	$331	$332	$333	$334	$335	$263
6	TC			$308	$309	$311	$312	$313	$314	$314	$315	$247
7	TC			$271	$272	$274	$275	$275	$276	$277	$278	$218
13	TC			$292	$294	$295	$296	$297	$298	$299	$299	$235

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

Table 5.160 Costs for 20 Percent Mass Reduction for Non-towing (Car curve) Vehicle Types (2013$)

Vehicle Type	Cost type	DMC: CurbWt IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	DMC	2629	30	$105	$101	$99	$96	$94	$92	$90	$88	$87
2	DMC	3131	30	$125	$121	$117	$114	$112	$109	$107	$105	$104
3	DMC	3557	30	$142	$137	$133	$130	$127	$124	$122	$120	$118
4	DMC	3495	30	$139	$135	$131	$128	$125	$122	$120	$118	$116
5	DMC	4215	30	$168	$163	$158	$154	$150	$147	$144	$142	$139
6	DMC	3967	30	$158	$153	$149	$145	$142	$139	$136	$133	$131
7	DMC	3494	30	$139	$135	$131	$128	$125	$122	$120	$118	$116
13	DMC	3767	30	$150	$145	$141	$138	$134	$132	$129	$127	$125
1	IC	Med2	2024	$418	$418	$418	$418	$418	$418	$418	$418	$337
2	IC	Med2	2024	$497	$497	$497	$497	$497	$497	$497	$497	$401
3	IC	Med2	2024	$565	$565	$565	$565	$565	$565	$565	$565	$456
4	IC	Med2	2024	$555	$555	$555	$555	$555	$555	$555	$555	$448
5	IC	Med2	2024	$670	$670	$670	$670	$670	$670	$670	$670	$540
6	IC	Med2	2024	$630	$630	$630	$630	$630	$630	$630	$630	$508
7	IC	Med2	2024	$555	$555	$555	$555	$555	$555	$555	$555	$448
13	IC	Med2	2024	$598	$598	$598	$598	$598	$598	$598	$598	$483
1	TC			$522	$519	$516	$514	$511	$509	$508	$506	$424
2	TC			$622	$618	$615	$612	$609	$607	$604	$603	$505
3	TC			$707	$702	$698	$695	$692	$689	$687	$685	$573
4	TC			$694	$690	$686	$683	$680	$677	$675	$673	$563
5	TC			$838	$832	$827	$823	$820	$817	$814	$811	$679
6	TC			$788	$783	$779	$775	$772	$769	$766	$764	$639
7	TC			$694	$690	$686	$683	$680	$677	$675	$673	$563
13	TC			$748	$744	$740	$736	$733	$730	$727	$725	$607

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

Table 5.161 Costs for 5 Percent Mass Reduction for Towing (Truck curve) Vehicle Types (2013$)

Vehicle Type	Cost type	DMC: CurbWt IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
8	DMC	4306	30	-$225	-$218	-$211	-$206	-$201	-$197	-$193	-$190	-$187
9	DMC	4272	30	-$223	-$216	-$210	-$204	-$200	-$196	-$192	-$188	-$185
10	DMC	4918	30	-$257	-$249	-$242	-$235	-$230	-$225	-$221	-$217	-$213
11	DMC	5158	30	-$269	-$261	-$253	-$247	-$241	-$236	-$231	-$227	-$224
12	DMC	5518	30	-$288	-$279	-$271	-$264	-$258	-$253	-$248	-$243	-$239
14	DMC	4575	30	-$239	-$231	-$225	-$219	-$214	-$209	-$205	-$202	-$198
15	DMC	4848	30	-$253	-$245	-$238	-$232	-$227	-$222	-$218	-$214	-$210
16	DMC	5507	30	-$288	-$278	-$270	-$264	-$257	-$252	-$247	-$243	-$239
17	DMC	6071	30	-$317	-$307	-$298	-$291	-$284	-$278	-$272	-$268	-$263
18	DMC	5975	30	-$312	-$302	-$293	-$286	-$279	-$273	-$268	-$263	-$259
19	DMC	5145	30	-$269	-$260	-$253	-$246	-$241	-$235	-$231	-$227	-$223
8	IC	Low2	2024	$65	$65	$65	$65	$65	$65	$65	$65	$52
9	IC	Low2	2024	$64	$64	$64	$64	$64	$64	$64	$64	$52
10	IC	Low2	2024	$74	$74	$74	$74	$74	$74	$74	$74	$60
11	IC	Low2	2024	$77	$77	$77	$77	$77	$77	$77	$77	$63
12	IC	Low2	2024	$83	$83	$83	$83	$83	$83	$83	$83	$67
14	IC	Low2	2024	$69	$69	$69	$69	$69	$69	$69	$69	$56
15	IC	Low2	2024	$73	$73	$73	$73	$73	$73	$73	$73	$59
16	IC	Low2	2024	$83	$83	$83	$83	$83	$83	$83	$83	$67
17	IC	Low2	2024	$91	$91	$91	$91	$91	$91	$91	$91	$74
18	IC	Low2	2024	$90	$90	$90	$90	$90	$90	$90	$90	$73
19	IC	Low2	2024	$77	$77	$77	$77	$77	$77	$77	$77	$63
8	TC			-$160	-$153	-$147	-$141	-$137	-$132	-$129	-$125	-$134
9	TC			-$159	-$152	-$146	-$140	-$136	-$131	-$128	-$124	-$133
10	TC			-$183	-$175	-$168	-$162	-$156	-$151	-$147	-$143	-$153
11	TC			-$192	-$183	-$176	-$169	-$164	-$159	-$154	-$150	-$161
12	TC			-$205	-$196	-$188	-$181	-$175	-$170	-$165	-$160	-$172
14	TC			-$170	-$163	-$156	-$150	-$145	-$141	-$137	-$133	-$143
15	TC			-$180	-$172	-$165	-$159	-$154	-$149	-$145	-$141	-$151
16	TC			-$205	-$196	-$188	-$181	-$175	-$169	-$165	-$160	-$172
17	TC			-$226	-$216	-$207	-$199	-$193	-$187	-$181	-$176	-$189
18	TC			-$222	-$212	-$204	-$196	-$190	-$184	-$178	-$174	-$186
19	TC			-$192	-$183	-$175	-$169	-$163	-$158	-$154	-$150	-$160

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

Table 5.162 Costs for 10 Percent Mass Reduction for Towing (Truck curve) Vehicle Types (2013$)

Vehicle Type	Cost type	DMC: CurbWt IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
8	DMC	4306	30	$66	$64	$62	$60	$59	$58	$56	$55	$54
9	DMC	4272	30	$65	$63	$61	$60	$58	$57	$56	$55	$54
10	DMC	4918	30	$75	$73	$70	$69	$67	$66	$64	$63	$62
11	DMC	5158	30	$79	$76	$74	$72	$70	$69	$68	$66	$65
12	DMC	5518	30	$84	$81	$79	$77	$75	$74	$72	$71	$70
14	DMC	4575	30	$70	$67	$66	$64	$62	$61	$60	$59	$58
15	DMC	4848	30	$74	$72	$69	$68	$66	$65	$64	$62	$61
16	DMC	5507	30	$84	$81	$79	$77	$75	$74	$72	$71	$70
17	DMC	6071	30	$93	$90	$87	$85	$83	$81	$80	$78	$77
18	DMC	5975	30	$91	$88	$86	$83	$82	$80	$78	$77	$76
19	DMC	5145	30	$78	$76	$74	$72	$70	$69	$67	$66	$65
8	IC	Low2	2024	$258	$258	$258	$258	$258	$258	$258	$258	$210
9	IC	Low2	2024	$256	$256	$256	$256	$256	$256	$256	$256	$208
10	IC	Low2	2024	$295	$295	$295	$295	$295	$295	$295	$295	$239
11	IC	Low2	2024	$310	$310	$310	$310	$310	$310	$310	$310	$251
12	IC	Low2	2024	$331	$331	$331	$331	$331	$331	$331	$331	$269
14	IC	Low2	2024	$275	$275	$275	$275	$275	$275	$275	$275	$223
15	IC	Low2	2024	$291	$291	$291	$291	$291	$291	$291	$291	$236
16	IC	Low2	2024	$331	$331	$331	$331	$331	$331	$331	$331	$268
17	IC	Low2	2024	$364	$364	$364	$364	$364	$364	$364	$364	$296
18	IC	Low2	2024	$359	$359	$359	$359	$359	$359	$359	$359	$291
19	IC	Low2	2024	$309	$309	$309	$309	$309	$309	$309	$309	$250
8	TC			$324	$322	$320	$319	$317	$316	$315	$314	$264
9	TC			$322	$319	$318	$316	$315	$313	$312	$311	$262
10	TC			$370	$368	$366	$364	$362	$361	$360	$358	$302
11	TC			$388	$386	$383	$382	$380	$378	$377	$376	$316
12	TC			$415	$413	$410	$408	$406	$405	$403	$402	$338
14	TC			$344	$342	$340	$338	$337	$336	$334	$333	$281
15	TC			$365	$363	$360	$359	$357	$356	$355	$353	$297
16	TC			$414	$412	$409	$407	$406	$404	$403	$401	$338
17	TC			$457	$454	$451	$449	$447	$445	$444	$442	$372
18	TC			$450	$447	$444	$442	$440	$438	$437	$435	$366
19	TC			$387	$385	$383	$381	$379	$377	$376	$375	$316

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

Table 5.163 Costs for 15 Percent Mass Reduction for Towing (Truck curve) Vehicle Types (2013$)

Vehicle Type	Cost type	DMC: CurbWt IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
8	DMC	4306	30	$551	$533	$518	$505	$493	$483	$473	$465	$457
9	DMC	4272	30	$546	$529	$514	$501	$489	$479	$469	$461	$453
10	DMC	4918	30	$629	$609	$591	$576	$563	$551	$541	$531	$522
11	DMC	5158	30	$660	$638	$620	$604	$591	$578	$567	$557	$547
12	DMC	5518	30	$706	$683	$664	$647	$632	$618	$606	$596	$586
14	DMC	4575	30	$585	$566	$550	$536	$524	$513	$503	$494	$485
15	DMC	4848	30	$620	$600	$583	$568	$555	$543	$533	$523	$514
16	DMC	5507	30	$704	$682	$662	$645	$630	$617	$605	$594	$584
17	DMC	6071	30	$777	$752	$730	$712	$695	$680	$667	$655	$644
18	DMC	5975	30	$764	$740	$719	$700	$684	$670	$657	$645	$634
19	DMC	5145	30	$658	$637	$619	$603	$589	$577	$565	$555	$546
8	IC	Med2	2024	$582	$582	$582	$582	$582	$582	$582	$582	$472
9	IC	Med2	2024	$577	$577	$577	$577	$577	$577	$577	$577	$468
10	IC	Med2	2024	$664	$664	$664	$664	$664	$664	$664	$664	$539
11	IC	Med2	2024	$696	$696	$696	$696	$696	$696	$696	$696	$565
12	IC	Med2	2024	$745	$745	$745	$745	$745	$745	$745	$745	$604
14	IC	Med2	2024	$618	$618	$618	$618	$618	$618	$618	$618	$501
15	IC	Med2	2024	$655	$655	$655	$655	$655	$655	$655	$655	$531
16	IC	Med2	2024	$744	$744	$744	$744	$744	$744	$744	$744	$603
17	IC	Med2	2024	$820	$820	$820	$820	$820	$820	$820	$820	$665
18	IC	Med2	2024	$807	$807	$807	$807	$807	$807	$807	$807	$655
19	IC	Med2	2024	$695	$695	$695	$695	$695	$695	$695	$695	$564
8	TC			$1,132	$1,115	$1,099	$1,086	$1,075	$1,064	$1,055	$1,046	$929
9	TC			$1,123	$1,106	$1,091	$1,078	$1,066	$1,056	$1,046	$1,038	$921
10	TC			$1,293	$1,273	$1,256	$1,241	$1,227	$1,215	$1,205	$1,195	$1,061
11	TC			$1,356	$1,335	$1,317	$1,301	$1,287	$1,275	$1,263	$1,253	$1,112
12	TC			$1,451	$1,428	$1,409	$1,392	$1,377	$1,364	$1,352	$1,341	$1,190
14	TC			$1,203	$1,184	$1,168	$1,154	$1,142	$1,130	$1,121	$1,111	$987
15	TC			$1,275	$1,255	$1,238	$1,223	$1,210	$1,198	$1,188	$1,178	$1,046
16	TC			$1,448	$1,425	$1,406	$1,389	$1,374	$1,361	$1,349	$1,338	$1,188
17	TC			$1,596	$1,571	$1,550	$1,531	$1,515	$1,500	$1,487	$1,475	$1,309
18	TC			$1,571	$1,546	$1,525	$1,507	$1,491	$1,476	$1,463	$1,452	$1,289
19	TC			$1,353	$1,332	$1,313	$1,298	$1,284	$1,271	$1,260	$1,250	$1,110

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

Table 5.164 Costs for 20 Percent Mass Reduction for Towing (Truck curve) Vehicle Types (2013$)

Vehicle Type	Cost type	DMC: CurbWt IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
8	DMC	4306	30	$1,162	$1,125	$1,093	$1,065	$1,040	$1,018	$999	$981	$964
9	DMC	4272	30	$1,153	$1,116	$1,084	$1,057	$1,032	$1,010	$991	$973	$957
10	DMC	4918	30	$1,327	$1,285	$1,248	$1,216	$1,188	$1,163	$1,141	$1,120	$1,101
11	DMC	5158	30	$1,392	$1,347	$1,309	$1,276	$1,246	$1,220	$1,196	$1,175	$1,155
12	DMC	5518	30	$1,489	$1,441	$1,400	$1,365	$1,333	$1,305	$1,280	$1,257	$1,236
14	DMC	4575	30	$1,235	$1,195	$1,161	$1,131	$1,105	$1,082	$1,061	$1,042	$1,024
15	DMC	4848	30	$1,309	$1,266	$1,230	$1,199	$1,171	$1,147	$1,124	$1,104	$1,086
16	DMC	5507	30	$1,486	$1,438	$1,397	$1,362	$1,330	$1,302	$1,277	$1,254	$1,233
17	DMC	6071	30	$1,639	$1,586	$1,541	$1,502	$1,467	$1,436	$1,408	$1,383	$1,360
18	DMC	5975	30	$1,613	$1,561	$1,516	$1,478	$1,444	$1,413	$1,386	$1,361	$1,338
19	DMC	5145	30	$1,389	$1,344	$1,306	$1,272	$1,243	$1,217	$1,193	$1,172	$1,152
8	IC	Med2	2024	$1,034	$1,034	$1,034	$1,034	$1,034	$1,034	$1,034	$1,034	$839
9	IC	Med2	2024	$1,026	$1,026	$1,026	$1,026	$1,026	$1,026	$1,026	$1,026	$832
10	IC	Med2	2024	$1,181	$1,181	$1,181	$1,181	$1,181	$1,181	$1,181	$1,181	$958
11	IC	Med2	2024	$1,238	$1,238	$1,238	$1,238	$1,238	$1,238	$1,238	$1,238	$1,004
12	IC	Med2	2024	$1,325	$1,325	$1,325	$1,325	$1,325	$1,325	$1,325	$1,325	$1,075
14	IC	Med2	2024	$1,098	$1,098	$1,098	$1,098	$1,098	$1,098	$1,098	$1,098	$891
15	IC	Med2	2024	$1,164	$1,164	$1,164	$1,164	$1,164	$1,164	$1,164	$1,164	$944
16	IC	Med2	2024	$1,322	$1,322	$1,322	$1,322	$1,322	$1,322	$1,322	$1,322	$1,072
17	IC	Med2	2024	$1,458	$1,458	$1,458	$1,458	$1,458	$1,458	$1,458	$1,458	$1,182
18	IC	Med2	2024	$1,434	$1,434	$1,434	$1,434	$1,434	$1,434	$1,434	$1,434	$1,164
19	IC	Med2	2024	$1,235	$1,235	$1,235	$1,235	$1,235	$1,235	$1,235	$1,235	$1,002
8	TC			$2,196	$2,159	$2,127	$2,099	$2,074	$2,052	$2,032	$2,015	$1,803
9	TC			$2,179	$2,141	$2,110	$2,082	$2,058	$2,036	$2,016	$1,998	$1,789
10	TC			$2,508	$2,465	$2,429	$2,397	$2,369	$2,344	$2,321	$2,301	$2,059
11	TC			$2,630	$2,585	$2,547	$2,514	$2,484	$2,458	$2,434	$2,413	$2,159
12	TC			$2,814	$2,766	$2,725	$2,689	$2,658	$2,630	$2,604	$2,581	$2,310
14	TC			$2,333	$2,293	$2,259	$2,230	$2,203	$2,180	$2,159	$2,140	$1,915
15	TC			$2,473	$2,430	$2,394	$2,363	$2,335	$2,311	$2,288	$2,268	$2,030
16	TC			$2,808	$2,760	$2,720	$2,684	$2,652	$2,624	$2,599	$2,576	$2,306
17	TC			$3,096	$3,043	$2,998	$2,959	$2,924	$2,894	$2,866	$2,840	$2,542
18	TC			$3,047	$2,995	$2,951	$2,912	$2,878	$2,847	$2,820	$2,795	$2,501
19	TC			$2,624	$2,579	$2,541	$2,507	$2,478	$2,452	$2,428	$2,407	$2,154

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

5.3.4.7 Other Vehicle Technologies

5.3.4.7.1 Electrified Power Steering: Data and Assumptions for this Assessment

For the 2017-2025 final rule, EPA and NHTSA estimated a 1 to 2 percent effectiveness for electrified power steering in light duty vehicles, based on the 2015 NAS report, Sierra Research Report and confidential OEM data. The 2010 Ricardo study also confirmed this estimate. NHTSA and EPA reviewed these effectiveness estimates and found them to be accurate, thus they have been retained for this Draft TAR.

Costs associated with electric power steering are equivalent to those used in the 2012 FRM except for updates to 2013 dollars and use of new learning curves (curve 24). The electric power steering costs incremental to hydraulic power steering are shown below.

Table 5.165 Costs for Electric Power Steering (dollar values in 2013$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$96	24	$92	$90	$88	$87	$85	$84	$83	$82	$81
IC	Low2	2018	$23	$23	$18	$18	$18	$18	$18	$18	$18
TC			$115	$113	$106	$105	$104	$102	$101	$100	$99

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.3.4.7.2 *Improved Accessories: Data and Assumptions for this Assessment*

In MYs 2017-2025 final rule, the agencies used an effectiveness value in the range of 1 to 2 percent.

For this Draft TAR GHG assessment, EPA considered two levels of improved accessories. Level 1 of this technology (IACC1) incorporates a high efficiency alternator (70 percent efficiency). The second level of improved accessories (IACC2) adds the higher efficiency alternator and incorporates a mild regenerative alternator strategy, as well as intelligent cooling. NHTSA and EPA jointly reviewed the estimates of 1 to 2 percent effectiveness estimates used in the 2017-2025 final rule for level IACC1. EPA used effectiveness values in the 1.2 to 1.8 percent range, varying with vehicle subclass.

Costs associated with improved accessories are equivalent to those used in the 2012 FRM except for updates to 2013 dollars and use of new learning curves (curve 24). The improved accessory costs (levels 1 and 2) are shown below. Cost is higher for improved accessories level 2 due to the inclusion of a higher efficiency alternator and a mild level of regeneration, hence the $40 to $50 higher cost. Both improved accessory costs are incremental to the baseline.

Table 5.166 Costs for Improved Accessories Level 1 (dollar values in 2013$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$78	24	$74	$73	$72	$70	$69	$68	$67	$66	$66
IC	Low2	2018	$19	$19	$15	$15	$15	$15	$15	$15	$15
TC			$93	$92	$87	$85	$84	$83	$82	$81	$81

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 5.167 Costs for Improved Accessories Level 2 (dollar values in 2013$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$126	24	$120	$118	$116	$114	$112	$111	$109	$108	$106
IC	Low2	2018	$30	$30	$24	$24	$24	$24	$24	$24	$24
TC			$151	$148	$140	$138	$136	$135	$133	$132	$130

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.3.4.7.3 *Secondary Axle Disconnect: Data and Assumptions for this Assessment*

The 2017-2025 final rule estimated an effectiveness improvement of 1.0 to 1.5 percent for axle disconnect. Based on the 2011 Ricardo report, NHTSA and EPA refined this range to 1.2 to 1.4 percent. EPA retains these figures for this Draft TAR GHG assessment.

The cost associated with secondary axle disconnect is equivalent to that used in the 2012 FRM except for updates to 2013 dollars and use of new learning curves (curve 24). The costs are shown below.

Table 5.168 Costs for Secondary Axle Disconnect (dollar values in 2013$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$85	24	$82	$80	$79	$77	$76	$75	$74	$73	$72
IC	Low2	2018	$21	$21	$16	$16	$16	$16	$16	$16	$16
TC			$102	$101	$95	$94	$93	$91	$90	$89	$88

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.3.4.7.4 Low Drag Brakes: Data and Assumptions for this Assessment

The 2017-2025 final rule estimated the effectiveness of low drag brakes to be to 0.8 percent. The agencies continue to use this estimate for this Draft TAR based on the 2011 Ricardo study and the 2015 NAS report.

The cost associated with low drag brakes is equivalent to that used in the 2012 FRM except for updates to 2013 dollars. The costs are shown below.

Table 5.169 Costs for Low Drag Brakes (dollar values in 2013$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$62	1	$62	$62	$62	$62	$62	$62	$62	$62	$62
IC	Low2	2018	$15	$15	$12	$12	$12	$12	$12	$12	$12
TC			$77	$77	$74	$74	$74	$74	$74	$74	$74

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.3.4.8 Air Conditioning: Data and Assumptions for this Assessment

Air conditioning (A/C) system technologies include improved hoses, connectors and seals for leakage control. They also include improved compressors, expansion valves, heat exchangers and the control of these components for the purposes of improving tailpipe CO_2 emissions and fuel economy as a result of A/C use.

For this Draft TAR analysis, EPA is continuing to use the GHG and fuel economy effectiveness estimates that were used in the 2012 FRM analysis, with costs adjusted to 2013 dollars (presented below). For more information on these estimates, see Section 5.1 of the 2012 TSD.

Table 5.170 Costs for A/C Controls (dollar values in 2013$)

Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
TC	$91	$117	$134	$141	$154	$152	$146	$143	$140

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.3.4.9 Cost Tables for Individual Technologies Not Presented Above

Costs associated with SCR-equipped diesel vehicles are equivalent to those used in the FRM except for updates to 2013 dollars and use of new learning curve (curve 23). The costs incremental to the baseline engine configuration for our different vehicle classes are shown below. These costs are used to characterize technology costs in the baseline fleet; EPA does not build OMEGA packages using this technology and instead uses the advanced diesel technology presented below.

Table 5.171 Costs for SCR-equipped Diesel Technology for Different Vehicle Classes (dollar values in 2013$)

Tech	Cost type	DMC: base cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
Small car	DMC	$2,456	23	$2,223	$2,188	$2,156	$2,126	$2,098	$2,072	$2,047	$2,024	$2,002
Standard car	DMC	$2,456	23	$2,223	$2,188	$2,156	$2,126	$2,098	$2,072	$2,047	$2,024	$2,002
Large car	DMC	$3,019	23	$2,734	$2,691	$2,651	$2,614	$2,580	$2,548	$2,517	$2,489	$2,462
Small MPV	DMC	$2,483	23	$2,248	$2,213	$2,180	$2,150	$2,121	$2,095	$2,070	$2,047	$2,024
Large MPV	DMC	$2,483	23	$2,248	$2,213	$2,180	$2,150	$2,121	$2,095	$2,070	$2,047	$2,024
Truck	DMC	$3,462	23	$3,135	$3,086	$3,040	$2,998	$2,958	$2,921	$2,887	$2,854	$2,823
Small car	IC	Med2	2018	$941	$939	$702	$701	$700	$699	$699	$698	$697
Standard car	IC	Med2	2018	$941	$939	$702	$701	$700	$699	$699	$698	$697
Large car	IC	Med2	2018	$1,156	$1,155	$863	$862	$861	$860	$859	$858	$857
Small MPV	IC	Med2	2018	$951	$949	$710	$709	$708	$707	$706	$706	$705
Large MPV	IC	Med2	2018	$951	$949	$710	$709	$708	$707	$706	$706	$705
Truck	IC	Med2	2018	$1,326	$1,324	$990	$989	$987	$986	$985	$984	$983
Small car	TC			$3,164	$3,127	$2,858	$2,827	$2,799	$2,772	$2,746	$2,722	$2,700
Standard car	TC			$3,164	$3,127	$2,858	$2,827	$2,799	$2,772	$2,746	$2,722	$2,700
Large car	TC			$3,890	$3,846	$3,515	$3,477	$3,441	$3,408	$3,377	$3,347	$3,319
Small MPV	TC			$3,199	$3,162	$2,890	$2,858	$2,829	$2,802	$2,776	$2,752	$2,729
Large MPV	TC			$3,199	$3,162	$2,890	$2,858	$2,829	$2,802	$2,776	$2,752	$2,729
Truck	TC			$4,461	$4,410	$4,030	$3,986	$3,946	$3,908	$3,872	$3,838	$3,806

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Costs associated with advanced diesel vehicles (i.e., Tier 3 compliant) are equivalent to those used in the FRM except for updates to 2013 dollars and use of new learning curve (curve 23). The costs incremental to the baseline engine configuration for our different vehicle classes are shown below. These costs are used when building OMEGA diesel packages.

Table 5.172 Costs for Advanced Diesel Technology for Different Vehicle Classes (dollar values in 2013$)

Tech	Cost type	DMC: base cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
Small car	DMC	$2,506	23	$2,269	$2,233	$2,200	$2,170	$2,141	$2,114	$2,089	$2,065	$2,043
Standard car	DMC	$2,506	23	$2,269	$2,233	$2,200	$2,170	$2,141	$2,114	$2,089	$2,065	$2,043
Large car	DMC	$3,069	23	$2,779	$2,735	$2,695	$2,658	$2,623	$2,590	$2,559	$2,530	$2,503
Small MPV	DMC	$2,533	23	$2,293	$2,257	$2,224	$2,193	$2,164	$2,137	$2,112	$2,088	$2,065
Large MPV	DMC	$2,533	23	$2,293	$2,257	$2,224	$2,193	$2,164	$2,137	$2,112	$2,088	$2,065
Truck	DMC	$3,512	23	$3,180	$3,130	$3,084	$3,041	$3,001	$2,964	$2,928	$2,895	$2,864
Small car	IC	Med2	2018	$960	$958	$716	$715	$715	$714	$713	$712	$711
Standard car	IC	Med2	2018	$960	$958	$716	$715	$715	$714	$713	$712	$711
Large car	IC	Med2	2018	$1,176	$1,174	$878	$876	$875	$874	$873	$872	$872
Small MPV	IC	Med2	2018	$970	$968	$724	$723	$722	$721	$721	$720	$719
Large MPV	IC	Med2	2018	$970	$968	$724	$723	$722	$721	$721	$720	$719
Truck	IC	Med2	2018	$1,345	$1,343	$1,004	$1,003	$1,002	$1,000	$999	$998	$997
Small car	TC			$3,228	$3,191	$2,916	$2,885	$2,856	$2,828	$2,802	$2,778	$2,755
Standard car	TC			$3,228	$3,191	$2,916	$2,885	$2,856	$2,828	$2,802	$2,778	$2,755
Large car	TC			$3,955	$3,909	$3,573	$3,534	$3,498	$3,464	$3,433	$3,403	$3,374
Small MPV	TC			$3,263	$3,226	$2,948	$2,916	$2,886	$2,858	$2,832	$2,808	$2,784
Large MPV	TC			$3,263	$3,226	$2,948	$2,916	$2,886	$2,858	$2,832	$2,808	$2,784
Truck	TC			$4,525	$4,473	$4,088	$4,044	$4,003	$3,964	$3,928	$3,894	$3,861

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Costs associated with powersplit HEVs are equivalent to those used in the FRM except for updates to 2013 dollars and use of new learning curve (curve 24). The costs incremental to the baseline configuration for our different vehicle classes are shown below. These costs are used to characterize technology costs in the baseline fleet; EPA does not build OMEGA packages using this technology and instead uses the strong HEV technology presented earlier.

Table 5.173 Costs for Powersplit HEV Technology for Different Vehicle Classes (dollar values in 2013$)

Tech	Cost type	DMC: base cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
Small car	DMC	$3,128	24	$2,992	$2,934	$2,881	$2,832	$2,788	$2,747	$2,709	$2,673	$2,640
Standard car	DMC	$3,482	24	$3,330	$3,265	$3,206	$3,152	$3,103	$3,057	$3,015	$2,975	$2,938
Large car	DMC	$3,767	24	$3,602	$3,532	$3,469	$3,410	$3,357	$3,307	$3,261	$3,219	$3,178
Small MPV	DMC	$4,570	24	$4,370	$4,286	$4,209	$4,138	$4,073	$4,013	$3,957	$3,905	$3,856
Large MPV	DMC	$5,620	24	$5,374	$5,270	$5,175	$5,088	$5,008	$4,935	$4,866	$4,802	$4,742
Truck	DMC	$5,620	24	$5,374	$5,270	$5,175	$5,088	$5,008	$4,935	$4,866	$4,802	$4,742
Small car	IC	High1	2018	$1,754	$1,751	$1,073	$1,071	$1,070	$1,068	$1,067	$1,066	$1,065
Standard car	IC	High1	2018	$1,952	$1,948	$1,194	$1,192	$1,191	$1,189	$1,188	$1,186	$1,185
Large car	IC	High1	2018	$2,112	$2,108	$1,291	$1,290	$1,288	$1,286	$1,285	$1,284	$1,282
Small MPV	IC	High1	2018	$2,563	$2,557	$1,567	$1,565	$1,563	$1,561	$1,559	$1,557	$1,556
Large MPV	IC	High1	2018	$3,151	$3,145	$1,927	$1,924	$1,922	$1,919	$1,917	$1,915	$1,913
Truck	IC	High1	2018	$3,151	$3,145	$1,927	$1,924	$1,922	$1,919	$1,917	$1,915	$1,913
Small car	TC			$4,746	$4,684	$3,953	$3,904	$3,858	$3,815	$3,776	$3,739	$3,705
Standard car	TC			$5,282	$5,213	$4,400	$4,344	$4,293	$4,246	$4,202	$4,161	$4,123
Large car	TC			$5,714	$5,640	$4,760	$4,700	$4,645	$4,594	$4,546	$4,502	$4,461
Small MPV	TC			$6,933	$6,843	$5,776	$5,703	$5,636	$5,574	$5,516	$5,462	$5,412
Large MPV	TC			$8,525	$8,414	$7,102	$7,012	$6,930	$6,854	$6,783	$6,717	$6,655
Truck	TC			$8,525	$8,414	$7,102	$7,012	$6,930	$6,854	$6,783	$6,717	$6,655

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

5.4 CAFE Technology Assessment

This section describes the cost and technical analysis conducted by NHTSA for this report. Section 5.4.1 describes the development of direct and indirect costs and the application of learning curves in the NHTSA analysis. Section 5.4.2 details GT Power and Autonomie simulation modeling to develop technology effectiveness values for use in the CAFE model.

5.4.1 <u>Technology Costs Used in CAFE Assessment</u>

5.4.1.1 Direct Costs

The majority of technology costs used by NHTSA in this analysis are the same as those used in the 2012 FRM. These costs, however, have been updated to 2013 dollars since all costs in this analysis are in 2013 dollars. Based on new information, stakeholder feedback, and the 2015 NAS report, NHTSA updated DMC for the technologies discussed below. [589]

5.4.1.1.1 Improved Low Friction Lubricants and Engine Friction Reduction Levels 2 & 3 (LUBEFR2 & LUBFFR3)

For this analysis, NHTSA assumed that incremental improvements in low friction lubricants and engine friction reductions could be realized. Based on the Massachusetts Institute of

Technology Sloan Automotive Laboratory's "On the Road toward 2050" report, a 3 percent combined improvement was assumed to be achievable by 2030.[590] This translates into a 0.275 percent improvement compounded annually for the MY2015-2030 timeframe. The DMC basis for this technology is the 2012 FRM EFR2_LUB2 technology cost ($12.65/cylinder). The yearly per cylinder DMC then becomes $0.84 ($12.65/15 years). Converting this from 2010$ to 2013$ yields a DMC of $0.8875/cylinder. The yearly cost and effectiveness values are accumulated and then applied in two discrete MYs. LUBEFR2 with an effectiveness improvement of 0.823 percent is applied in MY2018 for a DMC of $2.66/cylinder ($0.8875 x 3 years). LUBEFR3 with an effectiveness improvement of 2.18 percent is applied in MY2023, incremental to LUBEFR2, for a DMC of $4.44/cylinder ($0.8875 x 5 years).

5.4.1.1.2 Automatic Transmission Improvements Levels 1 & 2 (ATI1 & ATI2)

A 1.5 percent improvement by MY2025, or 0.151 percent compounded annually for the MY2015-2025 timeframe, was assumed based on comments received in stakeholder meetings. The cost basis is the 2012 FRM HEG technology cost of $202 for 2.64 percent improvement (average improvement across all the vehicle classes) or $76.52/ percent ($202/2.64 percent). This equates to a DMC of $114.77 ($76.52/percent x 1.5 percent) for a 1.5 percent improvement. This yields a yearly DMC of $11.48 ($114.77/10 years). Converting this from 2010$ to 2013$ yields a yearly DMC of $12.13. The yearly cost and effectiveness values are accumulated and then applied in two discrete MYs. ATI1 with an effectiveness improvement of 0.45 percent is applied in MY2018 for a DMC of $36.39 ($12.13 x 3 years). ATI2 with an effectiveness improvement of 1.20 percent is applied in MY2023, incremental to ATI2, for a DMC of $60.65 ($12.13 x 5 years).

5.4.1.1.3 High Compression Ratio Engine

This is analogous to Mazda's SkyActiv engine technology. The costs for the HCR technology are from the 2015 NAS report. The NAS report's DMC include the DMC for direct injection so these DMC are subtracted to get the DMC for HCR with direct injection. The DMC costs for MY2017 in 2010$ are $86 for an I4 engine, $129 for a V6 engine and $204 for a V8 engine. In 2013$ the DMC become $90.84, $136.27 and $215.50, respectively.

5.4.1.1.4 Advanced Diesel Engine (ADSL) Engine

The DMC for the ADSL technology are also from the 2015 NAS report. The DMC for MY2017 in 2010$ is $3,023 for an I4 engine, $3,565 for a V6 engine and $3,795 for a V8 engine. In 2013$ the DMC become $3,193.47, $3,766.03 and $4,009.00 respectively.

5.4.1.1.5 7-speed Manual Transmission

Due to limited availability of cost information on 7-speed manual transmissions, NHTSA is using the DCT8 technology DMC, which is sourced from the 2012 FRM.

5.4.1.1.6 6-speed Automatic Transmission

The DMC for the AT6 technology is from the 2015 NAS report. The DMC for MY2017 in 2010$ is -$13.00. In 2013$ the DMC becomes -$13.73. The AT6 technology cost is relative to the 4-speed automatic. In contrast to this estimate, the TSD for the earlier 2012-2016 MY CAFE standards (EPA/NHTSA 2010) developed a cost of $101 for a six-speed automatic transmission relative to a four-speed automatic transmission. The FEV teardown cost analysis determined that the six-speed transmission was $106 less costly than the five-speed transmission.[591] The 2012 TSD indicated that this counterintuitive result was attributed to the six-speed transmission having a Lepelletier-type gear set instead of a conventional planetary gear set, which requires an additional one way clutch. Subsequent to the 2012-2016 MY TSD, the EPA/NHTSA 2017-2025 MY Technical Support Document estimated a direct manufacturing cost of −$13 (savings) for a six-speed automatic transmission relative to a four-speed automatic transmission, which appears to have resulted from using only the case with the Lepelletier gear set.[592]

5.4.1.1.7 8-speed Automatic Transmission

The DMC for the AT8 technology is from the updated FEV teardown study.[593] The DMC for MY2012 in 2007$ is $74.81. In 2013$ the DMC becomes $82.18. This cost increase is relative to the AT6 technology as indicated by the FEV teardown. The net incremental direct manufacturing cost shown is solely based on the physical hardware evaluated. Many of the subsystems were deemed cost neutral between the 6AT and 8AT. Much of the cost analysis work was focused on the cost difference in the gear train and internal clutch subsystems.

5.4.1.1.8 6-speed Dual Clutch Transmission

Due to concerns regarding the challenges associated with the noise, vibration and harshness (NVH), integration, and drivability issues of dual clutch transmissions, NHTSA believes that the DMC for the DCT6 is higher than the negative DMC used in the 2012 FRM. To better account for these issues, NHTSA chose to update the DCT6 technology DMC using the upper cost for the 6-speed Dry DCT found in the 2015 NAS report. The DMC in this analysis for MY2017 in 2010$ is $31.00 relative to 6 speed automatic – Lepelletier type. In 2013$ the DMC becomes $32.75. Similarly the DMC using the upper cost for the 6-speed DCT for MY2017 is $88.00 relative to 6 speed automatic – Lepelletier type. In 2013$ the DMC becomes $94.01. Estimated 2025 MY DMC for DCT6 dry and wet clutch costs of $26 and $75 (2010$) relative to AT6-Lepelletier type and using the upper cost. These costs adjusted for 2013$ are $27.78 and $80.13

The committee found that the currently high costs of DCTs stem from the relatively low sales volumes, compounded by the fact that DCTs used by different vehicle manufacturers have different mechatronics for clutch and shift fork actuation. The actuation units can be electromechanical, electrohydraulic, or a mixture of both. The clutch modules vary significantly. Although the main difference is between wet and dry clutch configurations, other differences include the use of torsional dampers, while others rely on a damper in the separate dual mass flywheel. Since the hardware components from one DCT to another can vary significantly, a large variation in costs can be expected.[589]

5.4.1.1.9 8-speed Dual Clutch Transmission

For this analysis NHTSA continued to rely on the FEV teardown study for the DMC of the DCT8 technology. However, since the 2012 FRM, FEV has updated the teardown study for 8-speed transmission technologies. The DMC for the DCT8 technology has been updated from the 2012 FRM and is now $217.65 in MY2012 in 2007$. In 2013$ the DMC becomes $229.92.

The committee found that the currently high costs of DCTs stem from the relatively low sales volumes, compounded by the fact that DCTs used by different vehicle manufacturers have different mechatronics for clutch and shift fork actuation. The actuation units can be electromechanical, electrohydraulic, or a mixture of both. The clutch modules vary significantly.

Although the main difference is between wet and dry clutch configurations, other differences include the use of torsional dampers, while others rely on a damper in the separate dual mass flywheel. Since the hardware components from one DCT to another can vary significantly, a large variation in costs can be expected. This large variation in hardware components is partly responsible for DCTs not achieving significant cost reductions at current production volumes.

5.4.1.1.10 *Continuously Variable Transmission*

The DMC for the CVT technology is sourced from the 2015 NAS report. The DMC for MY2017 in 2010$ is $179.00. In 2013$ the DMC becomes $189.09. NHTSA provided an estimated 2012 MY direct manufacturing cost of $200 (2007 dollars) for the CVT relative to a four-speed automatic transmission. Some manufacturers' estimates significantly exceeded NHTSAs maximum range. This wide range of estimates is believed to reflect wide variations in losses in the CVT.

5.4.1.1.11 *Belt Integrated Starter Generator*

For the last FRM, NHTSA considered high-voltage BISG systems, or systems over 60V (SAE J2232)[594] In recent years, manufacturers have commercialized low-voltage BISG systems (such as 48V) as an alternative to high-voltage BISG systems. With limited need for high voltage protection, the 48V BISG systems may have lower direct manufacturing costs than their high voltage counterparts.

The 2015 light duty fleet has many examples of 48V BISG systems for small sized and medium sized vehicles, but the fleet has few examples of low-voltage BISG on trucks and large sport utility vehicles. The low voltage BISG systems operate in much the same way as the high voltage systems but require higher current to produce a given amount of power. On trucks and large SUVs, engineering performance of a 48V BISG system may or may not perform as well as high voltage BISG systems. NHTSA seeks comment on the functionality and practicability of low-voltage BISG systems for truck and large SUV applications. Based on an EPA teardown study conducted by FEV of a 48V BISG system and 115V BISG system, NHTSA has lowered the projected cost of BISG technology.[595] For Small Car, Medium Car, and Small SUV the BISG DMC is $1013.00 in MY2017.

5.4.1.1.12 *Crank Integrated Starter Generator*

For this analysis, NHTSA is using the Integrated Motor Assist DMC from Table 3-47 found in the 2012 FRM TAR. The DMC for MY2017 in 2010$ is $2008.00 for Small Car, $2541.00 for Medium Car, $2552.00 for Small SUV and Medium SUV, and $3118.00 for Pickup. In 2013$ those costs become $2121.23, $2684.28, $2695.91, and $3293.82, respectively.

5.4.1.1.13 *Electric Power Steering*

For this analysis, NHTSA is using DMC from the 2012 FRM. The DMC for MY2017 in 2010$ is $92.00 per vehicle. In 2013$ the cost becomes $95.86 per vehicle.

5.4.1.1.14 *Improved Accessories (IACC1 & IACC2)*

For this analysis, NHTSA is using DMC from the 2012 FRM. Level 1 technology (IACC1) provides a high-efficiency alternator and level 2 (IACC2) provides a high-efficiency alternator and incorporates mild regeneration. For level 1, the DMC for MY2017 in 2010$ is $75.00 per vehicle, which becomes $77.96 after adjusting for 2013 dollars. For level 2, the DMC for MY2017 in 2010$ adds another $45.00 per vehicle ($120 total), which is an additional $48.12 per vehicle ($126.08 total) in 2013 dollars.

5.4.1.1.15 Low Drag Brakes

For this analysis, NHTSA is using DMC from the 2012 FRM. The DMC for MY2017 in 2010$ is $59.00 per vehicle. In 2013$ the cost becomes $62.03 per vehicle.

5.4.1.1.16 Secondary Axle Disconnect

For this analysis, NHTSA is using DMC from the 2012 FRM. The DMC for MY2017 is $82.00 per vehicle. After adjusting for 2013 dollars, the cost becomes $85.57 per vehicle.

5.4.1.1.17 Low Rolling Resistance Tires

For this analysis, NHTSA is using DMC from the 2012 FRM. Level 1 technology (ROLL10) provides a ten percent reduction in rolling resistance and level 2 (ROLL20) provides a twenty percent reduction. For level 1, the DMC for MY2017 in 2010$ is $5.40 per vehicle, which becomes $5.64 after adjusting for 2013 dollars. For level 2, the DMC for MY2017 in 2010$ is $40.00 per vehicle, and becomes $42.77 per vehicle in 2013 dollars.

5.4.1.1.18 Aerodynamic Drag Reduction

For this analysis, NHTSA is using DMC from the 2012 FRM. Level 1 technology (AERO10) provides a ten percent reduction in aerodynamic drag resistance and Level 2 (AERO20) provides a twenty percent reduction. For level 1, the DMC for MY2017 in 2010$ is $41.00 per vehicle, which becomes $42.86 after adjusting for 2013 dollars. For level 2, the DMC for MY2017 in 2010$ is $123.00 per vehicle, and becomes $128.57 in 2013 dollars.

5.4.1.1.19 Mass Reduction

NHTSA awarded a contract to an engineering team consisting of Electricore, Inc. (prime contractor), EDAG, and George Washington University to design a future midsize lightweight vehicle (LWV). This vehicle is assumed to be manufactured using processes available in model year 2017-2025 and be capable of high volume production (200,000 units per year). The team's goal was to determine the maximum feasible weight reduction while maintaining the same vehicle functionalities as the baseline vehicle, such as performance, safety, and crash rating.

Furthermore, the retail price of the LWV must be within +10 percent of the original vehicle. Based upon its production volume, market share, and five-star crash rating, the team selected the model year 2011 Honda Accord as its baseline vehicle. Because a lighter vehicle needs less power, the vehicle powertrain was downsized but limited to the same naturally aspirated engine. Any analysis of an advanced powertrain, such as a hybrid electric vehicle, was outside the scope of this project. The major boundary conditions for this project included the following:

- Maintain or improve vehicle size compared to the baseline vehicle.
- Maintain retail price parity (±10 percent variation) with the baseline vehicle.
- Maintain or improve vehicle functionalities compared to the baseline vehicle, including maintaining comparable performance in NHTSA's New Car Assessment

Program (NCAP) frontal, side, side pole and IIHS test programs through appropriate crash simulations.

- Powertrain may be downsized, however alternate powertrain configurations (i.e. hybrid electric, battery electric, and diesel) will not be considered.
- All advanced design, material, technologies and manufacturing processes must be realistically projected to be available for fleet wide production in time frame of model years 2017-2025 and capable of high volume production (200,000 units per year).
- Achieve the maximum feasible amount of mass reduction within the above listed constraints

Overall, the complete LWV 1.0 achieved a total weight savings of 22 percent (332 kg) from the baseline vehicle (1480 kg) at an incremental cost increase of $319 or $0.96 per kg. To achieve the same vehicle performance as the baseline vehicle, the size of the engine for the LWV was proportionally reduced from 2.4L-177 HP to 1.8L-140HP. Without the mass and cost reduction allowance for the powertrain (engine and transmission) the mass saving for the ‘glider’ was 24 percent (264kg) at a mass saving cost premium of $1.63 per kg mass saving.

NHTSA released the first version of the report after it was peer reviewed.[596] Subsequent to the release of the report, Honda examined the report in detail and offered their observations to NHTSA on the components chosen to light-weight the vehicle. In addition, Honda provided information on limitations to downsizing some of the components due to both within platform sharing and cross-platform sharing. The other main observation from Honda was in the area of crashworthiness, performance and drivability issues and ground clearance.[597]

In 2013, NHTSA awarded a subsequent contract to Electricore with EDAG as subcontractor to perform additional crash simulations on the light-weight Honda Accord vehicle (LWV 1.0) to address Honda’s comments. The light-weight 2011 Honda Accord (LWV 1.0) was modified to address Honda's suggestion in areas of crashworthiness, Noise & Vibration and in drivability performance (LWV 1.1). NHTSA used modified light-weighted 2011 Honda Accord (LWV 1.1) to perform additional design and crash simulation to meet Insurance Institute of Highway Safety (IIHS) evaluation of Small Overlap Test (SOL). The light-weighted version (LWV 1.2) of 2011 Honda Accord incorporates Honda's suggestion and meets IIHS small overlap test requirements. The following paragraph describes the progression of changes in mass reduction and cost changes as a result of Honda's suggestion and also in meeting IIHS small overlap test requirements relative to LWV 1.0.

In addressing Honda’s comments, the weight of the body structure of the LWV 1.1 was increased by 11.5 kg and the cost was reduced by $13.08 from the original LWV 1.0 design. In addition, some of Honda’s recommendations for NVH and durability were accepted. The total weight and cost of the LWV 1.1 increased by 21.75 kg and $18.13, respectively. To address the IIHS SOL test (LWV 1.2) the weight of the vehicle was increased by 6.90 kg and the cost by $26.88. The new LWV 1.2 design was modeled and assessed for the performance of crashworthiness in seven crash safety tests. The new design achieved a “good,” rating in all tests that are comparable to the safety rating of the model year 2013 Accord. Table 5.174 shows the mass reduction and associated costs from light weighted vehicle version 1.0 to light-weighted version 1.2. The baseline is a Honda Accord with a weight of 1,480 kg.

Table 5.174 Mass Reduction and Associated Costs Going From Vehicle Version 1.0 to Vehicle Version 1.2

Model	Mass savings (kg)	Percentage Mass Reduction	Cost Increase	$/kg	Comments
LW 1.0	332	22.43%	$ 319.00	$ 0.96	
LWV 1.1	320.8	21.68%	$ 305.92	$ 0.95	Addressing Honda's comments, 11.5kg was added, Cost was reduced by $13.08
	310.55	20.98%	$ 337.13	$ 1.09	NVH mass add was 10.25kg
LWV 1.2	303.65	20.52%	$ 364.01	$ 1.20	IIHS SOL mass add was 6.6kg, cost increase of $26.88

The list of components that were light-weighted was rearranged in sequence based on cost effectiveness as shown in Table 5.175. Figure 5.141 shows a graphical representation of cost per kilogram at various levels of mass reduction plotted from Table 5.175. As can be seen from the cost curve in Figure 5.141, cost per kilogram increases progressively as some of the vehicle structural components are light-weighted due to adoption of higher strength materials and in some cases switching from steel to aluminum. The powertrain components which include engine, transmission, and fuel systems such as fuel filler pipe, fuel tank, fuel pump, etc., exhaust systems and cooling systems were not considered for application of primary mass reduction but benefits of secondary mass reduction were accounted for. These powertrain components are assumed to be downsized only after the primary vehicle structural components (Body-In-White) achieve certain level of mass reduction. The National Academy of Sciences (NAS) estimated mass reduction costs assuming that powertrain downsizing be considered after the primary vehicle mass is reduced by 10 percent of original mass. NHTSA considered the NAS approach and applied powertrain downsizing (secondary mass savings) after the vehicle structural components (primary mass savings) had achieved 10 percent mass reduction. In the case of the mass reduction study of the 2011 Honda Accord passenger car, the baseline 2.4L engine was replaced by 1.8L engine which was already in production. The 1.8L engine was used in Honda Civic model which is a compact passenger car. As a consequence of using a smaller engine, the fuel system and exhaust system were downsized to match 1.8L engine while maintaining the same driving range and performance. The mass reduction and cost savings from smaller powertrain components along with primary vehicle structural components resulted in a 20 percent overall mass reduction from the baseline 2011 Honda Accord. This design configuration is represented as the AHSS+AL solution point in Figure 5.141. Due to this approach, the cost curve bends after 10 percent to reach the solution point as shown in Figure 5.141. As a consequence, the cost per kilogram at the final solution point is less than the cost per kilogram at 10 percent mass reduction. Note here, at 10 percent mass reduction, no secondary mass savings are considered.

Additional mass reduction solution points shown in Figure 5.141 were analytically developed such as Aluminum (AL) intensive solution and Carbon Fiber Reinforced Plastics (CFRP) intensive solution. Note here that AL and CFRP intensive solutions are analytical solutions only and no computational models were built to verify all the performance metrics to the baseline 2011 Honda Accord. Computational models were built for only the most cost effective light-weight solution to verify for all performance metrics (AHSS+AL Solution).

Table 5.175 Mass Reduction and Costs for Vehicle Components/System

Vehicle Component/System	Cumulative Mass Saving	Cumulative MR%	Cumulative Cost	Cumulative Cost $/kg
Front Bumper	3.59	0.24%	-1.23	-0.34
Front Door Trim	4.93	0.33%	-1.23	-0.25
Front Door Wiring Harness	5.23	0.35%	-1.23	-0.24
Head Lamps	6.94	0.47%	-1.23	-0.18
HVAC	9.54	0.64%	-1.23	-0.13
Insulation	12.74	0.86%	-1.23	-0.10
Interior Trim	15.77	1.07%	-1.23	-0.08
Parking Brake	16.76	1.13%	-1.23	-0.07
Rear Door Trim	17.89	1.21%	-1.23	-0.07
Rear Door Wiring Harness	18	1.22%	-1.23	-0.07
Tail Lamps	18.63	1.26%	-1.23	-0.07
Tires	23.08	1.56%	-1.23	-0.05
Wiring and Harness	27.38	1.85%	-1.23	-0.04
Wheels	28.82	1.95%	-$1.23	-0.04
Rear Bumper	32.33	2.18%	$0.53	0.02
Instrument Panel	41.78	2.82%	$17.27	0.41
Body Structure	96.18	6.50%	$173.13	1.80
Deck lid	101.39	6.85%	$188.97	1.86
Hood	108.86	7.36%	$211.49	1.94
Front Door Frames	124.26	8.40%	$262.88	2.12
Fenders	127.53	8.62%	$274.98	2.16
Seats	147.56	9.97%	$374.02	2.53
Rear Door Frames	159.02	10.74%	$428.47	2.69
Powertrain components (Engine, transmission, Fuel system, Exhaust system, coolant system), Brakes etc.	303.65	20.52%	364.01	1.20

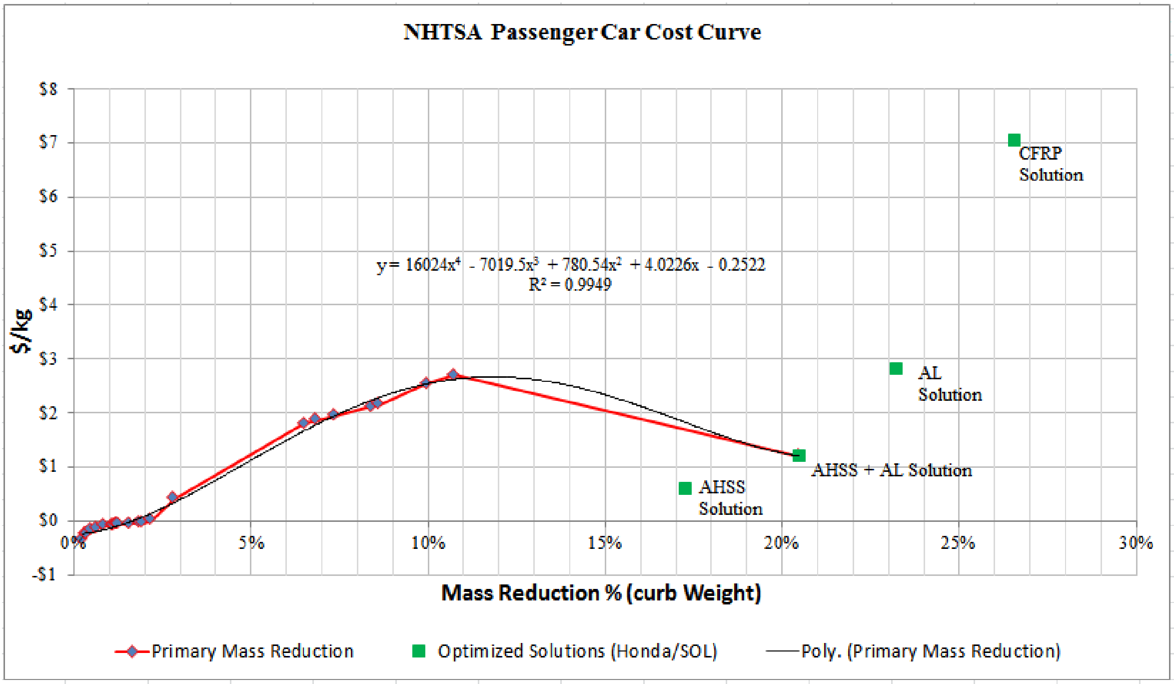


Figure 5.141 NHTSA Passenger Car Cost Curve

A fitted curve was developed based on the above listed mass reduction points to derive cost per kilogram at distinct mass reduction points. These are shown in Table 5.176.

Table 5.176 Cost Per Kilogram at Distinct Mass Reduction Points MR%

PC	$/kg
MR0	$0
MR1 - 5%	$1.12
MR2 - 7.5%	$1.99
MR3 - 10%	$2.54
MR4 - 15%	$2.33
MR5 - 20%	$1.26

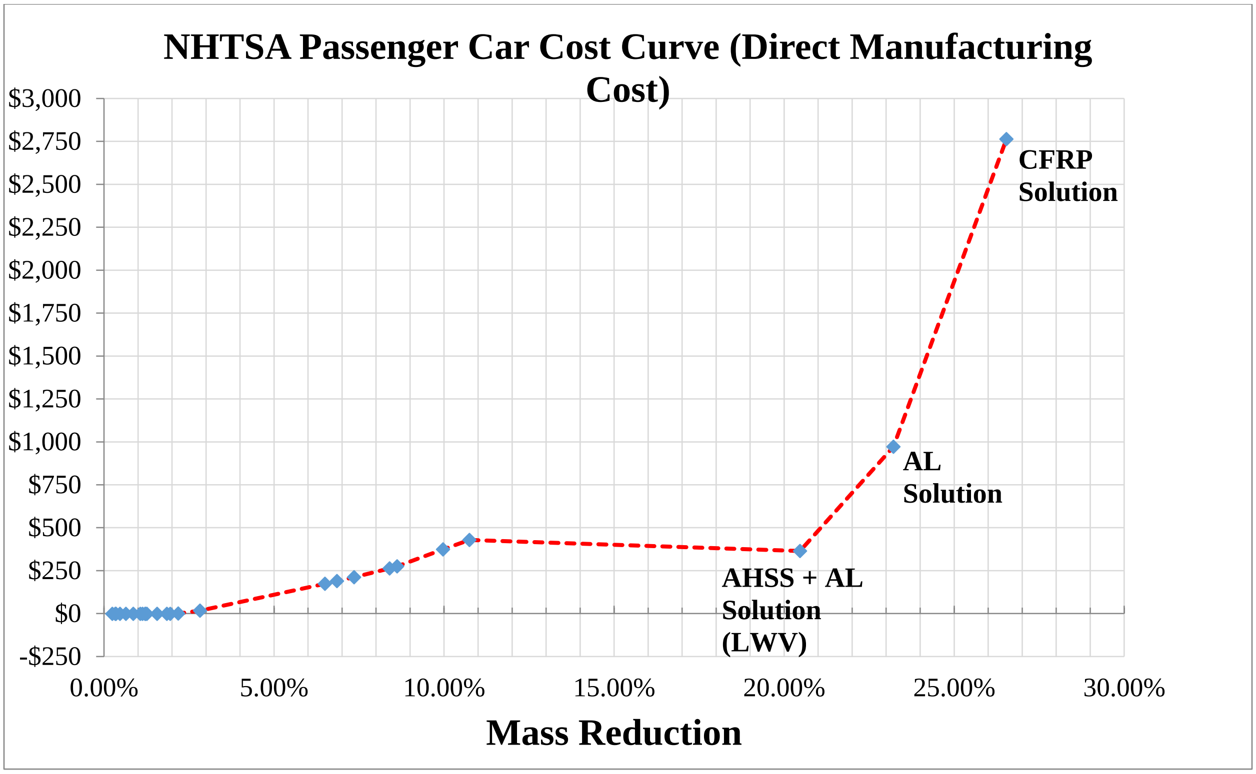


Figure 5.142 Direct Manufacturing Costs for Light-Weighting Approaches Analyzed

5.4.1.1.19.1 Light Duty Pickup Truck Light-Weighting Study

NHTSA also awarded a contract to EDAG to conduct a vehicle weight reduction feasibility and cost study of a 2014MY full size pick-up truck. The light weighted version of the full size pick-up truck (LWT) used manufacturing processes that will likely be available during the model years 2025-2030 and with the capability of high volume production. The goal was to determine the maximum feasible weight reduction while maintaining the same vehicle functionalities, such as towing, hauling, performance, noise, vibration, harshness, safety, and crash rating, as the baseline vehicle, as well as the functionality and capability of designs to meet the needs of sharing components across same or cross vehicle platform. Consideration was also given to the sharing of engines and other components with vehicles built on other platforms to achieve manufacturing economies of scale, and in recognition of resource constraints which limit the ability to optimize every component for every vehicle. At the time of writing for this Draft TAR, the report is in peer review and will be finalized by the NHTSA NPRM and EPA Proposed Determination in 2017.

A comprehensive teardown/benchmarking of the baseline vehicle was conducted for the engineering analysis. The analysis included geometric optimization of load bearing vehicle structures, advanced material utilization along with a manufacturing technology assessment that would be available in the 2017 to 2025 time frame. As part of the analysis, the baseline vehicle's overall mass, center of gravity and all key dimensions were determined. Before the vehicle teardown, laboratory torsional stiffness tests, bending stiffness tests and normal modes of vibration tests were performed on baseline vehicles so that these results could be compared with the CAE model of the light weighted design. After conducting a full tear down and benchmarking of the baseline vehicle, a detailed CAE model of the baseline vehicle was created and correlated with the available crash test results. The project team then used computer modeling and optimization techniques to design the light-weighted pickup truck and optimized the vehicle structure considering redesign of structural geometry, material grade and material gauge to achieve the maximum amount of mass reduction while achieving comparable vehicle performance as the baseline vehicle. Only technologies and materials projected to be available for large scale production and available within two to three design generations (e.g. model years 2020, 2025 and 2030) were chosen for the LWT design. Three design concepts were evaluated: 1) a multi-material approach; 2) an aluminum intensive approach; and 3) a Carbon Fiber Reinforced Plastics approach. The multi-material approach was identified as the most cost effective. The recommended materials (advanced high strength steels, aluminum, magnesium and plastics), manufacturing processes, (stamping, hot stamping, die casting, extrusions, and roll forming) and assembly methods (spot welding, laser welding, riveting and adhesive bonding) are currently used, although some to a lesser degree than others. These technologies can be fully developed within the normal product design cycle using the current design and development methods.

The design of the LWT was verified, through CAE modeling, that it meets all relevant crash tests performance. The LS-DYNA finite element software used by the EDAG team is an industry standard for crash simulation and modeling. The researchers modeled the crashworthiness of the LWT design using the NCAP Frontal, Lateral Moving Deformable Barrier, and Lateral Pole tests, along with the IIHS Roof, Lateral Moving Deformable Barrier, and Frontal Offset (40 percent and 25 percent) tests. All of the modeled tests were comparable to the actual crash tests performed on the 2014 Silverado in the NHTSA database. Furthermore, the FMVSS No. 301 rear impact test was modeled and it showed no damage to the fuel system.

The baseline 2014 MY Chevrolet Silverado's platform shares components across several platforms. Some of the chassis components and other structural components were designed to accommodate platform derivatives, similar to the components in the baseline vehicle which are shared across platforms such as GMT 920 (GM Tahoe, Cadillac Escalade, GMC Yukon), GMT 930 platform (Chevy Suburban, Cadillac Escalade ESV, GMC Yukon XL), and GMT 940 platform (Chevy Avalanche and Cadillac Escalade EXT) and GMT 900 platform (GMC Sierra). As per the National Academy of Science's guidelines, the study assumes engines would be downsized or redesigned for mass reduction levels at or greater than 10 percent. As a consequence of mass reduction, several of the components used designs that were developed for other vehicles in the weight category of light-weighted designed vehicles were used to maximize economies of scale and resource limitations. Examples include brake systems, fuel tanks, fuel lines, exhaust systems, wheels, and other components.

Cost is a key consideration when vehicle manufacturers decide which fuel-saving technology to apply to a vehicle. Incremental cost analysis for all of the new technologies applied to reduce mass of the light-duty full-size pickup truck designed were calculated. The cost estimates include variable costs as well as non-variable costs, such as the manufacturer’s investment cost for tooling. The cost estimates include all the costs directly related to manufacturing the components. For example, for a stamped sheet metal part, the cost models estimate the costs for each of the operations involved in the manufacturing process, starting from blanking the steel from coil through the final stamping operation to fabricate the component. The final estimated total manufacturing cost and assembly cost are a sum total of all the respective cost elements including the costs for material, tooling, equipment, direct labor, energy, building and maintenance.

The information from the LWT design study was used to develop a cost curve representing cost effective full vehicle solutions for a wide range of mass reduction levels. The cost curve is shown in Figure 5.143. At lower levels of mass reduction, non-structural components and aluminum closures provide weight reduction which can be incorporated independently without the redesign of other components and are stand-alone solutions for the LWV. The holistic vehicle design using a combination of AHSS and aluminum provides good levels of mass reduction at reasonably acceptable cost. The LWV solution achieves 17.6 percent mass reduction from the baseline curb mass. Further two more analytical mass reduction solutions (all aluminum and all carbon fiber reinforced plastics) were developed to show additional mass reduction that could be potentially achieved beyond the LWV mass reduction solution point. The aluminum analytical solution predominantly uses aluminum including chassis frame and other components. The carbon fiber reinforced plastics analytical solution predominantly uses CFRP in many of the components. The CFRP analytical solution shows higher level of mass reduction but at very high costs. Note here that both all-Aluminum and all CFRP mass reduction solutions are analytical solutions only and no computational models were developed to examine all the performance metrics.

An analysis was also conducted to examine the cost sensitivity of major vehicle systems to material cost and production volume variations.

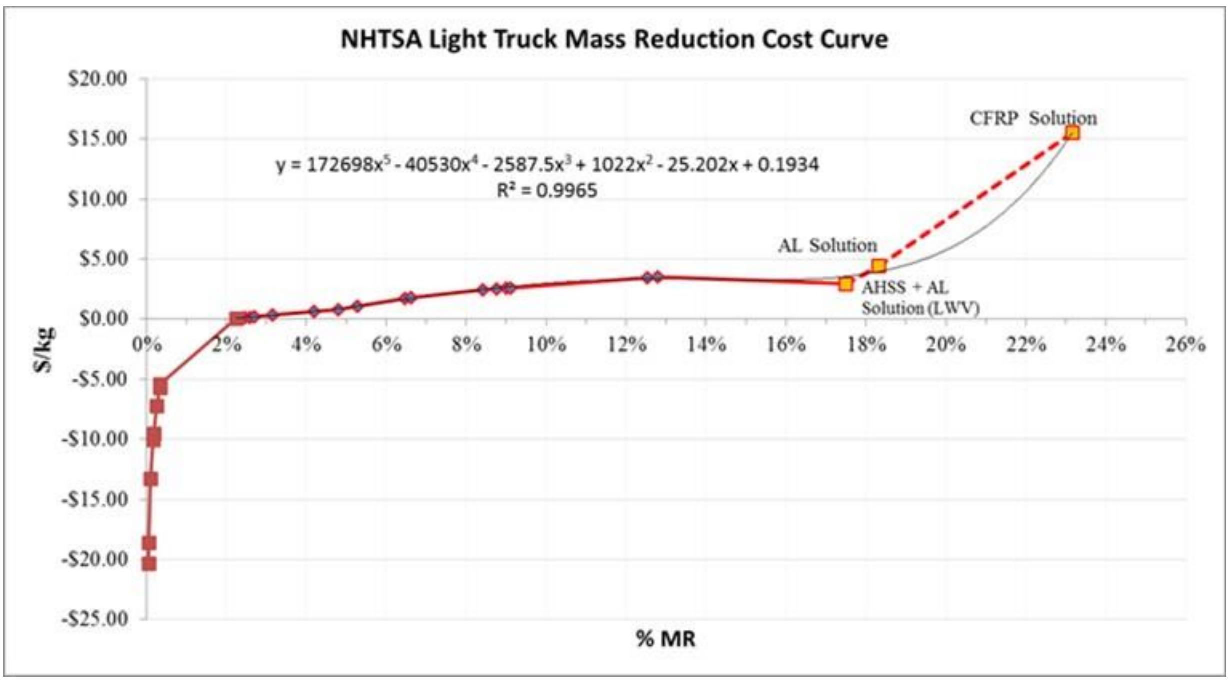


Figure 5.143 NHTSA Draft Light Duty Pickup Truck Lightweighting (AHSS Frame with Aluminum Intensive) Cost Curve (DMC $/kg v %MR)

Table 5.177 lists the components included in the various levels of mass reduction for the LWV solution. The components are incorporated in a progression based on cost effectiveness.

Table 5.177 Components Included for Different Levels of Mass Reduction

Vehicle Component/System	Cumulative Mass Saving	Cumulative MR%	Cumulative Cost	Cumulative Cost $/kg
Interior Electrical Wiring	1.38	0.06%	($28.07)	-20.34
Headliner	1.56	0.06%	($29.00)	-18.59
Trim - Plastic	2.59	0.11%	($34.30)	-13.24
Trim - misc.	4.32	0.18%	($43.19)	-10.00
Floor Covering	4.81	0.20%	($45.69)	-9.50
Headlamps	6.35	0.26%	($45.69)	-7.20
HVAC System	8.06	0.33%	($45.69)	-5.67
Tail Lamps	8.46	0.35%	($45.69)	-5.40
Chassis Frame	54.82	2.25%	$2.57	0.05
Front Bumper	59.93	2.46%	$7.89	0.13
Rear Bumper	62.96	2.59%	$11.04	0.18
Towing Hitch	65.93	2.71%	$14.13	0.21
Rear Doors	77	3.17%	$28.09	0.36
Wheels	102.25	4.20%	$68.89	0.67
Front Doors	116.66	4.80%	$92.53	0.79
Fenders	128.32	5.28%	$134.87	1.05
Front/Rear Seat & Console	157.56	6.48%	$272.57	1.73
Steering Column Assy	160.78	6.61%	$287.90	1.79
Pickup Box	204.74	8.42%	$498.35	2.43
Tailgate	213.14	8.76%	$538.55	2.53
Instrument Panel	218.66	8.99%	$565.06	2.58
Instrument Panel Plastic Parts	221.57	9.11%	$580.49	2.62
Cab	304.97	12.54%	$1,047.35	3.43
Radiator Support	310.87	12.78%	$1,095.34	3.52
Powertrain	425.82	17.51%	1246.68	2.93

A fitted curve was developed based on the above listed mass reduction points to derive cost per kilogram at distinct mass reduction points as shown in Table 5.178.

Table 5.178 Cost Per Kilogram of Mass Reduced

MR%	$/kg
5.0%	$0.97
7.5%	$2.09
10.0%	$2.98
15.0%	$3.27
20.0%	$5.75

As explained above, the direct manufacturing costs for the components listed above are shown in Figure 5.144.

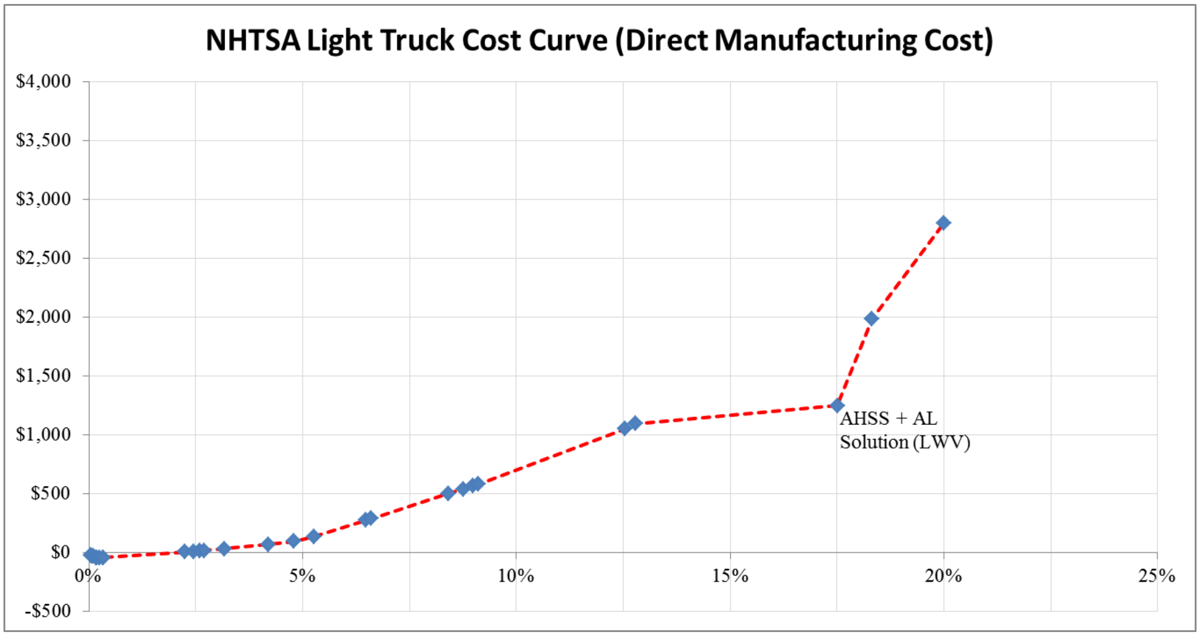


Figure 5.144 NHTSA Light Truck Cost Curve ($/Vehicle vs. % Mas Reduction)

Table 5.179 shows the direct manufacturing costs at distinct mass reduction levels.

Table 5.179 Direct Manufacturing Costs for Different Mass Reduction Levels

LT Baseline Curb Wt. 2432 kg	Mass Reduction (kg)	DMC ($)
MR0	0	$0
MR1 - 5%	122	$118
MR2 - 7.5%	182	$381
MR3 - 10%	243	$725
MR4 - 15%	365	$1193
MR5 - 20%	486	$2797

5.4.1.2 Indirect Costs

5.4.1.2.1 *Methodologies for Determining Indirect Costs*

To produce a unit of output, vehicle manufacturers incur direct and indirect costs. Direct costs include cost of materials and labor costs. Indirect costs are all the costs associated with producing the unit of output that are not direct costs – for example, they may be related to production (such as research and development), corporate operations (such as salaries, pensions, and health care costs for corporate staff), or selling (such as transportation, dealer support, and marketing). Indirect costs are generally recovered by allocating a share of the costs to each unit of good sold. Although it is possible to account for direct costs allocated to each unit of good sold, it is more challenging to account for indirect costs allocated to a unit of goods sold. To make a cost analysis process more feasible, markup factors, which relate total indirect costs to total direct costs, have been developed. These factors are often referred to as retail price equivalent multipliers.

Cost analysts and regulatory agencies (including both NHTSA and EPA) have frequently used these multipliers to predict the resultant impact on costs associated with manufacturers' responses to regulatory requirements. The best approach, if it were possible, to determining the impact of changes in direct manufacturing costs on a manufacturer's indirect costs would be to actually estimate the cost impact on each indirect cost element. However, doing this within the constraints of an agency's time or budget is not always feasible, and the technical, financial, and accounting information to carry out such an analysis may simply be unavailable.

The one empirically derived metric that addresses the markup of direct costs to consumer costs is the RPE multiplier, which is measured from manufacturer 10-K accounting statements filed with the Securities and Exchange Commission. Over roughly a three decade period, the measured RPE has been remarkably stable, averaging 1.5, with minor annual variation. The National Research Council notes that, "Based on available data, a reasonable RPE multiplier would be 1.5." The historical trend in the RPE is illustrated in Figure 5.145.

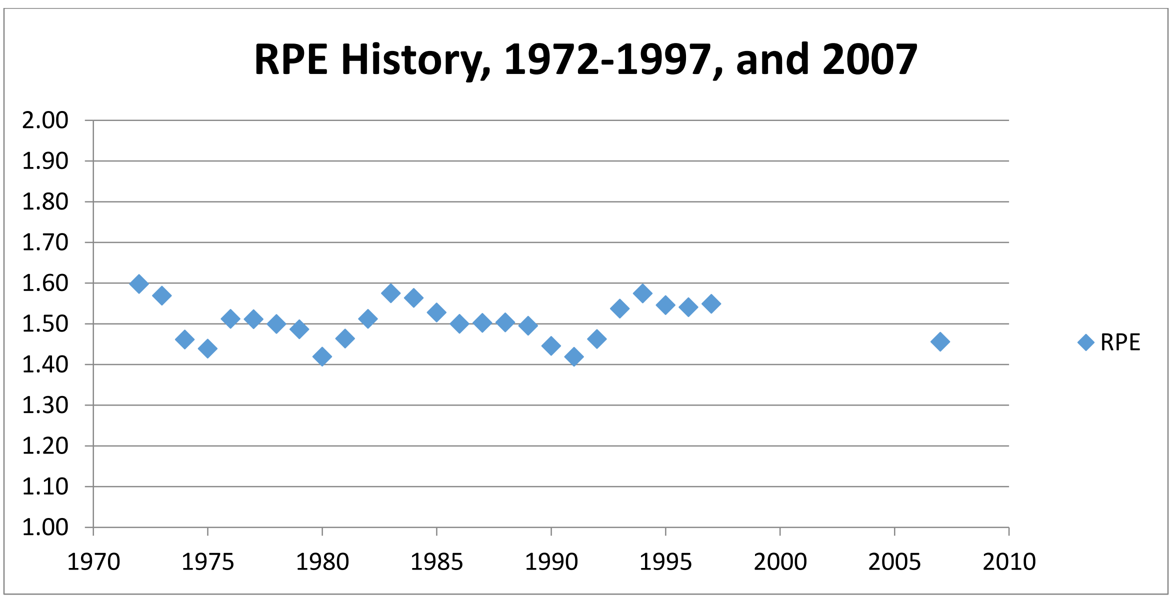


Figure 5.145 RPE History 1972-1997 and 2007

RPE multipliers provide, at an aggregate level, the relationship between revenue and direct manufacturing costs. They are measured by dividing total revenue by direct costs. However, because this provides only a single aggregate measure, using RPE multipliers results in the application of a common incremental markup to all technologies. It assures that the aggregate cost impact across all technologies is consistent with empirical data, but does not allow for indirect cost discrimination among different technologies. Thus, a concern in using the RPE multiplier in cost analysis for new technologies added in response to regulatory requirements is that the indirect costs of vehicle modifications are not likely to be the same for all different technologies. For example, less complex technologies could require fewer R&D efforts or less warranty coverage than more complex technologies. In addition, some simple technological adjustments may, for example, have no effect on the number of corporate personnel and the indirect costs attributable to those personnel. The use of RPEs, with their assumption that all technologies have the same proportion of indirect costs, is likely to overestimate the costs of less complex technologies and underestimate the costs of more complex technologies. However, for regulations such as the CAFE and GHG emission standards under consideration, which drive changes to nearly every vehicle system, overall average indirect costs should align with the RPE value. Applying RPE to the cost for each technology assures that alignment.

Modified multipliers have been developed by EPA, working with a contractor, for use in rulemakings.[598] These multipliers are referred to as indirect cost multipliers (or ICMs). ICMs assign unique incremental changes to each indirect cost contributor at several different technology levels.

ICM = (direct cost + adjusted indirect cost)/(direct cost)

Developing the ICMs from the RPE multipliers requires developing adjustment factors based on the complexity of the technology and the time frame under consideration: the less complex a technology, the lower its ICM, and the longer the time frame for applying the technology, the lower the ICM. This methodology was used in the cost estimation for the recent light-duty MYs 2012-2016 and MYs 2017-2025 rulemaking and for the heavy-duty MYs 2014-2018 rulemaking. The ICMs for the light-duty context were developed in a peer-reviewed report from RTI International and were subsequently discussed in a peer-reviewed journal article.[599] Importantly, since publication of that peer-reviewed journal article, the agencies have revised the methodology to include a return on capital (i.e., profits) based on the assumption implicit in ICMs (and RPEs) that capital costs are proportional to direct costs, and businesses need to be able to earn returns on their investments.

5.4.1.2.2 Indirect Cost Multipliers Used in this Analysis

Since their original development in February 2009, the agencies have made some changes to both the ICMs factors and to the method of applying those factors relative to the factors developed by RTI and presented in their reports. We have described and explained those changes in several rulemakings over the years, most notably the 2017-2025 FR for light vehicles and the more recent Heavy-duty GHG Phase 2 NPRM.[600] In the 2015 NAS study, the committee stated a conceptual agreement with the ICM method since ICM takes into account design challenges and the activities required to implement each technology. However, although endorsing ICMs as a concept, the NAS Committee stated that "…the empirical basis for such multipliers is still lacking, and, since their application depends on expert judgment, it is not possible to determine whether the Agencies' ICMs are accurate or not." NAS also states that "…the specific values for the ICMs are critical since they may affect the overall estimates of costs and benefits for the overall standards and the cost effectiveness of the individual technologies." The committee did encourage continued research into ICMs given the lack of empirical data for them to evaluate the ICMs used by the agencies in past analyses. EPA, for its part, continues to study the issue surrounding ICMs but has not pursued further efforts given resource constraints and demands in areas such as technology benchmarking and cost teardowns. On balance, NHTSA believes that the empirically derived RPE is a more reliable basis for estimating indirect costs. To ensure overall indirect costs in the analysis align with the RPE value, NHTSA has developed its primary analysis based on applying the RPE value of 1.5 to each technology. NHTSA also has conducted a sensitivity analysis examining the impact of applying the ICM approach using the same methodology and multiplier values described in Section 5.3 for EPA's analysis.

The ICMs used in NHTSA's sensitivity analysis are shown in Table 5.180.[601] Near term values account for differences in the levels of R&D, tooling, and other indirect costs that will be incurred. Once the program has been fully implemented, some of the indirect costs will no longer be attributable to the standards and, as such, a lower ICM factor is applied to direct costs.

Table 5.180 Indirect Cost Multipliers Used in this Analysis

	2017-2025 FRM & this TAR	
Complexity	Near term	Long term
Low	1.24	1.19
Medium	1.39	1.29
High1	1.56	1.35
High2	1.77	1.50

We note two important aspects to the ICM method. First, the ICM consists of two portions: a small warranty-related term and a second, larger term to cover all other indirect costs elements. The breakout of warranty versus non-warranty portions to the ICMs are presented in Table 5.181. The latter of these terms does not decrease with learning and, instead, remains constant year-over-year despite learning effects which serve to decrease direct manufacturing costs. Learning effects are described in the next section. The second important note is that all indirect costs are forced to be positive, even for those technologies estimated to have negative direct manufacturing costs.

Table 5.181 Warranty and Non-Warranty Portions of ICMs

	Near term		Long term	
Complexity	Warranty	Non-warranty	Warranty	Non-warranty
Low	0.012	0.230	0.005	0.187
Medium	0.045	0.343	0.031	0.259
High1	0.065	0.499	0.032	0.314
High2	0.074	0.696	0.049	0.448

The ICM categories assigned to each technology and their long-term cutoffs are shown in Table 5.182.

Table 5.182 ICM categories and Short Term ICM Schedules for CAFE Technologies

Technology	ICM Category	Short Term Through
Low Friction Lubricants - Level 1	Low2	2018
Engine Friction Reduction - Level 1	Low2	2018
Low Friction Lubricants and Engine Friction Reduction - Level 2	Low2	2024
Variable Valve Timing (VVT) - Coupled Cam Phasing (CCP) on SOHC	Low2	2018
Discrete Variable Valve Lift (DVVL) on SOHC	Medium2	2018
Cylinder Deactivation on SOHC	Medium2	2018
Variable Valve Timing (VVT) - Intake Cam Phasing (ICP)	Low2	2018
Variable Valve Timing (VVT) - Dual Cam Phasing (DCP)	Medium2	2018
Discrete Variable Valve Lift (DVVL) on DOHC	Medium2	2018
Continuously Variable Valve Lift (CVVL)	Medium2	2018
Cylinder Deactivation on DOHC	Medium2	2018
Stoichiometric Gasoline Direct Injection (GDI)	Medium2	2018
Cylinder Deactivation on OHV	Medium2	2018
Variable Valve Actuation - CCP and DVVL on OHV	Medium2	2018
Stoichiometric Gasoline Direct Injection (GDI) on OHV	Medium2	2018
Turbocharging and Downsizing - Level 1 (18 bar BMEP) - Small Displacement - Turbo	Medium2	2018
Turbocharging and Downsizing - Level 1 (18 bar BMEP) - Small Displacement - Downsize	Medium2	2018
Turbocharging and Downsizing - Level 1 (18 bar BMEP) - Medium Displacement -Turbo	Medium2	2018
Turbocharging and Downsizing - Level 1 (18 bar BMEP) - Medium Displacement - Downsize	Medium2	2018
Turbocharging and Downsizing - Level 1 (18 bar BMEP) - Large Displacement - Turbo	Medium2	2018
Turbocharging and Downsizing - Level 1 (18 bar BMEP) - Large Displacement - Downsize	Medium2	2018
Turbocharging and Downsizing - Level 2 (24 bar BMEP) - Small Displacement - Turbo	Medium2	2024
Turbocharging and Downsizing - Level 2 (24 bar BMEP) - Small Displacement - Downsize	Medium2	2018
Turbocharging and Downsizing - Level 2 (24 bar BMEP) - Medium Displacement - Turbo	Medium2	2024
Turbocharging and Downsizing - Level 2 (24 bar BMEP) - Medium Displacement - Downsize	Medium2	2018
Turbocharging and Downsizing - Level 2 (24 bar BMEP) - Large Displacement - Turbo	Medium2	2024
Turbocharging and Downsizing - Level 2 (24 bar BMEP) - Large Displacement - Downsize	Medium2	2018
Cooled Exhaust Gas Recirculation (EGR) - Level 1 (24 bar BMEP) - Small Displacement - Turbo	Medium2	2024
Cooled Exhaust Gas Recirculation (EGR) - Level 1 (24 bar BMEP) - Small Displacement - Downsize	Medium2	2018
Cooled Exhaust Gas Recirculation (EGR) - Level 1 (24 bar BMEP) - Medium Displacement - Turbo	Medium2	2024
Cooled Exhaust Gas Recirculation (EGR) - Level 1 (24 bar BMEP) - Medium Displacement - Downsize	Medium2	2018
Cooled Exhaust Gas Recirculation (EGR) - Level 1 (24 bar BMEP) - Large Displacement - Turbo	Medium2	2024
Cooled Exhaust Gas Recirculation (EGR) - Level 1 (24 bar BMEP) - Large Displacement - Downsize	Medium2	2018
Cooled Exhaust Gas Recirculation (EGR) - Level 2 (27 bar BMEP) - Small Displacement - Turbo	Medium2	2024

Cooled Exhaust Gas Recirculation (EGR) - Level 2 (27 bar BMEP) - Small Displacement - Downsize	Medium2	2018
Cooled Exhaust Gas Recirculation (EGR) - Level 2 (27 bar BMEP) - Medium Displacement - Turbo	Medium2	2024
Cooled Exhaust Gas Recirculation (EGR) - Level 2 (27 bar BMEP) - Medium Displacement - Downsize	Medium2	2018
Cooled Exhaust Gas Recirculation (EGR) - Level 2 (27 bar BMEP) - Large Displacement - Turbo	Medium2	2024
Cooled Exhaust Gas Recirculation (EGR) - Level 2 (27 bar BMEP) - Large Displacement - Downsize	Medium2	2018
Advanced Diesel - Small Displacement	Medium2	2024
Advanced Diesel - Medium Displacement	Medium2	2024
Advanced Diesel - Large Displacement	Medium2	2024
6-Speed Manual/Improved Internals	Low2	2018
Improved Auto. Trans. Controls/Externals	Low2	2018
6-Speed Trans with Improved Internals (Auto)	Low2	2018
6-speed DCT	Medium2	2018
8-Speed Trans (Auto or DCT)	Medium2	2018
High Efficiency Gearbox w/ dry sump (Auto or DCT)	Low2	2024
Shift Optimizer	Low2	2024
Electric Power Steering	Low2	2018
Improved Accessories - Level 1	Low2	2018
Improved Accessories - Level 2 (w/ Alternator Regen and 70% efficient alternator)	Low2	2024
12V Micro-Hybrid (Stop-Start)	Medium2	2018
Integrated Starter Generator	High1	2018
Strong Hybrid (Powersplit or 2-Mode) - Level 1 – Battery	High1	2024
Strong Hybrid (Powersplit or 2-Mode) - Level 1 - Non-Battery	High1	2018
Conversion from SHEV1 to SHEV2	HIgh1	2018
Strong Hybrid (P2 Parallel or 2-Mode) - Level 2 – Battery	High1	2024
Strong Hybrid (P2 Parallel or 2-Mode) - Level 2 - Non-Battery	High1	2018
Plug-in Hybrid - 20 mi range – Battery	High2	2024
Plug-in Hybrid - 20 mi range - Non-Battery	High1	2018
Plug-in Hybrid - 40 mi range – Battery	High2	2024
Plug-in Hybrid - 40 mi range - Non-Battery	High1	2018
Electric Vehicle (Early Adopter) - 75 mile range – Battery	High2	2024
Electric Vehicle (Early Adopter) - 75 mile range - Non-Battery	High2	2024
Electric Vehicle (Early Adopter) - 100 mile range – Battery	High2	2024
Electric Vehicle (Early Adopter) - 100 mile range - Non-Battery	High2	2024
Electric Vehicle (Early Adopter) - 150 mile range – Battery	High2	2024
Electric Vehicle (Early Adopter) - 150 mile range - Non-Battery	High2	2024
Electric Vehicle (Broad Market) - 150 mile range – Battery	High2	2024
Electric Vehicle (Broad Market) - 150 mile range - Non-Battery	High2	2024
Fuel Cell Vehicle	High2	2024
Charger-PHEV20	High1	2024
Charger-PHEV40	High1	2024
Charger-EV	High1	2024
Charger Labor	None	2024
Mass Reduction - Level 1	Low2	2018
Mass Reduction - Level 2	Low2	2018
Mass Reduction - Level 3	Low2	2018
Mass Reduction - Level 4	Low2	2018

Mass Reduction - Level 5	Low2	2018
Low Rolling Resistance Tires - Level 1	Low2	2018
Low Rolling Resistance Tires - Level 2	Low2	2024
Low Rolling Resistance Tires - Level 3	Low2	2024
Low Drag Brakes	Low2	2018
Secondary Axle Disconnect	Low2	2018
Aero Drag Reduction, Level 1	Low2	2018
Aero Drag Reduction, Level 2	Medium2	2024

There is some level of uncertainty surrounding both the ICM and RPE markup factors. The ICM estimates used in this TAR, consistent with the 2012 final rule, group all technologies into three broad categories and treat them as if individual technologies within each of the three categories (low, medium, and high complexity) will have exactly the same ratio of indirect costs to direct costs. This simplification means it is likely that the direct cost for some technologies within a category will be higher and some lower than the estimate for the category in general. Additionally, the ICM estimates were developed using adjustment factors developed in two separate occasions: the first, a consensus process, was reported in the RTI report; the second, a modified Delphi method, was conducted separately and reported in an EPA memorandum. Both of these panels were composed of EPA staff members with previous background in the automobile industry; the memberships of the two panels overlapped but were not the same. The panels evaluated each element of the industry's RPE estimates and estimated the degree to which those elements would be expected to change in proportion to changes in direct manufacturing costs. The method and the estimates in the RTI report were peer reviewed by three industry experts and subsequently by reviewers for the International Journal of Production Economics. However, the ICM estimates have not been validated through a direct accounting of actual indirect costs for individual technologies. Finally, only a handful of technologies were examined out of roughly 50 that will be used to meet the CAFE standards. There is thus uncertainty regarding both the absolute values estimated for ICMs and their validity as representatives of the universe of technologies.

RPEs are also difficult to estimate because the accounting statements of manufacturers do not neatly categorize all cost elements as either direct or indirect costs. Hence, each researcher developing an RPE estimate must apply a certain amount of judgment to the allocation of the costs. We note, however, that the two independent researchers that have measured RPEs each reached essentially identical conclusions, placing the RPE at roughly 1.5. Since empirical estimates of ICMs are ultimately derived from the same data used to measure RPEs, both measures are dependent on the accuracy of RPE measurement. As noted above, the value of RPE has not been measured for specific technologies, or for groups of specific technologies. Thus applying a single average RPE to any given technology by definition overstates costs for very simple technologies, or understates them for advanced technologies. This same concern applies to ICMs within each of the general ICM complexity categories.

5.4.1.2.3 NHTSA's Application of Learning Curves

NHTSA applies estimates of learning curves to the various technologies that will be used to meet CAFE standards. Learning curves reflect the impact of experience and volume on the cost of production. As manufacturers gain experience through production, they refine production techniques, raw material and component sources, and assembly methods to maximize efficiency and reduce production costs. Typically, learning curves reflect initial learning rates that are relatively high, followed by slower learning as the easier improvements are made and production efficiency peaks. This eventually produces an asymptotic shape to the learning curve as small percent decreases are applied to gradually declining cost levels (see Figure 5.146)

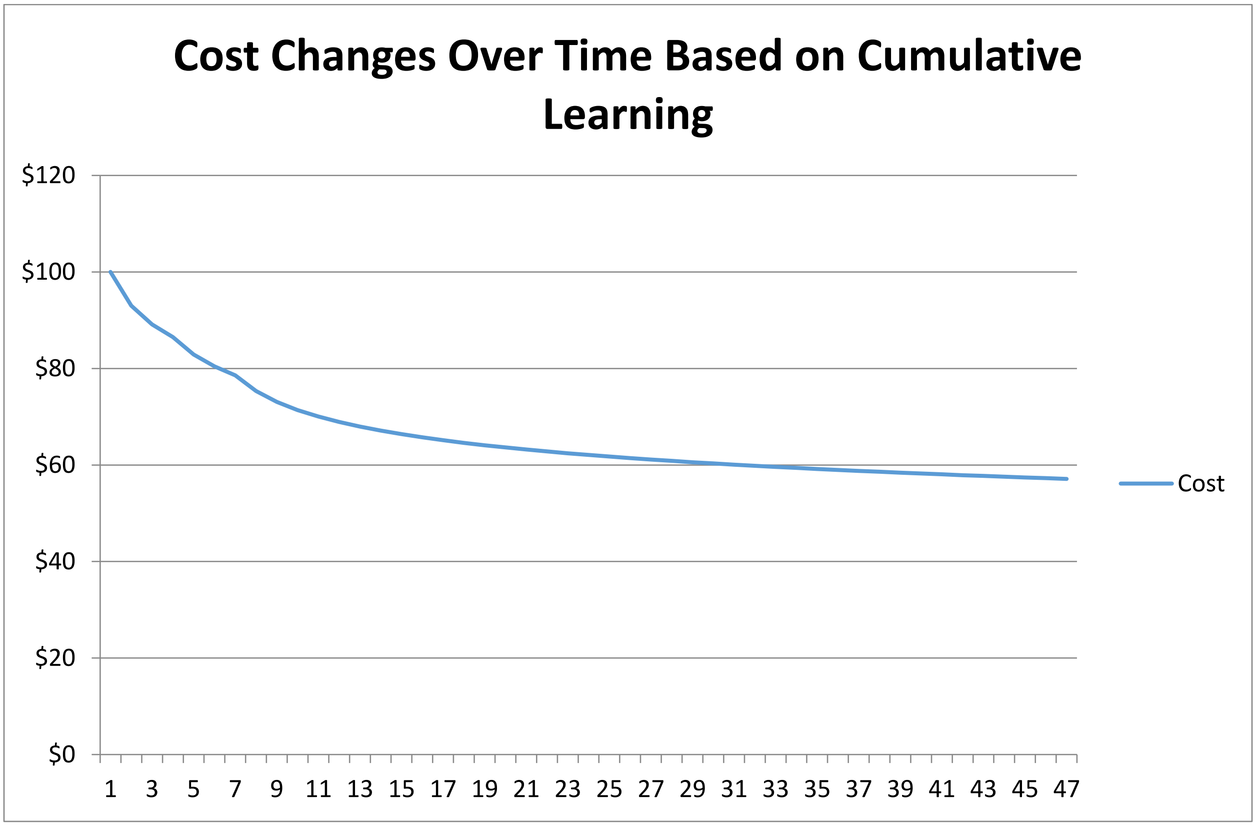


Figure 5.146 Hypothetical Illustration of Cumulative Production Based Learning

The learning curves the agency currently uses represent our current estimates regarding the pace of learning. Depending on the technology, the curves assume a learning rate of 3 percent over the previous years' cost for a number of years, followed by 2 percent over several more years, followed by 1 percent indefinitely. In a few cases, larger decreases of 20 percent are applied every 2 years during the initial years of production before learning decreases to the more typical levels described above. This occurs for the changes that involve relatively new emerging technologies that are not yet mature enough to warrant the slower learning rates.

Table 5.183 lists the various learning schedules that NHTSA applies to technologies for the 2017-2025 FRIA. The schedules are identified by a reference schedule number that was originally assigned to each schedule during the development of the agencies learning methodology. Many other schedules were originally developed, but only those shown in Table 5.183 were considered relevant to the technology costs used in the current analysis. The table illustrates cost reduction rates for years 2015 through 2030. However, only a subset of these years is relevant to each technology, depending on the year in which its direct cost estimate is based and the years in which the technology is applied. The learning rates that are indicated prior to the direct manufacturing costs

base year reflect "prior learning" that was estimated to occur before the base year direct manufacturing cost estimate used by the agencies were developed. So, for example, if a cost estimate for a mature technology reflects expected conditions in MY 2017, there would have already been learning prior to that which would have impacted the MY 2017 costs. Additional learning would then commence in MY 2018.

Table 5.183 Learning Schedules by Model Year Applied to Specific CAFE Technologies

		Schedule #										
		6	**11**	**12**	**16**	**18**	**19**	**21**	**24**	**25**	**26**	**30**	**31**
Model Year	**2015**	1	0.913	1.000	1.000	1.000	2.441	1.063	1.250	1.563	1.146	0	0
	2016	1	0.885	0.970	1.000	1.000	1.953	1.031	1.000	1.563	1.114	0	0
	2017	1	0.868	0.951	0.970	1.000	1.953	1.000	1.000	1.563	1.095	0	0
	2018	1	0.850	0.932	0.941	1.000	1.563	0.970	0.970	1.563	1.065	3	0
	2019	1	0.833	0.913	0.913	0.800	1.563	0.941	0.941	1.250	1.029	3	0
	2020	1	0.817	0.895	0.885	0.800	1.250	0.913	0.913	1.250	1.000	3	0
	2021	1	0.800	0.877	0.859	0.640	1.250	0.885	0.885	1.000	0.973	3	0
	2022	1	0.784	0.859	0.833	0.640	1.250	0.859	0.859	0.970	0.944	3	0
	2023	1	0.769	0.842	0.808	0.627	1.250	0.842	0.833	0.941	0.920	3	5
	2024	1	0.753	0.825	0.784	0.615	1.250	0.825	0.808	0.913	0.898	3	5
	2025	1	0.738	0.809	0.760	0.602	1.000	0.808	0.784	0.885	0.876	3	5
	2026	1	0.731	0.801	0.745	0.590	0.970	0.792	0.768	0.859	0.859	3	5
	2027	1	0.723	0.793	0.730	0.579	0.941	0.776	0.753	0.842	0.842	3	5
	2028	1	0.716	0.785	0.716	0.567	0.913	0.768	0.738	0.825	0.827	3	5
	2029	1	0.709	0.777	0.701	0.556	0.885	0.761	0.723	0.808	0.812	3	5
	2030	1	0.702	0.769	0.687	0.544	0.859	0.753	0.708	0.792	0.798	3	5

Table 5.184 lists the technologies that manufacturers may use to achieve higher CAFE levels, and the learning schedule that is applied to each technology. Selection of specific learning curves was based on the agency's best judgment as to the maturity of each technology and where they would best fit along the learning curve, as well as the year on which their direct manufacturing costs are based.

For example, schedules 11, 12, and 21 are appropriate for technologies that are more mature and have already passed through the steep portion of the learning curve, while schedules 16, 19, 24, and 25 are more appropriate for emerging technologies that will be experiencing learning along the steep part of the curve between MYs 2014-2025.

Table 5.184 Learning Schedules for Specific CAFE Technologies

Technology	Learning Schedule
Low Friction Lubricants - Level 1	6
Engine Friction Reduction - Level 1	6
Low Friction Lubricants and Engine Friction Reduction - Level 2	6
Variable Valve Timing (VVT) - Coupled Cam Phasing (CCP) on SOHC	12
Discrete Variable Valve Lift (DVVL) on SOHC	12
Cylinder Deactivation on SOHC	11
Variable Valve Timing (VVT) - Intake Cam Phasing (ICP)	12
Variable Valve Timing (VVT) - Dual Cam Phasing (DCP)	12
Discrete Variable Valve Lift (DVVL) on DOHC	12
Continuously Variable Valve Lift (CVVL)	12
Cylinder Deactivation on DOHC	11
Stoichiometric Gasoline Direct Injection (GDI)	11
Cylinder Deactivation on OHV	12
Variable Valve Actuation - CCP and DVVL on OHV	12
Stoichiometric Gasoline Direct Injection (GDI) on OHV	11
Turbocharging and Downsizing - Level 1 (18 bar BMEP) - Small Displacement – Turbo	11
Turbocharging and Downsizing - Level 1 (18 bar BMEP) - Small Displacement - Downsize	11
Turbocharging and Downsizing - Level 1 (18 bar BMEP) - Medium Displacement –Turbo	11
Turbocharging and Downsizing - Level 1 (18 bar BMEP) - Medium Displacement - Downsize	11
Turbocharging and Downsizing - Level 1 (18 bar BMEP) - Large Displacement – Turbo	11
Turbocharging and Downsizing - Level 1 (18 bar BMEP) - Large Displacement - Downsize	11
Turbocharging and Downsizing - Level 2 (24 bar BMEP) - Small Displacement - Turbo	11
Turbocharging and Downsizing - Level 2 (24 bar BMEP) - Small Displacement - Downsize	11
Turbocharging and Downsizing - Level 2 (24 bar BMEP) - Medium Displacement - Turbo	11
Turbocharging and Downsizing - Level 2 (24 bar BMEP) - Medium Displacement - Downsize	11
Turbocharging and Downsizing - Level 2 (24 bar BMEP) - Large Displacement - Turbo	11
Turbocharging and Downsizing - Level 2 (24 bar BMEP) - Large Displacement - Downsize	11
Cooled Exhaust Gas Recirculation (EGR) - Level 1 (24 bar BMEP) - Small Displacement - Turbo	11
Cooled Exhaust Gas Recirculation (EGR) - Level 1 (24 bar BMEP) - Small Displacement – Downsize	11
Cooled Exhaust Gas Recirculation (EGR) - Level 1 (24 bar BMEP) - Medium Displacement - Turbo	11
Cooled Exhaust Gas Recirculation (EGR) - Level 1 (24 bar BMEP) - Medium Displacement – Downsize	11
Cooled Exhaust Gas Recirculation (EGR) - Level 1 (24 bar BMEP) - Large Displacement – Turbo	11
Cooled Exhaust Gas Recirculation (EGR) - Level 1 (24 bar BMEP) - Large Displacement – Downsize	11
Cooled Exhaust Gas Recirculation (EGR) - Level 2 (27 bar BMEP) - Small Displacement – Turbo	11
Cooled Exhaust Gas Recirculation (EGR) - Level 2 (27 bar BMEP) - Small Displacement – Downsize	11
Cooled Exhaust Gas Recirculation (EGR) - Level 2 (27 bar BMEP) - Medium Displacement – Turbo	11
Cooled Exhaust Gas Recirculation (EGR) - Level 2 (27 bar BMEP) - Medium Displacement – Downsize	11
Cooled Exhaust Gas Recirculation (EGR) - Level 2 (27 bar BMEP) - Large Displacement – Turbo	11
Cooled Exhaust Gas Recirculation (EGR) - Level 2 (27 bar BMEP) - Large Displacement – Downsize	11
Advanced Diesel - Small Displacement	11
Advanced Diesel - Medium Displacement	11
Advanced Diesel - Large Displacement	11
6-Speed Manual/Improved Internals	12
Improved Auto. Trans. Controls/Externals	12
6-Speed Trans with Improved Internals (Auto)	11

6-speed DCT	11
8-Speed Trans (Auto or DCT)	11
High Efficiency Gearbox w/ dry sump (Auto or DCT)	21
Shift Optimizer	21
Electric Power Steering	12
Improved Accessories - Level 1	12
Improved Accessories - Level 2 (w/ Alternator Regen and 70% efficient alternator)	12
12V Micro-Hybrid (Stop-Start)	16
Integrated Starter Generator	16
Strong Hybrid (Powersplit or 2-Mode) - Level 1 – Battery	24
Strong Hybrid (Powersplit or 2-Mode) - Level 1 - Non-Battery	11
Conversion from SHEV1 to SHEV2	N/A
Strong Hybrid (P2 Parallel or 2-Mode) - Level 2 – Battery	24
Strong Hybrid (P2 Parallel or 2-Mode) - Level 2 - Non-Battery	11
Plug-in Hybrid - 20 mi range – Battery	19
Plug-in Hybrid - 20 mi range - Non-Battery	11
Plug-in Hybrid - 40 mi range – Battery	19
Plug-in Hybrid - 40 mi range - Non-Battery	11
Electric Vehicle (Early Adopter) - 75 mile range – Battery	19
Electric Vehicle (Early Adopter) - 75 mile range - Non-Battery	21
Electric Vehicle (Early Adopter) - 100 mile range – Battery	19
Electric Vehicle (Early Adopter) - 100 mile range - Non-Battery	21
Electric Vehicle (Early Adopter) - 150 mile range – Battery	19
Electric Vehicle (Early Adopter) - 150 mile range - Non-Battery	21
Electric Vehicle (Broad Market) - 150 mile range – Battery	19
Electric Vehicle (Broad Market) - 150 mile range - Non-Battery	21
Charger-PHEV20	19
Charger-PHEV40	19
Charger-EV	19
Charger Labor	6
Mass Reduction - Level 1	21
Mass Reduction - Level 2	21
Mass Reduction - Level 3	21
Mass Reduction - Level 4	21
Mass Reduction - Level 5	21
Low Rolling Resistance Tires - Level 1	6
Low Rolling Resistance Tires - Level 2	25
Low Rolling Resistance Tires - Level 3	N/A
Low Drag Brakes	6
Secondary Axle Disconnect	12
Aero Drag Reduction, Level 1	12
Aero Drag Reduction, Level 2	12

5.4.1.3 Technology Cost Summary Tables

The following tables summarize incremental costs and total costs for advanced technologies in 2013 dollars. Incremental costs reflect the additional costs that the Volpe model applies over the previous step in the technology track for a specific piece of technology. Absolute costs reflect cost to add an advanced technology and requisite enabling technologies over the low technology baseline in the technology path.

The following cost tables show the combined results of direct manufacturing costs, indirect costs, learning curves, and technology progression paths for 2017MY and 2025 MY. To calculate direct manufacturing costs for a given year from the costs listed in these tables, divide by the RPE (1.5) and adjust for the appropriate learning schedule factors as well as incremental costs for removing technologies that are no longer needed. The costs for all years are relevant inputs for the CAFE model.

Many technologies have projected costs that vary by application. For instance, the incremental cost of many engine technologies takes into account the engine configuration, like number of banks and number cylinders. Similarly, many advanced vehicle technologies have a specific cost for each vehicle class. The following tables summarize the costs for CAFE model inputs by application.

5.4.1.3.1 *Basic Gasoline Engine Costs*

This section shows projected costs for basic gasoline engine technologies. Table 5.185 demonstrates how technology costs may scale with application attributes. Table 5.186 and Table 5.188 show incremental and absolute costs for advanced technologies on the basic engine path.

Table 5.185 Examples of Engine Technology Costs that Scale with Engine Attributes

Gasoline Engine Technologies - Direct Manufacturer Costs - Small Displacement DOHC								
Tech	Basis	Unit DMC	Learning Factor	DMC for 4-Cylinder 1-Bank Engine	DMC for 4-Cylinder 2-Bank Engine[YYY]	DMC for 6-Cylinder 1-Bank Engine	DMC for 6-Cylinder 2-Bank Engine	DMC for 8-Cylinder 2-Bank Engine
LUBEFR1	cylinder	$ 13.36	6	$ 53.45	$ 53.45	$ 80.18	$ 80.18	$ 106.91
LUBEFR2	cylinder	$ 0.89	30	$ 3.55	$ 3.55	$ 5.32	$ 5.32	$ 7.10
LUBEFR3	cylinder	$ 0.89	31	$ 3.55	$ 3.55	$ 5.32	$ 5.32	$ 7.10
VVT	bank	$ 75.20	12	$ 75.20	$ 150.40	$ 75.20	$ 150.40	$ 150.40
VVL	cylinder	$ 51.31	12	$ 205.26	$ 205.26	$ 307.88	$ 307.88	$ 410.51
SGDI	cylinder	$ 56.76	11	$ 227.05	$ 227.05	$ 340.57	$ 340.57	$ 454.09
DEAC	none	$ 28.19	11	$ 28.19	$ 28.19	$ 28.19	$ 28.19	$ 28.19
HCR	none	$ 90.85 – $ 215.5	21	$ 90.85	$ 90.85	$ 136.27	$ 136.27	$ 215.50

[YYY] Illustrative example for cost calculation purposes, only.

Table 5.186 Projected MY2017 Incremental Costs for Gasoline Engine Technology

Technology	4-Cylinder 1-Bank	4-Cylinder 2-Bank[ZZZ]	6-Cylinder 1-Bank	6-Cylinder 2-Bank	8-Cylinder 2-Bank	Cost Adjustment SOHC (per basis)	Cost Adjustment OHV (per basis)
LUBEFR1	80.18	80.18	120.27	120.27	160.36		
LUBEFR2	-	-	-	-	-		
LUBEFR3 [AAAA]	-	-	-	-	-		
VVT	107.23	214.46	107.23	214.46	214.46	(30.68)	(30.68)
VVL	292.67	292.67	439.01	439.01	585.35	(17.24)	(17.24)
SGDI	295.47	295.47	443.21	443.21	590.95		
DEAC	36.69	36.69	36.69	36.69	36.69		
HCR	136.27	136.27	204.41	204.41	323.26		

Table 5.187 Projected MY2025 Incremental Costs for Gasoline Engine Technology

Technology	4-Cylinder 1-Bank	4-Cylinder 2-Bank[BBBB]	6-Cylinder 1-Bank	6-Cylinder 2-Bank	8-Cylinder 2-Bank	Cost Adjustment SOHC (per basis)	Cost Adjustment OHV (per basis)
LUBEFR1	80.18	80.18	120.27	120.27	160.36		
LUBEFR2	15.97	15.97	23.96	23.96	31.95		
LUBEFR3	26.62	26.62	39.93	39.93	53.24		
VVT	93.09	186.17	93.09	186.17	186.17	(30.68)	(30.68)
VVL	254.08	254.08	381.12	381.12	508.15	(17.24)	(17.24)
SGDI	256.51	256.51	384.76	384.76	513.02		
DEAC	31.85	31.85	31.85	31.85	31.85		
HCR	112.39	112.39	168.58	168.58	266.60		

[ZZZ] Illustrative example for cost calculation purposes, only.
[AAAA] LUBEFR2 and LUBEFR3 are not available until MY2018 and MY2023, respectively.
[BBBB] Illustrative example for cost calculation purposes, only.

Table 5.188 Projected MY2017 Absolute Costs for Gasoline Engine Technology

Technology	4-Cylinder 1-Bank	4-Cylinder 2-Bank[CCCC]	6-Cylinder 1-Bank	6-Cylinder 2-Bank	8-Cylinder 2-Bank
LUBEFR1	80.18	80.18	120.27	120.27	160.36
LUBEFR2	80.18	80.18	120.27	120.27	160.36
LUBEFR3[DDDD]	80.18	80.18	120.27	120.27	160.36
VVT	187.41	294.64	227.50	334.73	374.82
VVL	480.08	587.31	666.51	773.74	960.16
SGDI	775.56	882.78	1,109.72	1,216.95	1,551.11
DEAC	812.25	919.48	1,146.41	1,253.64	1,587.80
HCR	948.52	1,055.75	1,350.82	1,458.05	1,911.06

Table 5.189 Projected MY2025 Absolute Costs for Gasoline Engine Technology

Technology	4-Cylinder 1-Bank	4-Cylinder 2-Bank[EEEE]	6-Cylinder 1-Bank	6-Cylinder 2-Bank	8-Cylinder 2-Bank
LUBEFR1	80.18	80.18	120.27	120.27	160.36
LUBEFR2	96.15	96.15	144.23	144.23	192.31
LUBEFR3	122.77	122.77	184.16	184.16	245.55
VVT	215.86	308.95	277.25	370.34	431.72
VVL	469.94	563.03	658.36	751.45	939.88
SGDI	726.45	819.53	1,043.13	1,136.21	1,452.90
DEAC	758.30	851.39	1,074.98	1,168.07	1,484.75
HCR	870.69	963.78	1,243.56	1,336.65	1,751.35

[CCCC] Illustrative example for cost calculation purposes, only.
[DDDD] LUBEFR2 and LUBEFR3 are not available until MY2018 and MY2023, respectively.
[EEEE] Illustrative example for cost calculation purposes, only.

5.4.1.3.2 *Gasoline Turbo Engine Costs*

Table 5.190 Projected MY2017 Incremental Costs for Turbo and Turbo-Downsize Technology

Technology	Engine Type	Displacement	Learning Factor	Incremental Cost	Downsizing Costs Adjustment	Technology Costs After Downsizing	Incremental Combined Tech Cost
Turbo-1 SOHC	SOHC	Small	11	577.57		577.57	500.42
Downsize-1 SOHC	SOHC	Small	11	-40.46	-36.69	-77.15	
Turbo-1 SOHC	SOHC	Medium	11	577.57		577.57	358.66
Downsize-1 SOHC	SOHC	Medium	11	-182.22	-36.69	-218.91	
Turbo-1 SOHC	SOHC	Large	11	973.57		973.57	896.96
Downsize-1 SOHC	SOHC	Large	11	-39.92	-36.69	-76.61	
Turbo-1 DOHC	DOHC	Small	11	577.57		577.57	500.42
Downsize-1 DOHC	DOHC	Small	11	-40.46	-36.69	-77.15	
Turbo-1 DOHC	DOHC	Medium	11	577.57		577.57	280.08
Downsize-1 DOHC	DOHC	Medium	11	-260.79	-36.69	-297.48	
Turbo-1 DOHC	DOHC	Large	11	973.57		973.57	806.35
Downsize-1 DOHC	DOHC	Large	11	-130.53	-36.69	-167.22	
Turbo-1 OHV	OHV	Small	11	0.00		0.00	-36.69
Downsize-1 OHV	OHV	Small	11	0.00	-36.69	-36.69	
Turbo-1 OHV	OHV	Medium	11	577.57		577.57	926.87
Downsize-1 OHV	OHV	Medium	11	386.00	-36.69	349.31	
Turbo-1 OHV	OHV	Large	11	973.57		973.57	1,387.21
Downsize-1 OHV	OHV	Large	11	450.33	-36.69	413.64	

Table 5.191 Projected MY2025 Incremental Costs for Turbo and Turbo-Downsize Technology

Technology	Engine Type	Displacement	Learning Factor	Incremental Cost	Downsizing Costs Adjustment	Technology Costs After Downsizing	Incremental Combined Tech Cost
Turbo-1 SOHC	SOHC	Small	11	491.37		491.37	425.10
Downsize-1 SOHC	SOHC	Small	11	-34.42	-31.85	-66.27	
Turbo-1 SOHC	SOHC	Medium	11	491.37		491.37	304.50
Downsize-1 SOHC	SOHC	Medium	11	-155.02	-31.85	-186.87	
Turbo-1 SOHC	SOHC	Large	11	828.28		828.28	762.47
Downsize-1 SOHC	SOHC	Large	11	-33.96	-31.85	-65.82	
Turbo-1 DOHC	DOHC	Small	11	491.37		491.37	425.10
Downsize-1 DOHC	DOHC	Small	11	-34.42	-31.85	-66.27	
Turbo-1 DOHC	DOHC	Medium	11	491.37		491.37	237.65
Downsize-1 DOHC	DOHC	Medium	11	-221.87	-31.85	-253.73	
Turbo-1 DOHC	DOHC	Large	11	828.28		828.28	685.38
Downsize-1 DOHC	DOHC	Large	11	-111.05	-31.85	-142.90	
Turbo-1 OHV	OHV	Small	11	0.00		0.00	-31.85
Downsize-1 OHV	OHV	Small	11	0.00	-31.85	-31.85	
Turbo-1 OHV	OHV	Medium	11	491.37		491.37	787.91
Downsize-1 OHV	OHV	Medium	11	328.39	-31.85	296.54	
Turbo-1 OHV	OHV	Large	11	828.28		828.28	1,179.55
Downsize-1 OHV	OHV	Large	11	383.13	-31.85	351.27	

Table 5.192 Projected MY2017 and MY2025 Absolute Costs for Turbo and Turbo-Downsizing Technology

Technology	Engine Type	Displacement	Learning Factor	MY2017 Absolute Combined Tech Cost	MY2025 Absolute Combined Tech Cost
Turbo-1 SOHC	SOHC	Small	11	1,419.89	1,276.49
Downsize-1 SOHC	SOHC	Small	11		
Turbo-1 SOHC	SOHC	Medium	11	1,505.07	1,379.48
Downsize-1 SOHC	SOHC	Medium	11		
Turbo-1 SOHC	SOHC	Large	11	2,150.60	1,930.53
Downsize-1 SOHC	SOHC	Large	11		
Turbo-1 DOHC	DOHC	Small	11	1,419.89	1,276.49
Downsize-1 DOHC	DOHC	Small	11		
Turbo-1 DOHC	DOHC	Medium	11	1,426.50	1,312.63
Downsize-1 DOHC	DOHC	Medium	11		
Turbo-1 DOHC	DOHC	Large	11	2,059.99	1,853.45
Downsize-1 DOHC	DOHC	Large	11		
Turbo-1 OHV	OHV	Small	11	882.78	819.53
Downsize-1 OHV	OHV	Small	11		
Turbo-1 OHV	OHV	Medium	11	2,073.29	1,862.89
Downsize-1 OHV	OHV	Medium	11		
Turbo-1 OHV	OHV	Large	11	2,640.85	2,347.62
Downsize-1 OHV	OHV	Large	11		

5.4.1.3.3 *Other Advanced Gasoline Engine Technologies*

Table 5.193 Direct Manufacturing Costs and Learning Schedules for Advanced Engine Technologies

Technology	DMC (Small Displacement)	DMC (Medium Displacement)	DMC (Large Displacement)	Learning Schedule
SEGR	307.20	307.20	307.20	11
DWSP	54.93	54.93	54.93	11
TURBO2	9.89	221.91	374.05	11
CEGR1	255.59	255.59	255.59	11
CEGR1P	0.00	0.00	0.00	11
CEGR2	443.85	443.85	443.85	11
HCR2	28.19	28.19	28.19	11

Table 5.194 Projected MY2017 Incremental Costs for Advanced Gasoline Engine Technologies

Technology	4-Cylinder 1-Bank	4-Cylinder 2-Bank[FFFF]	6-Cylinder 1-Bank	6-Cylinder 2-Bank	8-Cylinder 2-Bank
SEGR	399.78	399.78	399.78	399.78	399.78
DWSP	71.48	71.48	71.48	71.48	71.48
TURBO2	196.81	196.81	288.78	288.78	486.79
CEGR1	332.62	332.62	332.62	332.62	332.62
CEGR1P	0.00	0.00	0.00	0.00	0.00
CEGR2	577.62	577.62	577.62	577.62	577.62
HCR2	36.69	36.69	36.69	36.69	36.69

Table 5.195 Projected MY2025 Incremental Costs for Advanced Gasoline Engine Technologies

Technology	4-Cylinder 1-Bank	4-Cylinder 2-Bank[GGGG]	6-Cylinder 1-Bank	6-Cylinder 2-Bank	8-Cylinder 2-Bank
SEGR	347.06	347.06	347.06	347.06	347.06
DWSP	62.05	62.05	62.05	62.05	62.05
TURBO2	170.86	170.86	250.70	250.70	422.59
CEGR1	288.76	288.76	288.76	288.76	288.76
CEGR1P	0.00	0.00	0.00	0.00	0.00
CEGR2	501.45	501.45	501.45	501.45	501.45
HCR2	31.85	31.85	31.85	31.85	31.85

[FFFF] Illustrative example for cost calculation purposes, only.
[GGGG] Illustrative example for cost calculation purposes, only.

Table 5.196 Projected MY2017 Absolute Costs for Advanced Gasoline Engine Technologies

Technology	4-Cylinder 1-Bank	4-Cylinder 2-Bank[HHHH]	6-Cylinder 1-Bank	6-Cylinder 2-Bank	8-Cylinder 2-Bank
SEGR	1,819.67	1,819.67	1,826.28	1,826.28	2,459.77
DWSP	1,891.16	1,891.16	1,897.76	1,897.76	2,531.25
TURBO2	2,087.97	2,087.97	2,186.54	2,186.54	3,018.04
CEGR1	2,420.59	2,420.59	2,519.17	2,519.17	3,350.67
CEGR1P	2,420.59	2,420.59	2,519.17	2,519.17	3,350.67
CEGR2	2,998.21	2,998.21	3,096.79	3,096.79	3,928.29
HCR2	3,034.91	3,034.91	3,133.48	3,133.48	3,964.98

Table 5.197 Projected MY2025 Absolute Costs for Advanced Gasoline Engine Technologies

Technology	4-Cylinder 1-Bank	4-Cylinder 2-Bank[IIII]	6-Cylinder 1-Bank	6-Cylinder 2-Bank	8-Cylinder 2-Bank
SEGR	1,623.55	1,623.55	1,659.69	1,659.69	2,200.51
DWSP	1,685.60	1,685.60	1,721.74	1,721.74	2,262.56
TURBO2	1,856.46	1,856.46	1,972.44	1,972.44	2,685.15
CEGR1	2,145.22	2,145.22	2,261.20	2,261.20	2,973.91
CEGR1P	2,145.22	2,145.22	2,261.20	2,261.20	2,973.91
CEGR2	2,646.67	2,646.67	2,762.65	2,762.65	3,475.36
HCR2	2,678.52	2,678.52	2,794.51	2,794.51	3,507.21

[HHHH] Illustrative example for cost calculation purposes, only.
[IIII] Illustrative example for cost calculation purposes, only.

5.4.1.3.4 Diesel Engine Costs

Table 5.198 Projected MY2017 Incremental Costs for Diesel Engines by Engine Type

Technology	4 Cylinder	6 Cylinder	8 Cylinder
ADSL	3977.96	4395.41	4425.70
TURBODSL	26.94	26.94	26.94
DWSPDSL	44.37	44.37	44.37
EFRDSL	101.41	152.12	152.12
CLCDSL	107.75	161.63	161.63
LPEGRDSL	210.75	263.04	263.04
DSIZEDSL	0.00	0.00	0.00

Table 5.199 Projected MY2025 Incremental Costs for Diesel Engines by Engine Type

Technology	4 Cylinder	6 Cylinder	8 Cylinder
ADSL	3192.32	3490.87	3474.76
TURBODSL	22.22	22.22	22.22
DWSPDSL	36.59	36.59	36.59
EFRDSL	83.64	125.46	125.46
CLCDSL	88.87	133.30	133.30
LPEGRDSL	173.81	216.94	216.94
DSIZEDSL	0.00	0.00	0.00

Table 5.200 Projected MY2017 Absolute Costs for Diesel Engines by Engine Type

Technology	4 Cylinder	6 Cylinder	8 Cylinder
ADSL	3977.96	4395.41	4425.70
TURBODSL	4004.90	4422.35	4452.64
DWSPDSL	4049.27	4466.72	4497.01
EFRDSL	4150.68	4618.84	4649.13
CLCDSL	4258.43	4780.47	4810.76
LPEGRDSL	4469.18	5043.51	5073.80
DSIZEDSL	4469.18	5043.51	5073.80

Table 5.201 Projected MY2025 Absolute Costs for Diesel Engines by Engine Type

Technology	4 Cylinder	6 Cylinder	8 Cylinder
ADSL	3192.32	3490.87	3474.76
TURBODSL	3214.53	3513.08	3496.98
DWSPDSL	3251.13	3549.67	3533.57
EFRDSL	3334.77	3675.13	3659.03
CLCDSL	3423.63	3808.43	3792.33
LPEGRDSL	3597.44	4025.37	4009.26
DSIZEDSL	3597.44	4025.37	4009.26

5.4.1.3.5 Transmission Costs

The transmission technology paths for manual and automatic transmissions are separate. Emerging advanced transmissions have learning schedules with greater opportunity for future cost reduction than the learning schedules for transmissions that have been widely used for many years.

Table 5.202 Direct Manufacturing Costs and Learning Schedules for Transmissions

Transmission	Direct manufacturing Cost	Learning Factor
MT5	0.00	12
MT6	247.42	12
MT7	239.10	11
AT5	0.00	12
AT6	-13.73	21
AT6P	0.00	21
AT8	82.18	11
AT8P	194.00	21
DCT6	32.75	21
DCT8	239.10	11
CVT	189.09	21

Table 5.203 Projected MY2017 Incremental Costs for Transmission Technologies by Vehicle Class

Transmission	SmallCar	MedCar	SmallSUV	MedSUV	Pickup
MT5	0.00	0.00	0.00	0.00	0.00
MT6	352.80	352.80	352.80	352.80	352.80
MT7	311.16	311.16	311.16	311.16	311.16
AT5	0.00	0.00	0.00	0.00	0.00
AT6	-6.87	-6.87	-6.87	-6.87	-6.87
AT6P	0.00	0.00	0.00	0.00	0.00
AT8	106.95	106.95	106.95	106.95	106.95
AT8P	291.00	291.00	291.00	291.00	291.00
DCT6	49.12	49.12	49.12	49.12	49.12
DCT8	311.16	311.16	311.16	311.16	311.16
CVT	283.64	283.64	283.64	283.64	283.64

Table 5.204 Projected MY2025 Incremental Costs for Transmission Technologies by Vehicle Class

Transmission	SmallCar	MedCar	SmallSUV	MedSUV	Pickup
MT5	0.00	0.00	0.00	0.00	0.00
MT6	300.15	300.15	300.15	300.15	300.15
MT7	264.72	264.72	264.72	264.72	264.72
AT5	0.00	0.00	0.00	0.00	0.00
AT6	-5.55	-5.55	-5.55	-5.55	-5.55
AT6P	0.00	0.00	0.00	0.00	0.00
AT8	90.99	90.99	90.99	90.99	90.99
AT8P	235.20	235.20	235.20	235.20	235.20
DCT6	39.70	39.70	39.70	39.70	39.70
DCT8	264.72	264.72	264.72	264.72	264.72
CVT	229.25	229.25	229.25	229.25	229.25

Table 5.205 Projected MY2017 Absolute Costs for Transmission Technologies by Vehicle Class

Transmission	SmallCar	MedCar	SmallSUV	MedSUV	Pickup
MT5	0.00	0.00	0.00	0.00	0.00
MT6	352.80	352.80	352.80	352.80	352.80
MT7	663.95	663.95	663.95	663.95	663.95
AT5	0.00	0.00	0.00	0.00	0.00
AT6	-6.87	-6.87	-6.87	-6.87	-6.87
AT6P	-6.87	-6.87	-6.87	-6.87	-6.87
AT8	100.08	100.08	100.08	100.08	100.08
AT8P	391.08	391.08	391.08	391.08	391.08
DCT6	49.12	49.12	49.12	49.12	49.12
DCT8	360.28	360.28	360.28	360.28	360.28
CVT	283.64	283.64	283.64	283.64	283.64

Table 5.206 Projected MY2025 Absolute Costs for Transmission Technologies by Vehicle Class

Transmission	SmallCar	MedCar	SmallSUV	MedSUV	Pickup
MT5	0.00	0.00	0.00	0.00	0.00
MT6	300.15	300.15	300.15	300.15	300.15
MT7	564.87	564.87	564.87	564.87	564.87
AT5	0.00	0.00	0.00	0.00	0.00
AT6	-5.55	-5.55	-5.55	-5.55	-5.55
AT6P	-5.55	-5.55	-5.55	-5.55	-5.55
AT8	85.44	85.44	85.44	85.44	85.44
AT8P	320.64	320.64	320.64	320.64	320.64
DCT6	39.70	39.70	39.70	39.70	39.70
DCT8	304.42	304.42	304.42	304.42	304.42
CVT	229.25	229.25	229.25	229.25	229.25

5.4.1.3.6 *Electric Vehicle and Accessory Costs*

Table 5.207 Direct Manufacturing Costs and Learning Schedules for Electric Vehicle and Accessory Systems by Vehicle Technology Class

Technology	Learning Factor	SmallCar	MedCar	SmallSUV	MedSUV	Pickup
EPS	12	95.86	95.86	95.86	95.86	95.86
IACC1	12	77.96	77.96	77.96	77.96	77.96
IACC2	12	48.12	48.12	48.12	48.12	48.12
SS12V	16	273.49	300.29	322.52	330.44	373.60
BISG	24	1,013.00	1,013.00	1,013.00	1,162.72	1,277.30
CISG	18	2,121.23	2,684.29	2,695.91	3,293.83	3,293.83
SHEVP2						
SHEVP2_battery	24	783.27	1,015.74	843.17	938.71	1,089.51
SHEVP2_non-battery	11	1,799.26	2,378.46	1,936.34	2,217.03	2,339.96
SHEVPS						
SHEVPS_battery	24	783.27	1,015.74	843.17	938.71	1,089.51
SHEVPS_non-battery	11	1,799.26	2,378.46	1,936.34	2,217.03	2,339.96
PHEV30						
PHEV30_battery	19	3,365.03	5,330.99	3,894.70	5,330.99	5,330.99
PHEV30_non-battery	11	3,156.00	5,716.96	3,656.28	5,716.96	5,716.96
PHEV30_C	19	177.50	177.50	177.50	177.50	177.50
CHRG_L	6	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00
PHEV50						
PHEV50_battery	19	4,594.74	7,838.02	5,408.55	7,838.02	7,838.02
PHEV50_non-battery	11	3,156.00	5,716.96	3,656.28	5,716.96	5,716.96
PHEV50_C	19	195.68	195.68	195.68	195.68	195.68
CHRG_L	6	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00
EV200						
EV200_battery	19	8,733.63	12,048.97	10,741.72	12,048.97	12,048.97
EV200_non-battery	21	406.34	2,214.28	132.17	2,214.28	2,214.28
EV_C	19	213.86	213.86	213.86	213.86	213.86
CHRG_L	6	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00
FCV	26	15,566.29	15,566.29	15,566.29	15,566.29	15,566.29

Table 5.208 Projected MY2017 Incremental Costs for Electric Vehicle and Accessory Systems by Vehicle Class

Technology	SmallCar	MedCar	SmallSUV	MedSUV	Pickup
EPS	136.69	136.69	136.69	136.69	136.69
IACC1	111.17	111.17	111.17	111.17	111.17
IACC2	68.61	68.61	68.61	68.61	68.61
SS12V	397.93	436.92	469.27	480.79	543.59
BISG	805.10	766.12	733.77	946.82	1,055.89
CISG	2,467.45	3,273.05	3,258.13	4,143.48	4,080.68
SHEVP2	1,996.92	3,099.39	2,265.16	2,549.19	2,763.50
SHEVPS	334.57	592.45	-259.20	-647.47	-261.29
PHEV30	12,469.24	20,459.21	14,403.82	20,784.83	20,398.65
PHEV50	5,675.96	9,418.11	6,508.38	9,418.11	9,418.11
EV200	10,754.55	10,344.76	13,191.12	10,344.76	10,344.76
FCV	7,999.51	-4,835.07	4,964.27	-4,835.07	-4,835.07

Table 5.209 Projected MY2025 Incremental Costs for Electric Vehicle and Accessory Systems by Vehicle Class

Technology	SmallCar	MedCar	SmallSUV	MedSUV	Pickup
EPS	116.29	116.29	116.29	116.29	116.29
IACC1	94.58	94.58	94.58	94.58	94.58
IACC2	58.37	58.37	58.37	58.37	58.37
SS12V	311.88	342.43	367.79	376.82	426.04
BISG	609.78	579.23	553.88	720.86	806.34
CISG	1,335.51	1,813.71	1,798.85	2,330.06	2,280.85
SHEVP2	1,722.00	2,636.57	1,944.19	2,191.27	2,369.96
SHEVPS	996.27	1,402.09	699.21	582.07	895.45
PHEV30	7,395.11	12,264.90	8,521.32	12,534.18	12,220.79
PHEV50	3,638.09	5,554.07	4,064.29	5,554.07	5,554.07
EV200	5,027.54	4,492.06	5,932.68	4,492.06	4,492.06
FCV	10,056.47	2,356.14	8,281.87	2,356.14	2,356.14

Table 5.210 Projected MY2017 Absolute Costs for Electric Vehicle and Accessory Systems by Vehicle Class

Technology	SmallCar	MedCar	SmallSUV	MedSUV	Pickup
EPS	136.69	136.69	136.69	136.69	136.69
IACC1	247.85	247.85	247.85	247.85	247.85
IACC2	316.46	316.46	316.46	316.46	316.46
SS12V	714.40	753.38	785.73	797.26	860.06
BISG	1,519.50	1,519.50	1,519.50	1,744.08	1,915.95
CISG	3,181.85	4,026.44	4,043.87	4,940.74	4,940.74
SHEVP2	3,516.42	4,618.89	3,784.66	4,293.27	4,679.45
SHEVPS	3,516.42	4,618.89	3,784.66	4,293.27	4,679.45
PHEV30	15,985.66	25,078.10	18,188.48	25,078.10	25,078.10
PHEV50	21,661.62	34,496.20	24,696.86	34,496.20	34,496.20
EV200	32,416.17	44,840.97	37,887.98	44,840.97	44,840.97
FCV	40,415.68	40,005.89	42,852.25	40,005.89	40,005.89

Table 5.211 Projected MY2025 Absolute Costs for Electric Vehicle and Accessory Systems by Vehicle Class

Technology	SmallCar	MedCar	SmallSUV	MedSUV	Pickup
EPS	116.29	116.29	116.29	116.29	116.29
IACC1	210.86	210.86	210.86	210.86	210.86
IACC2	269.24	269.24	269.24	269.24	269.24
SS12V	581.11	611.67	637.02	646.06	695.27
BISG	1,190.90	1,190.90	1,190.90	1,366.91	1,501.61
CISG	1,916.63	2,425.38	2,435.88	2,976.12	2,976.12
SHEVP2	2,912.90	3,827.47	3,135.09	3,558.19	3,871.57
SHEVPS	2,912.90	3,827.47	3,135.09	3,558.19	3,871.57
PHEV30	10,308.01	16,092.36	11,656.41	16,092.36	16,092.36
PHEV50	13,946.10	21,646.43	15,720.70	21,646.43	21,646.43
EV200	18,973.64	26,138.49	21,653.38	26,138.49	26,138.49
FCV	29,030.11	28,494.63	29,935.25	28,494.63	28,494.63

5.4.1.3.7 *Vehicle Technology Costs*

Table 5.212 Direct Manufacturing Costs and Learning Schedules for Vehicle Technologies

Technology	Direct Manufacturing Costs	Learning Factor
ROLL10	5.64	6
ROLL20	42.77	25
LDB	62.03	6
SAX	85.57	12
AERO10	42.86	12
AERO20	128.57	12
MR1	Refer to and Table 5.176 in the previous Mass Reduction section of the CAFE technology assessment. Also, refer to Figure 5.144 and Table 5.178.	21
MR2		21
MR3		21
MR4		21
MR5		21

Table 5.213 Projected MY2017 Incremental Costs for Vehicle Technologies

Technology	SmallCar	MedCar	SmallSUV	MedSUV	Pickup
ROLL1	8.46	8.46	8.46	8.46	8.46
ROLL2	100.25	100.25	100.25	100.25	100.25
LDB	93.04	93.04	93.04	93.04	93.04
SAX	122.01	122.01	122.01	122.01	122.01
AERO1	61.11	61.11	61.11	61.11	61.11
AERO2	183.32	183.32	183.32	183.32	183.32

Table 5.214 Projected MY2025 Incremental Costs for Vehicle Technologies

Technology	SmallCar	MedCar	SmallSUV	MedSUV	Pickup
ROLL10	8.46	8.46	8.46	8.46	8.46
ROLL20	56.80	56.80	56.80	56.80	56.80
LDB	93.04	93.04	93.04	93.04	93.04
SAX	103.80	103.80	103.80	103.80	103.80
AERO10	51.99	51.99	51.99	51.99	51.99
AERO20	155.96	155.96	155.96	155.96	155.96

Table 5.215 Projected MY2017 Absolute Costs for Vehicle Technologies

Technology	SmallCar	MedCar	SmallSUV	MedSUV	Pickup
ROLL10	8.46	8.46	8.46	8.46	8.46
ROLL20	108.70	108.70	108.70	108.70	108.70
LDB	93.04	93.04	93.04	93.04	93.04
SAX	122.01	122.01	122.01	122.01	122.01
AERO10	61.11	61.11	61.11	61.11	61.11
AERO20	244.43	244.43	244.43	244.43	244.43

Table 5.216 Projected MY2025 Absolute Costs for Vehicle Technologies

Technology	SmallCar	MedCar	SmallSUV	MedSUV	Pickup
ROLL10	8.46	8.46	8.46	8.46	8.46
ROLL20	65.26	65.26	65.26	65.26	65.26
LDB	93.04	93.04	93.04	93.04	93.04
SAX	103.80	103.80	103.80	103.80	103.80
AERO10	51.99	51.99	51.99	51.99	51.99
AERO20	207.95	207.95	207.95	207.95	207.95

5.4.2 Technology Effectiveness Modeling Method and Data Used in CAFE Assessment

This section provides an overview of Argonne National Laboratory simulation modeling conducted to estimate energy consumption reductions from combinations of light-duty powertrain and vehicle technologies. The modeling work was conducted under contract to NHTSA and provides inputs to DOT Volpe's CAFE Compliance and Effects Modeling System (commonly referred to as the Volpe Model) for light- and medium-duty vehicles.[602,603.] The section provides a description of baseline vehicles, model validation, technology assumptions, and methodology.

For this TAR, NHTSA is employing a world recognized full vehicle simulation model Autonomie developed by Argonne National Laboratory over the past 15 years under funding from the US DOE Vehicle Technologies Office. Autonomie has been developed and validated over a very wide range of powertrain configurations and component technologies leveraging vehicle test data from Argonne Advanced Powertrain Research Facility (APRF) and component performance data from the US National Laboratories, including Oak Ridge National Laboratory (ORNL), Idaho National Laboratory (INL) and the National Renewable National Laboratory (NREL). Using Autonomie will not only improve the transparency of the process, but also increase the robustness of the process by simulating every single combination of individual technologies. Input data for Autonomie has been created through a combination of benchmarking activities and high fidelity component modeling. Benchmarking is a commonly used technique that is intended to create a detailed characterization of a vehicle's operation and performance.

5.4.2.1 Volpe Model Background

The Volpe model combines technologies in sequence dictated by what are referred to as "decision trees." In the model there are seven vehicle classes and eight decision trees for each class. The decision trees include the following sub-systems: engine; transmission; powertrain electrification; hybridization; light-weighting; aerodynamics; rolling resistance; and dynamic load reduction. Each of the sub-systems is evaluated independently of each other, starting with the top-most technology and progressing down the decision tree. Figure 5.147 shows the decision trees for basic engine and transmission technologies.

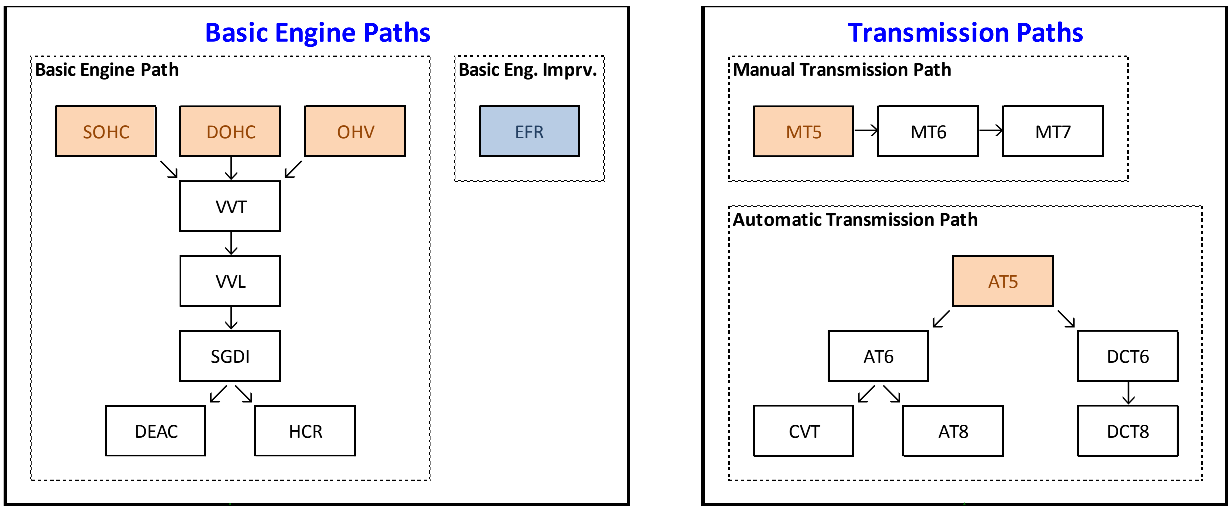


Figure 5.147 Volpe Model Engine and Transmission Decision Trees

In past rulemakings, the model relied on estimates of synergies between technologies, recognizing that multiple technologies can address the same inefficiency. An example of this is a combination of variable valve timing, cylinder deactivation, and 6-speed automatic transmission technologies. For a specific vehicle platform, each technology individually offers a reduction in energy consumption. However, when modeled in combination, the package provides a reduction that is somewhat less than the sum of the individual technology benefits. The reason for this is that each of the three technologies reduces a portion of the throttling loss encountered at part loads. When a portion of the loss has been addressed by a technology, the loss has been eliminated and cannot be reduced by another technology. In some cases, combining technologies may produce fuel savings that are greater than the sum of the savings from the two technologies – or positive synergies. The synergy factor used previously in the Volpe model estimated the extent to which combinations of technologies result in less than additive (negative synergies) or more than additive (positive synergies) energy consumption savings. Synergy factors used in the Volpe model for prior rulemakings were based on engineering judgement of the impact on energy consumption from the combination of technologies.

To more accurately estimate the impact on light-duty energy consumption of combined powertrain and vehicle technologies in the Volpe model, NHTSA contracted with Argonne National Laboratory to simulate powertrain and vehicle technology combinations as shown in Figure 2. Modeling conducted for the light-duty MTE Draft TAR is the first time the results of the Argonne simulation results have been used directly in the Volpe model.

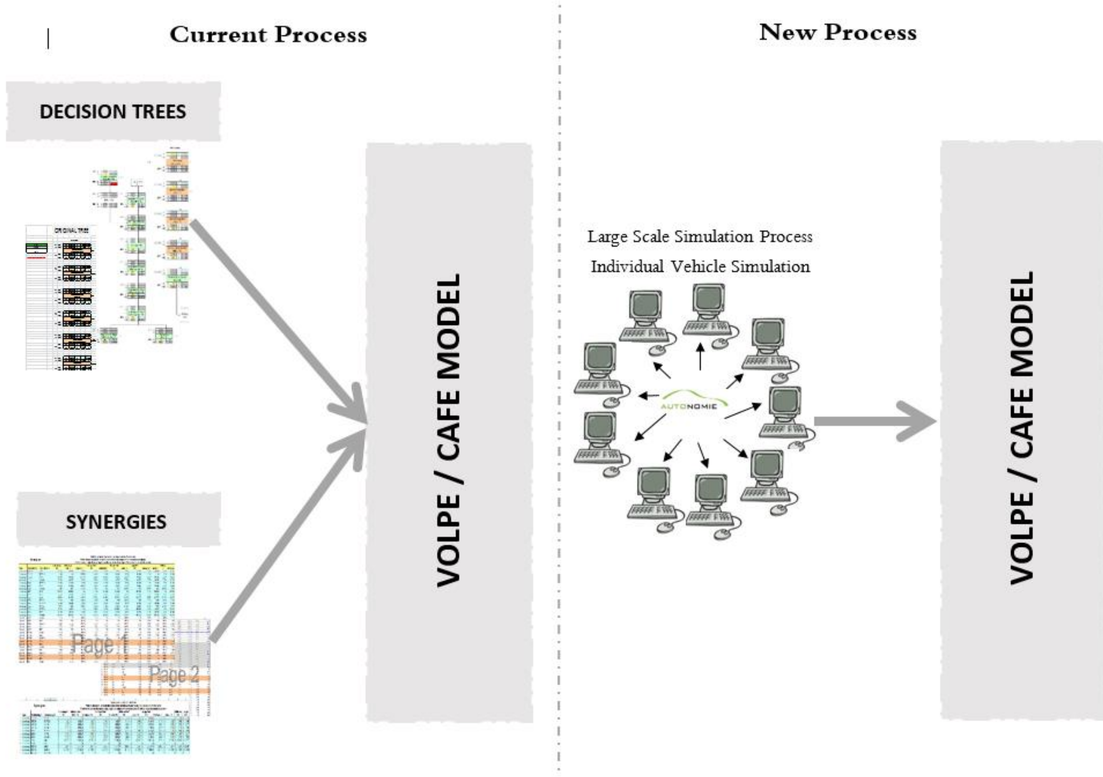


Figure 5.148 Model Input - Replacing Decision Trees and Synergies with Individual Simulations

This new process allow NHTSA to directly use Autonomie vehicle system simulation results as input to the Volpe model. The process workflow can be summarized as shown below:

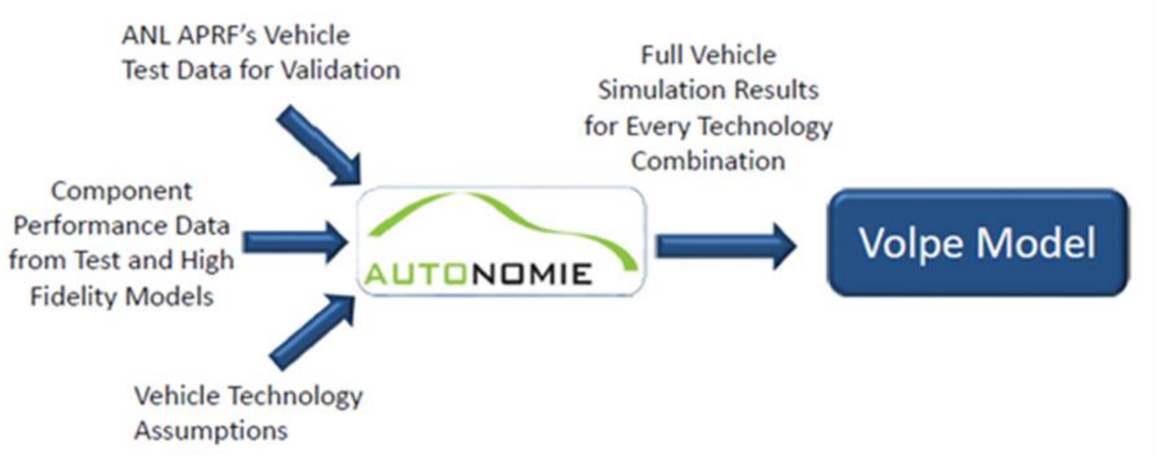


Figure 5.149 Autonomie Directly Feeds the Volpe Model

5.4.2.2 Autonomie Vehicle Simulation Tool

5.4.2.2.1 Overview

Many of today's automotive control-system simulation tools are suitable for modeling, but they provide rather limited support for model building and management. Setting up a simulation model requires more than writing down state equations and running them on a computer. With the introduction of EDVs, the number of components that can populate a vehicle has increased considerably, and more components translate into more possible drivetrain configurations and powertrain control options. In addition, building hardware is expensive. Traditional design paradigms in the automotive industry often delay control-system design until late in the process—in some cases requiring several costly hardware iterations. To reduce costs and improve time to market, it is imperative that greater emphasis be placed on modeling and simulation. This only becomes truer as time goes on because of the increasing complexity of vehicles and the greater number of vehicle configurations.

With the large number of possible advanced vehicle architectures and time and cost constraints, it is impossible to manually build every powertrain configuration model. As a result, processes have to be automated.

Autonomie is a MATLAB©-based software environment and framework for automotive control-system design, simulation, and analysis.[604] The tool is designed for rapid and easy integration of models with varying levels of detail (low to high fidelity) and abstraction (from subsystems to systems and entire architectures), as well as processes (e.g., calibration, validation). Developed by Argonne National Laboratory (ANL) in collaboration with General Motors, Autonomie was designed to serve as a single tool that can be used to meet the requirements of automotive engineering throughout the development process from modeling to control. Autonomie was built to accomplish the following:

- Support proper methods, from model-in-the-loop, software-in-the-loop, and hardware-in-the-loop to rapid-control prototyping;
- Integrate math-based engineering activities through all stages of development, from feasibility studies to production release;
- Promote re-use and exchange of models industry-wide through its modeling architecture and framework;
- Support users' customization of the entire software package, including system architecture, processes, and post-processing;
- Mix and match models of different levels of abstraction for execution efficiency with higher-fidelity models where analysis and high-detail understanding are critical;
- Link with commercial off-the-shelf software applications, including GT-Power©, AMESim©, and CarSim©, for detailed, physically based models;
- Provide configuration and database management.

By building models automatically, Autonomie allows the quick simulation of a very large number of component technologies and powertrain configurations. Autonomie can do the following:

- Simulate subsystems, systems, or entire vehicles;

- Predict and analyze fuel efficiency and performance;
- Perform analyses and tests for virtual calibration, verification, and validation of hardware models and algorithms;
- Support system hardware and software requirements;
- Link to optimization algorithms; and
- Supply libraries of models for propulsion architectures of conventional powertrains as well as EDVs.

Autonomie was used to assess the energy consumption of advanced powertrain technologies. Autonomie has been validated for several powertrain configurations and vehicle classes using Argonne's Advanced Powertrain Research Facility vehicle test data.[605]

With more than 400 different pre-defined powertrain configurations, Autonomie is an ideal tool for analyzing the advantages and drawbacks of the different options within each family, including conventional, parallel, series, and power-split HEVs. Various approaches have been used in previous studies to compare options ranging from global optimization to rule based control.[606]

Autonomie also allows users to evaluate the impact of component sizing on fuel consumption for different powertrain technologies as well as to define the component requirements (e.g., power, energy) to maximize fuel displacement for a specific application.[607] To properly evaluate any powertrain-configuration or component-sizing impact, the vehicle-level control is critical, especially for EDVs. Argonne has extensive expertise in developing vehicle-level controls based on different approaches, from global optimization to instantaneous optimization, rule-based optimization, and heuristic optimization.[608]

The ability to simulate a large number of powertrain configurations, component technologies, and vehicle-level controls over numerous drive cycles has been used to support many DOE and manufacturer studies. These studies focused on fuel efficiency, cost-benefit analysis, or greenhouse gases.[609] All the development performed in simulation can then be implemented in hardware to take into account non-modeled parameters, such as emissions and temperature.[610]

Autonomie is the primary vehicle simulation tool selected by DOE to support its U.S. DRIVE Program and Vehicle Technologies Office (VTO). Autonomie has been used for numerous studies to provide the U.S. government with guidance for future research.[611]

The vehicle models in Autonomie are developed under in Matlab/Simulink/Stateflow and are open for users to view and modify any equation or algorithm. Several hundreds of powertrain configurations and more than 100 full vehicle models including controls are included in the tool. Figure 5.150 shows the high level vehicle organization.

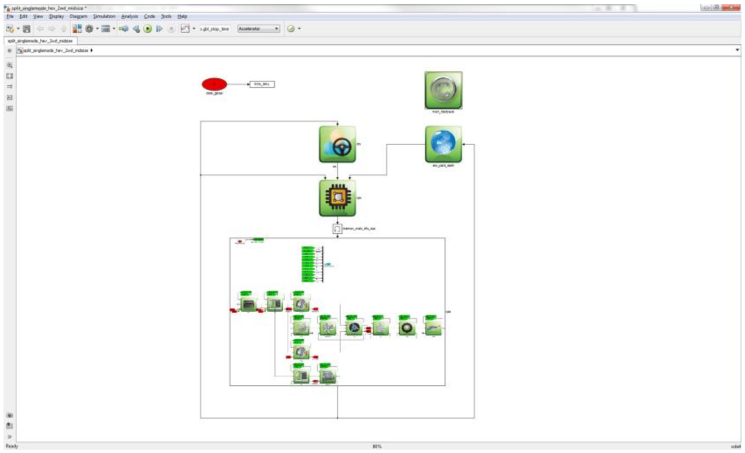


Figure 5.150 Autonomie Vehicle Model Organization

The following section will describe the plant models and controllers.

5.4.2.2.2 Plant Model Overview

5.4.2.2.2.1 Internal Combustion Engine Model

All Autonomie engine models use performance maps to predict fuel rate, operating temperature and, in some cases when maps are available, emissions. The output torque of the engine is computed from the engine controller command which takes a percentage of the spread between the maximum engine torque map and the minimum engine torque map. These maps are based on two sources: from test data which are measured from engines running at steady state points on an engine dyno or from high fidelity engine models such as GTPower. These GT Power engine maps can incorporate technologies such as GDI, VVL, VVT, camless and other advanced engine technologies. In addition, to these performance maps, the engine models also include a single time constant to represent the transient response of the engine output torque to the engine command.

However, some engine models use specific logic to represent some specific technology or fuels. For example, Autonomie uses a specific model for spark ignition engine with a turbo charger. The maps for turbo technologies were developed using GT-POWER©. With turbo engines, there is a ‘lag’ in torque delivery due to the operation of the turbo charger. This impacts vehicle performance, as well as the vehicle shifting on aggressive cycles. Turbo lag has been modelled for the turbo systems based on principles of a first order delay, where the turbo lag kicks in after the naturally aspirated torque limit of the turbo engines has been reached. The figure below shows the response of the turbo engine model for a step command.

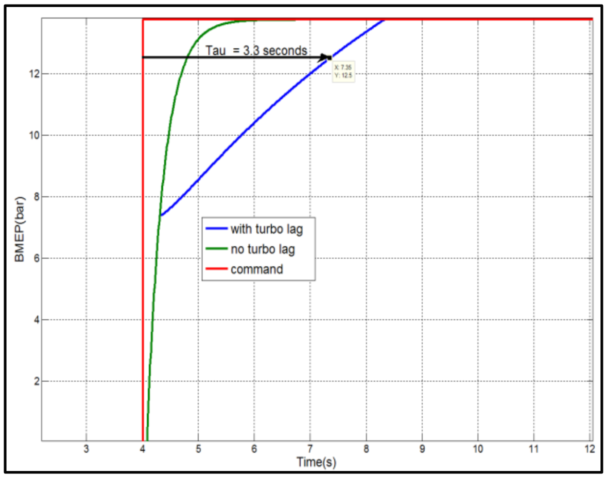


Figure 5.151 Turbo-charged Engine Response for a 1L Engine

It should be noted that the turbo response changes with engine speed (i.e., at higher speeds, the turbo response is faster due to higher exhaust flow rates).

Autonomie also uses a specific engine model for cylinder deactivation, as this model has a more advanced fuel calculation subsystem which includes different maps. Due to NVH considerations in production vehicles, cylinder deactivation operation is not performed during several vehicle operation modes, like vehicle warm-up, lower gear operation, idle, and low engine speed. In order to provide a realistic evaluation of the benefits of cylinder deactivation technology, cylinder deactivation is not been used under the following vehicle and engine conditions:

- Cylinder deactivation is disabled if the engine is at idle or any speed below 1000 RPM or above 3000 RPM.
- Cylinder deactivation is disabled if the vehicle is in the 1st of the 2nd gear.
- Cylinder deactivation is disabled if the engine load is above half the max BMEP of the engine (and a certain hysteresis is maintained to prevent constant activation and deactivation).

Typically, cylinder deactivation is not performed during the vehicle warm up phase, i.e. for a cold start. Since all the simulations considered in this study assume a ‘hot start’, where in the engine coolant temperature is steady around 95 degrees C, the cold start condition was not a factor for the simulations. In addition, changes in the transmission shifting calibration (like lugging speed limits) and additional torque converter slippage during cylinder deactivation have also been disregarded.

Autonomie also has a separate engine model for the spark ignition engine with fuel cut off. This engine has a specific torque calculation to calculate the engine torque loss when the engine fuel is cut off during deceleration events. In general, engine models in Autonomie are of two types, throttled engines and un-throttled engines. As shown in the figure below, both types of models provide motoring torque when fuel is cut to the engine (e.g. fuel cut off during deceleration). With throttled engines, the motoring torque is a function of throttle position.

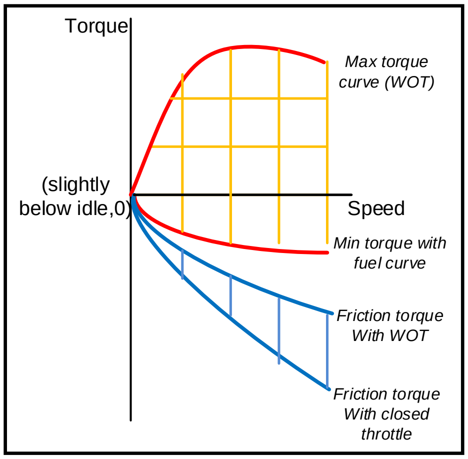


Figure 5.152 Engine Operating Regions for Throttled Engines

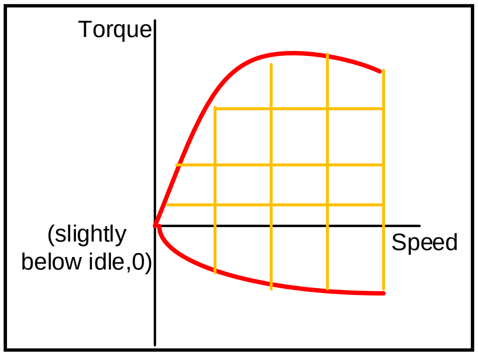


Figure 5.153 Engine Operating Regions for Un-throttled Engines

5.4.2.2.2.2 Transmission Models

Automatic Gearbox Model

The gearbox model allows for torque multiplication and speed division based on the gear number command from the powertrain controller. As for all the other models, the losses are taken into account using torque losses to easily deal with regenerative conditions.

Figure 5.154 Automatic Gearbox Model Input / Output

The drivetrain is considered rigidly attached to the wheels. Since the wheel speed and acceleration are calculated in the wheel model and propagated backward throughout the rest of the drivetrain model, the gearbox unit is modeled as a sequence of mechanical torque gains. The torque and speed are multiplied and divided, respectively, by the current ratio for the selected gear. Furthermore, torque losses corresponding to the torque/speed operating point are subtracted from the torque input. Torque losses are defined on the basis of a three-dimensional efficiency lookup table that has as inputs input shaft rotational speed, input shaft torque, and gear number.

When a gear is selected, the input inertia is fed forward to the next component after being reflected to the output shaft using the square of the gear ratio. When the neutral gear is engaged, the input gearbox rotational speed is calculated on the basis of the input shaft inertia.

Since this is an automatic gearbox model, it can be shifted in sequence from one gear to another without having to pass through neutral and without a complete torque interruption at its output. The torque passing through the transmission during shifting is reduced, but does not go to zero as it does for a manual gearbox. Also, the torque converter model is separate from the automatic gearbox model.

Dual Clutch Transmission

Dynamic models of the dual-clutch transmission are obtained including the clutch and gear-train, but no synchronizer dynamics. Figure 5.155 illustrates an example of DCT system that can be considered as a combination of two manual transmissions, with one providing odd gears connected to clutch1, and the other providing even gears connected to clutch2. With alternating control of the two clutches, the oncoming clutch engages and the off-going clutch releases to complete the shift process without torque interruption. It is necessary to preselect the gears to realize the benefits of the DCT system. The different plant models and controls have been validated using vehicle test data.

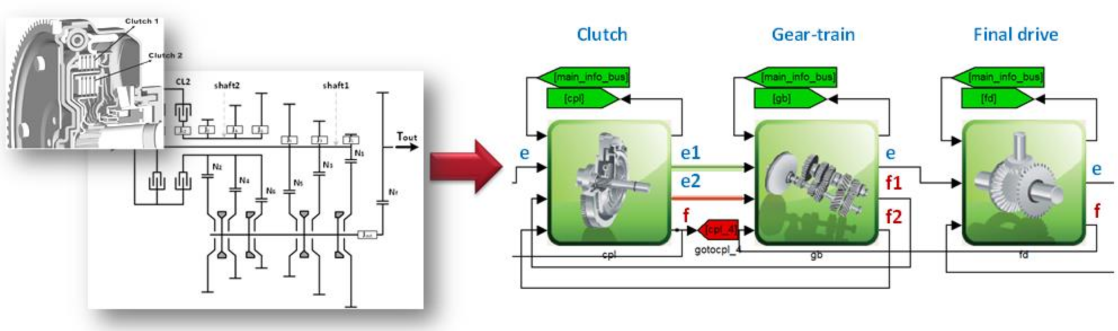


Figure 5.155 Dual Clutch Gearbox Model Input / Output

The pre-selection of gears can be implemented by considering the operating conditions of the DCT system. For example, if the first synchronizer is at the first-gear position, and the third through fifth synchronizers are at the neutral position (as they must be), then the gear ratio between shaft1 and the output shaft is first gear. At same time, the gear ratio between shaft2 and the output shaft can be selected in the same manner for the pre-selection mode. To achieve a desired input-output gear ratio, the corresponding synchronizer and clutch have to be applied.

Continuously Variable Transmission

A metal V-belt CVT model is considering hydraulic and mechanical loss. The hydraulic loss constitutes the majority of the total loss at low vehicle speed, whereas the mechanical loss is the main source of inefficiency at high speed. The operating conditions of the metal V-belt CVT system can be described by the following five parameters:

1) Primary clamping force (FP) or primary pressure (PP);
2) Secondary clamping force (FS) or secondary pressure (PS);
3) Primary revolution speed (ω_P);
4) Input torque (TIN); and
5) Pulley ratio (i).

On both the primary and the secondary pulleys, the belt is clamped by the forces produced by the hydraulic pressures in the cylinders. These two clamping forces, FP and Fs, counteract each other. Therefore, when the pulley ratio is constant, there is a balance between FP and FS. A ratio change occurs when their balance is lost.

In addition, CVT ratio control and clamping force control strategies, including the CVT shift dynamics, were developed. The following are considered in the low-level controller:

- The demanded CVT ratio is determined from the engine OOL;
- The secondary pressure is determined for the given input torque and CVT ratio; and
- The primary pressure is controlled to meet the demanded CVT ratio.

Figure 5.156 shows a block diagram of the model-based ratio control and plant.

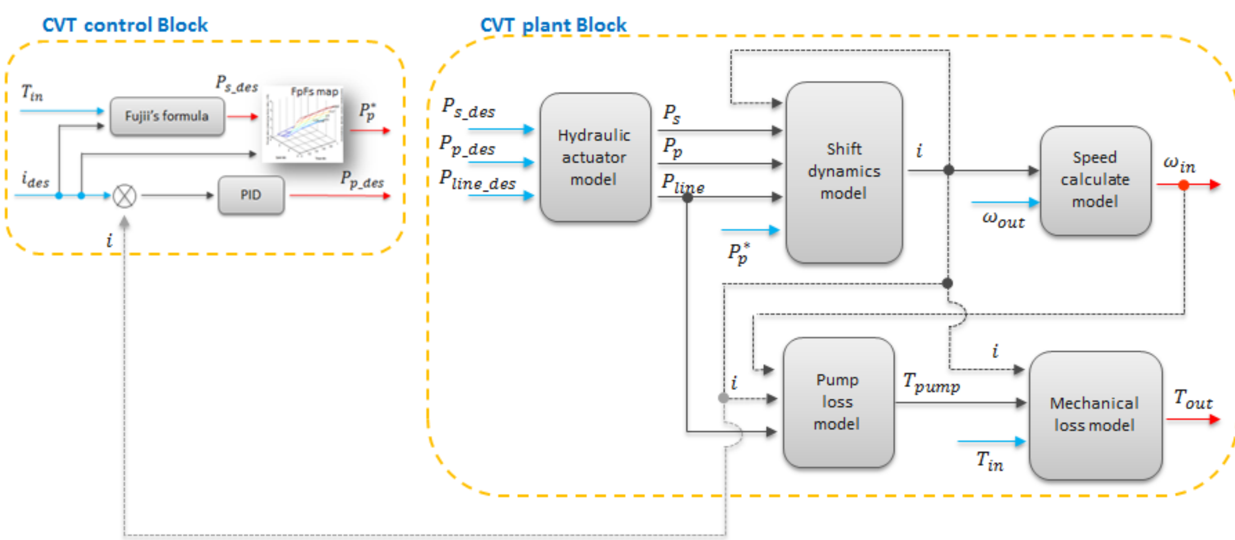


Figure 5.156 CVT Model Block Diagram

Torque Converter

The torque converter is modeled as two separate rigid bodies when the coupling is unlocked and as one rigid body when the coupling is locked. The downstream portion of the torque converter unit is treated as being rigidly connected to the drivetrain. Therefore, there is only one degree of dynamic freedom, and the model has only one integrator.

The effective inertias are propagated downstream until the point where actual integration takes place. When the coupling is unlocked, the engine inertia is propagated up to the coupling input, where it is used for calculating the rate of change of the input speed of the coupling. When the coupling is locked, the engine inertia is propagated all the way to the wheels.

The torque converter model is based on a lookup table, which determines the output torque depending on the lockup command. The upstream acceleration during slip and the downstream acceleration are taken into account in calculating the output speed.

5.4.2.2.2.3 Electric Machine Models

Electric machine plant models in Autonomie can take in Torque or Power as the command and produce a Torque output. Operating speed of the motor is determined by the components connected to the motor. In a vehicle, the vehicle speed and gear ratios determine the operating speed of the motor.

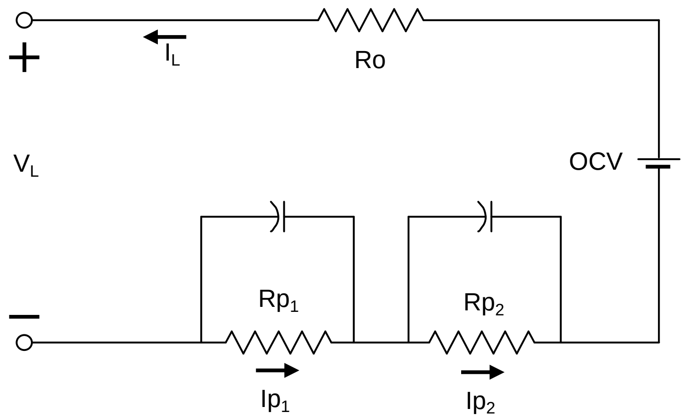
The lookup table used in a motor model estimates the operational losses over the entire operating region of the motor. This map is typically derived from the efficiency map provided in the initialization file.

Typically, every motor has a continuous operating region (region under the continuous torque curve as shown in figure), and a transient region where the motor can operate for a short period of time (peak torque capability of a motor is defined for a specific duration, e.g. 30s). The maximum torque output gets de-rated to the continuous torque levels, when the electric machine temperature increases. The electric machine model in Autonomie has this general logic built into it.

Autonomie provides a logic to scale an existing motor to a different power rating. The shape of the efficiency map is kept the same, but the torque axis is scaled to meet the desired power rating.

5.4.2.2.2.4 Energy Storage Models

Autonomie includes several energy storage models depending on the application (i.e. high power, high energy). The default battery model is a charge reservoir and an equivalent circuit whose parameters are a function of the remaining charge in the reservoir, also known as the state of charge (SOC). The equivalent circuit accounts for the circuit parameters of the battery pack as if it were a perfect open circuit voltage source in series with an internal resistance. Another battery model in Autonomie is the one used for high energy batteries. The equations and schematic of this type of battery is shown in Figure 5.157. This model uses two time constants to represent the polarization behavior of the battery pack. This lumped parameter model can represent many different battery chemistries for the internal resistances, capacitances and open circuit voltage are all maps based on SOC and, in some cases, temperature.



Equation (1) $1000*(OCV-V_L)/I_L = R = Ro+Rp_1*Ip_1/I_L+Rp_2*Ip_2/I_L$

Where,
OCV = open circuit voltage, V
V_L = cell voltage, V
R = total cell impedance, milliohms
Ro = cell internal ohmic resistance, milliohms
Rp_1 = first internal polarization resistance, milliohms
Rp_2 = second internal polarization resistance, milliohms
I_L = cell load current, A
Ip_1 = current through first polarization resistance, A
Ip_2 = current through second polarization resistance, A

Figure 5.157 High Energy Battery Model Schematic

Another important aspect to consider for sizing is the pulse power limits of the battery pack. There are several different options to represent the maximum power of the battery in Autonomie. The most basic represents maximum power as a function of SOC. Other models introduce a time constraint for the maximum power. These battery packs have different power limits for 10 second, 2 second and continuous power. The Autonomie model accounts for the duration of the pulse and limits the power accordingly. This aspect is not necessary a feature of the plant, but is handled by the low level control and is dependent on the battery chemistry and plant's performance characteristics.

5.4.2.2.2.5 Chassis Models

The chassis plant model in Autonomie translates the force from wheel to vehicle acceleration and linear speed. The losses related to moving the vehicle is estimated in this model. Two types of initialization data can be used for estimating this behavior.

- Coefficients derived from a coast down test. The losses estimated from these coefficients will cover both rolling resistance & aero dynamic losses. Dyno set values for nearly every vehicle is available from EPA.
- Values for coefficient of drag, frontal area, rolling resistance of tires etc.

The model based on coast down is used for validation purposes while the model based on the aerodynamic equations is used to predict the impact of non-existing vehicles

5.4.2.2.2.6 Tire Models

Just as the two chassis models, there are two wheel models corresponding to each of the chassis models. The initialization data for the wheel rolling resistance can be provided by the user in many ways. Wheel radius can be provided by the user, or this could be computed by Autonomie from a sidewall label of the tire e.g. P225/50/R17. The tire losses model uses a constant and a speed term to represent the losses.

5.4.2.2.2.7 Auxiliaries Model

Most powertrains in Autonomie have two accessory models. The mechanical accessories driven by the engine through a belt and the electrical accessories connected to the lower voltage bus.

The main electrical accessory model in Autonomie is a constant power draw. If the vehicle has a high voltage bus, a step down power conditioner is connected between the high voltage bus and low voltage bus to supply the electrical accessories. When a vehicle contains thermal models, a current draw is added to represent the electrical power draw of the cooling fans.

5.4.2.2.2.8 Driver Models

Autonomie uses a look-ahead driver to better approximate the behavior of a real driver. Forward looking models are especially sensitive to how well the driver follows the trace and how aggressive the driver is in doing so. Both of these factors can noticeably affect fuel economy results when simulating advanced vehicles. For example, a driver which is too aggressive can add additional engine on events for a hybrid or delay transmission shifts for a conventional, both of these events lower fuel economy. For this reason, Autonomie employs a look ahead driver, which at its core, is a PI controller with a feedforward part that, in addition, uses time advanced copies of the trace to replicate the ability of a human driver to look a few seconds ahead on the driver's aid to anticipate accelerations and decelerations. The result is a smoothing of the pedal demand from the driver, which leads to an overall more representative fuel economy. The added complexity yields several additional dimensions of tuning to the model, for the relative weightings of the time advanced copies have to be optimized.

The driver model also uses an additional layer of logic to manage the accelerator pedal demand, specifically, during shift events when the engine is disconnected from the wheels. On a manual transmission, during the shift through neutral, the driver must be capable of expecting a decrease in vehicle speed and not aggressively stomp on the accelerator pedal in an attempt to compensate for the decrease in vehicle speed.

5.4.2.2.2.9 Environment Models

The environment model in Autonomie outputs all of the relative information about the operating environment of a vehicle during a simulation such as ambient temperature, ambient pressure, relative humidity, air density and grade. There are two versions of the environment model in Autonomie, one for which the grade is a function of time, such as would be encountered on a chassis dynamometer test which follows a preset grade schedule, and the other for which the grade is a function of distance as when following a mapped route.

5.4.2.2.3 *Control Overview*

All the vehicle-level control algorithms used in the study were developed on the basis of vehicle test data collected at Argonne's Advanced Powertrain Research Facility. It is important to note that while the logic for the vehicle-level control algorithms were developed on the basis of test data, only the logic has been used for the present study, since the calibration parameters have been adapted for each vehicle to ensure energy consumption minimization with acceptable drive quality (i.e., number of engine on/off conditions, and shifting events).

5.4.2.2.3.1 *Transmission Shifting Algorithm*

The transmission shifting logic has a significant impact on vehicle fuel economy and should be carefully designed to maximize the powertrain efficiency while maintaining acceptable drive quality. The logic used in the simulated conventional light-duty vehicle models relies on two components: (1) the shifting controller, which provides the logic to select the appropriate gear during the simulation; and (2) the shifting initializer, the algorithm that defines the shifting maps (i.e., values of the parameters of the shifting controller) specific to a selected set of component assumptions.

Shifting Controller

The shifting controller determines the appropriate gear command at each simulation step. A simplified schematic of the controller is shown in Figure 5.158. The letters and numbers in the discussion that follows correspond to those shown in the figure.

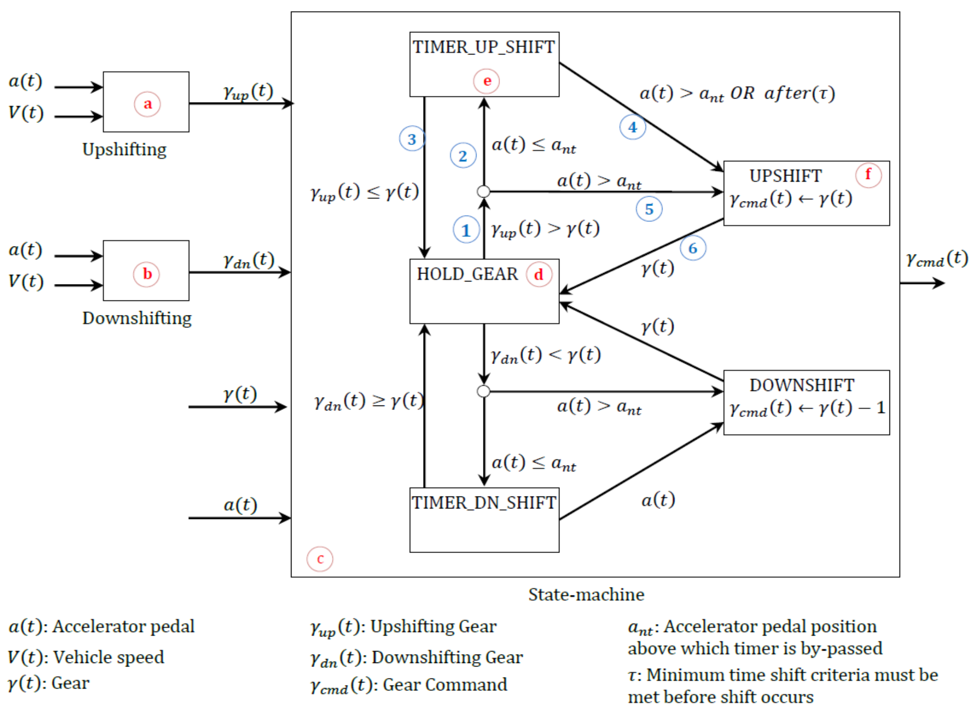


Figure 5.158 Shifting Controller Schematic in Autonomie

The controller is based on two main shifting maps — one for upshifting (a), moving from a lower gear to a higher gear, and another one for downshifting (b), moving from a higher gear to a lower gear — as well as a state-machine (c) that defines the status of the system (e.g., no shifting, upshifting). Each shifting map outputs a next-gear command $\gamma_{dn}(t)$ and $\gamma_{up}(t)$ based on the current accelerator pedal position a (t) and vehicle speed V(t). The state machine is composed of different states, of which only one is active at any time step; a change in state occurs whenever a transition condition from the active state becomes true (i.e., an upshift will occur only if a set of conditions is true). The state that is active most of the time is the hold-gear state (d), which makes sense because, most of the time, the vehicle should be in gear and not shifting for drivability reasons. An upshift occurs when the upshifting gear $\gamma_{up}(t)$ is strictly higher than the current gear $\gamma(t)$ (1) (e.g., $\gamma_{up}(t) = 5\ and\ \gamma(t) = 4$). For all vehicles, the shift does not necessarily happen instantly when the command to shift is given, depending on the current pedal position. In aggressive driving, i.e., at high accelerator-pedal positions (5), the shift happens as soon as the gear transition (1) becomes true, ensuring optimal performance. In contrast, in "normal" driving, i.e., at low pedal positions (2), there is an intermediate state (e) that allows the shift only when the gear condition (1) is true for a minimum time τ. This constraint is imposed to avoid an excessive number of shifting events, which would lead to unacceptable drive quality and increased energy consumption. The upshifting itself is executed in state (f), in which the shift command $\gamma_{cmd}(t)$ is incremented (i.e., the next upper gear is selected); once the shifting is completed (6), the state machine comes back to the hold-gear state (d). Downshifting occurs in a similar way.

Currently, in Autonomie, a shifting event can only result in moving one gear up or one gear down: there is no gear-skipping. Gear skipping is usually used under very specific conditions that are not encountered during the standard FTP and HFET drive cycles considered in the study. As an additional level of robustness in the Autonomie control algorithm, an upshift or downshift cannot occur if the resulting engine speed would be too low or too high, respectively. This approach ensures that the engine is not operated below idle or above its maximum rotational speed as shown in Figure 5.159.

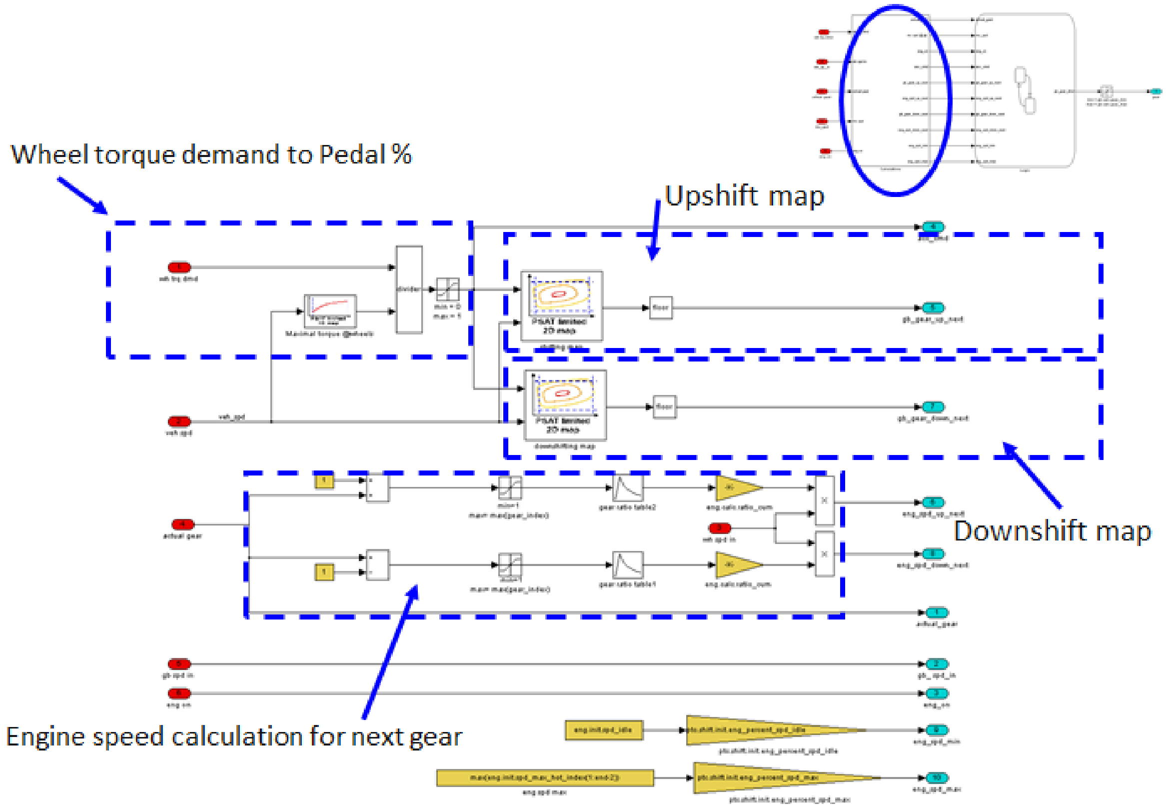


Figure 5.159 Shifting Calculations in Autonomie

Shifting Initializer

The shifting controller uses shifting maps to compute the gear command. In the controller, the shift map is a two-dimensional (2-D) look-up table indexed by vehicle speed and accelerator-pedal position. Defining such a map is equivalent to defining the "boundaries" of each gear area; those boundaries are the shifting speeds. Figure 5.160 illustrates that equivalence.

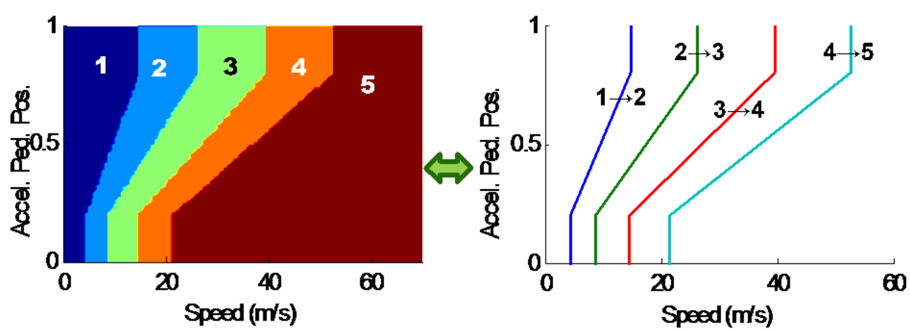


Figure 5.160 Upshifting Gear Map (left), Upshifting Vehicle Speeds (right)

For each shifting curve, there are two key points: the "economical" shifting speed (at very low pedal position) and the "performance" shifting speed (at high pedal position). The objective of the control engineer is to combine both goals of the shifting control to fulfill the driver expectations: minimization of energy consumption on the one hand and maximization of vehicle performance on the other.

The economical shifting speed for an upshift or a downshift is the speed at which the upshift/downshift occurs when the accelerator pedal position is very lightly pressed. $V_{eco}^{k \to k+1}$ is the economical vehicle speed for upshifting from gear k to gear k+1. $V_{eco}^{k+1 \to k}$ is the downshifting speed for this same set of gears. The vehicle speed shift points are computed from the engine shift points $\omega_{eco}^{k \to k+1}$ and $\omega_{eco}^{k+1 \to k}$. Figure 5.161 shows the engine speed shift points for an engine associated with a 5-speed transmission.

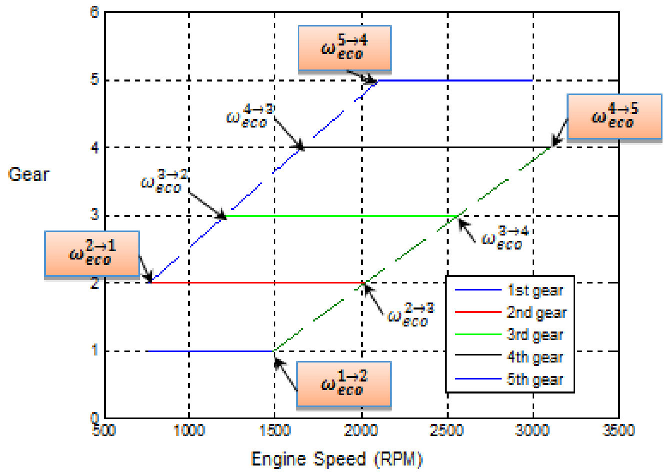


Figure 5.161 Example Engine Speed Range in Economical Driving, and Economical Shift

The initializing algorithm for the shifting controller computes the up- and downshifting speeds at zero pedal position based on the four "extreme" shift points: upshifting from lowest gear ($\omega_{eco}^{1 \to 2}$), upshifting into highest gear ($\omega_{eco}^{N-1 \to N}$), downshifting into lowest gear ($\omega_{eco}^{2 \to 1}$), and downshifting from highest gear ($\omega_{eco}^{N \to N-1}$). N is the number of gears. The speeds can be set by the user or left at their default values. Below is a description of their default values in Autonomie:

$\omega_{eco}^{2 \to 1} = \omega_{idle} + \omega_{margin}$ [ω_{idle}: engine idle speed; ω_{margin}: speed margin, ≈50–100 rpm]

$\omega_{eco}^{1 \to 2} = \omega_{idle} \frac{k_1}{k_2}(1 + \epsilon_{ud})$ [k1,k2: gear ratios for gears 1,2; ϵ_{ud}: margin to avoid overlap, ≈ 0.05–0.1]

$\omega_{eco}^{N-1 \to N}$: Engine speed at which best efficiency can be achieved

$\omega_{eco}^{N \to N-1} = \omega_{eco}^{N-1 \to N} - \omega_{\Delta}$ [$\omega_{\Delta} \approx 1{,}000$ rpm]

Once those four speeds are computed, the remaining ones are computed by linear interpolation to allow consistent shifting patterns that are acceptable to the drivers. For example, any upshifting speed is given by Equation 1:

$$\omega_{eco}^{i \to i+1} = \frac{\omega_{eco}^{N-1 \to N} - \omega_{eco}^{1 \to 2}}{N-2} \cdot (i-1) + \omega_{eco}^{1 \to 2}, 1 \le i \le N-1$$

In a shifting map, the vehicle upshifting speed from gear i to i+1 shall be strictly higher than the downshifting speed from gear i+1 to i. Otherwise, the downshifting speed will always request gear i while gear i+1 is engaged and vice-versa, resulting in oscillations between gears that would be unacceptable to the driver. For this study, the algorithm in the initialization file prevents that by making sure the following relation is true:

$$\omega_{eco}^{i \to i+1} > \omega_{eco}^{i+1 \to i} \cdot \frac{k_1}{k_2}(1 + \epsilon_{ud}), 1 \le i \le N - 1$$

The values of the engine economical shifting speeds at lowest and highest gears are automatically defined on the basis of the engine and transmission characteristics.

Finally, the vehicle economical up- and downshifting speeds can be computed using the engine up- and downshifting speeds, the gear ratio, the final drive ratio and the wheel radius:

$$V_{eco}^{i \to i+1} = \frac{\omega_{eco}^{i \to i+1}}{k_i k_{FD}} \cdot R_{wh} ,$$

Where: k_{FD} is the final drive ratio and R_{wh} is the wheel radius.

During performance, the gears are automatically selected to maximize the torque at the wheel. Figure 5.162 illustrates that gear selection, which consists of finding the point where the engine peak torque (reported at the wheels) curve at gear k falls under the one at gear k+1.

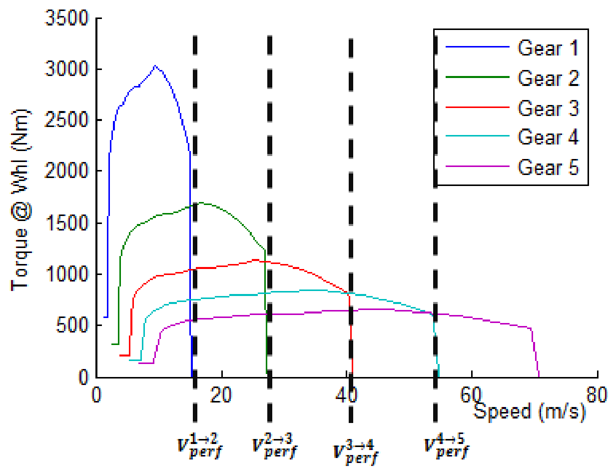


Figure 5.162 Maximum Engine Torque at Wheels and Performance Upshift Speeds

The performance downshifting speed is given by the performance upshifting speed and the difference between the economical shifting speeds:

$$\Delta V_{perf}^{i} = \alpha_{pf,ec} \cdot \Delta V_{eco}^{i} \iff V_{perf}^{i \to i+1} - V_{perf}^{i+1 \to i} = \alpha_{pf,ec} \cdot (V_{perf}^{i \to i+1} - V_{perf}^{i+1 \to i})$$

The definition of the final shifting curves is critical to properly evaluating the benefits of transmission technologies while maintaining acceptable performance. Figure 5.163 shows how a set of upshifting and downshifting curves for two adjacent gears is built, based on selected vehicle speeds and accelerator pedal positions. At low pedal positions (i.e., below a_{eco}^{up}), the upshifting speed is the economical upshifting speed. Similarly, below a_{eco}^{dn}, the downshifting speed is the economical downshifting speed. This approach ensures optimal engine operating conditions under gentle driving conditions. At high pedal positions (i.e., above a_{perf}), the shifting speed is the performance shifting speed, ensuring maximum torque at the wheels under aggressive driving conditions.

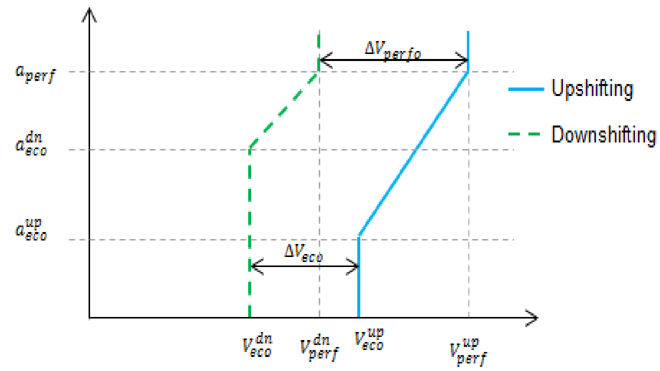


Figure 5.163 Design of Upshifting and Downshifting Speed Curves for Two Adjacent Gears

Torque Control during Shifting Events

Figure 5.164 shows the transmission clutch pressure, output torque, and engine speed curves during a change from 1st to 2nd gear. The output torque experienced both a trough period (lower than the torque in the original gear) and a crest period (higher than the torque in the original gear). The trough period is called a torque hole, while the crest period is called a torque overshoot. The torque hole is defined by depth and width, where the depth is the difference between minimum torque and the torque in previous gear, and the width is the half value of the maximum width of the torque hole.

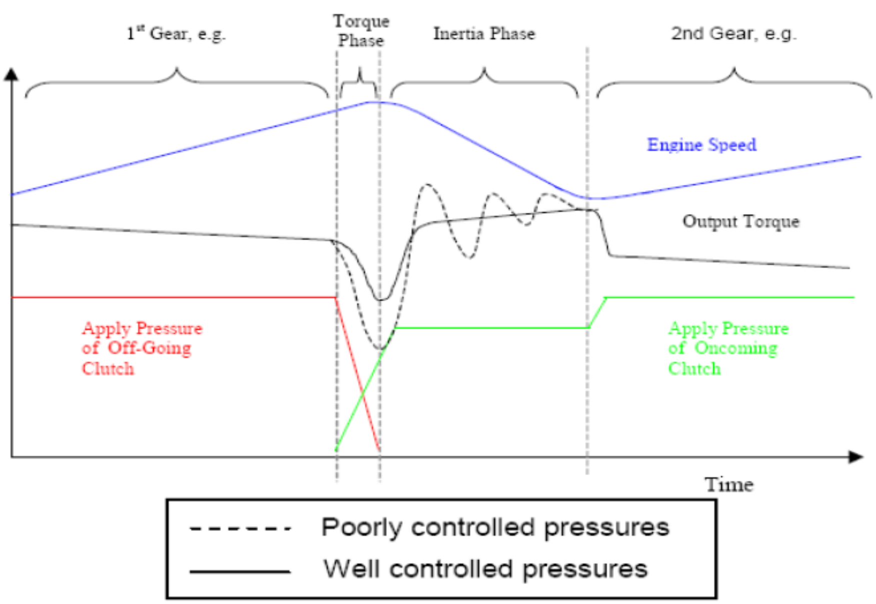


Figure 5.164 Generic Shift Process for Automatic Transmission

The bigger the torque hole, the larger the decrease of torque in torque phase, which results in a more significant reduction in acceleration. Because the decrease in acceleration causes discomfort for both the driver and passengers, the torque hole should be as shallow and narrow as possible. Torque reduction behavior is a well-known phenomenon, observed during vehicle testing and referenced in several papers and presentations.

Autonomie integrates a low-level control algorithm that reproduces the torque hole phenomenon. Figure 5.165 illustrates, in detail, the behavior of the vehicle model for a short period of time [205 sec to 205.8 sec]. The area highlighted by the grey circle indicated the torque hole during a shifting event.

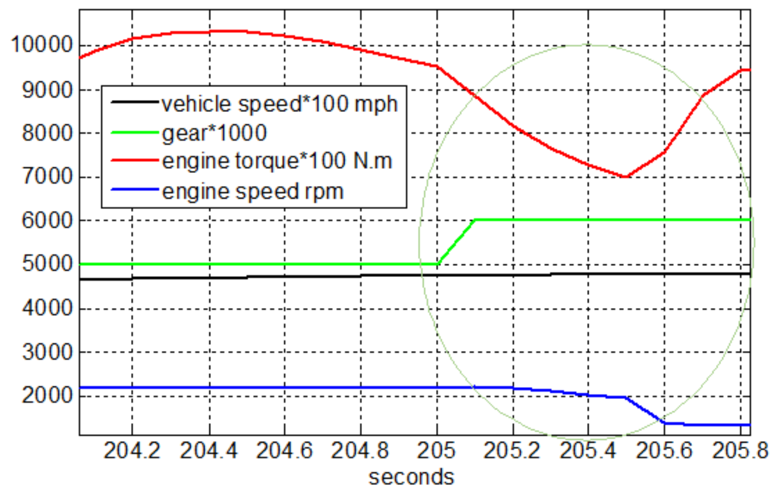


Figure 5.165 Torque Hole in Autonomie during Shifting Event

Engine Lugging Limits

Engine lugging limits are a critical NVH parameter. The assumptions shown in Table 5.217 describe the logic implemented in Autonomie to prevent lugging for multiple transmissions. The logic and values were developed based on APRF vehicle test data analysis.

Shift parameters are selected such that low speed, high torque operation is avoided. The selected shifting limits are based on test data observations relative to the number of gears available.

Table 5.217 Vehicle and Powertrain Technologies Evaluated

	5 speed Trans.	6 speed Trans.	7 speed Trans.	8 speed Trans.
Lugging speed (rad/s)	140	130	120	110

Figure 5.166 Example of Engine Operating Conditions to Prevent Lugging shows an example of how engine operating conditions are restricted to prevent lugging for multiple transmissions (5 and 8 speed automatic) on the UDDS driving schedule.

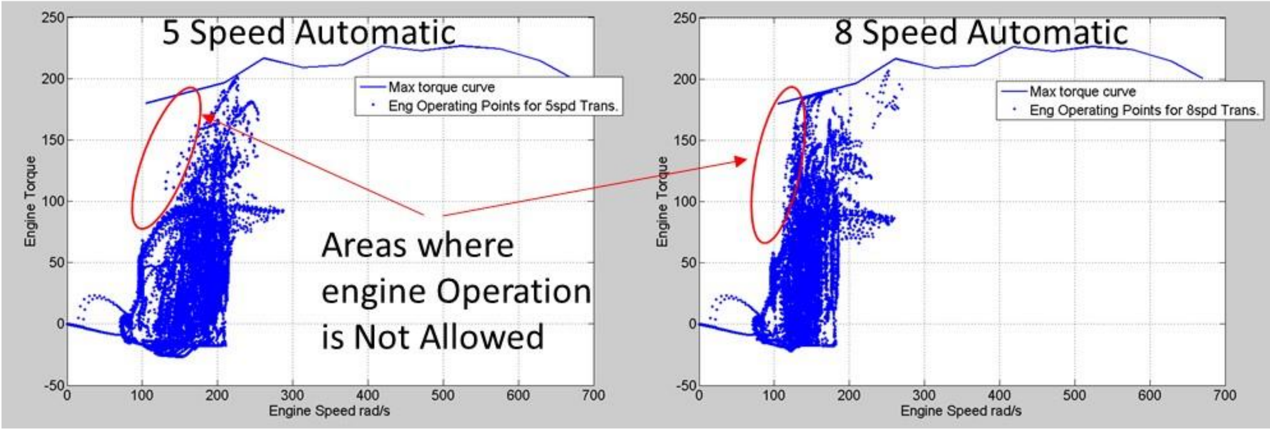


Figure 5.166 Example of Engine Operating Conditions to Prevent Lugging

Shifting Maps

All shifting maps used for the simulations are presented below. The shifting maps have been developed to ensure minimum energy consumption across all transmissions while maintaining an acceptable drivability. While plant models with higher degree of fidelity would be necessary to accurately model the impact of each technology on the drivability, using such models was not appropriate for the current study. As a result, the work related to the drive quality was focused on number of shifting events, time in between shifting events, engine time response and engine torque reserve.

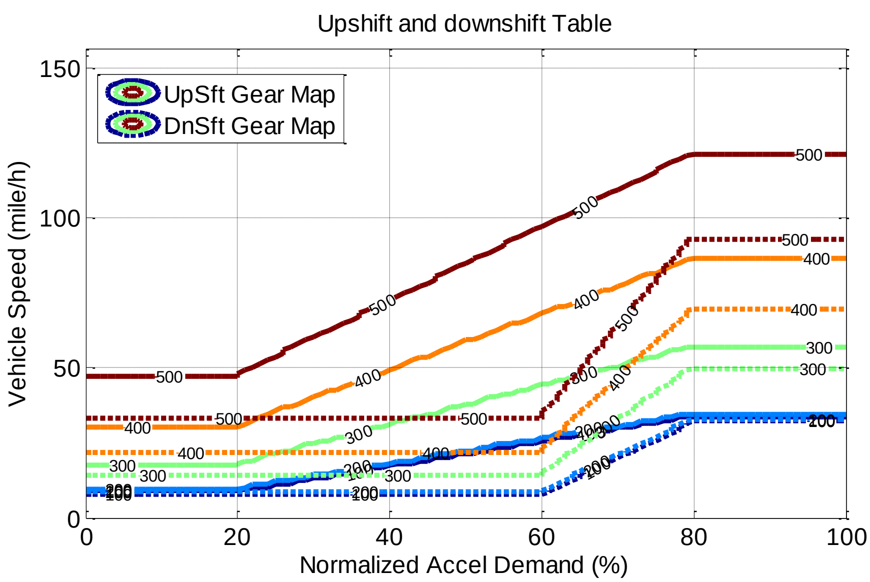


Figure 5.167 5-Speed Automatic Up (plain lines) and Down (dotted lines) Shifting Map

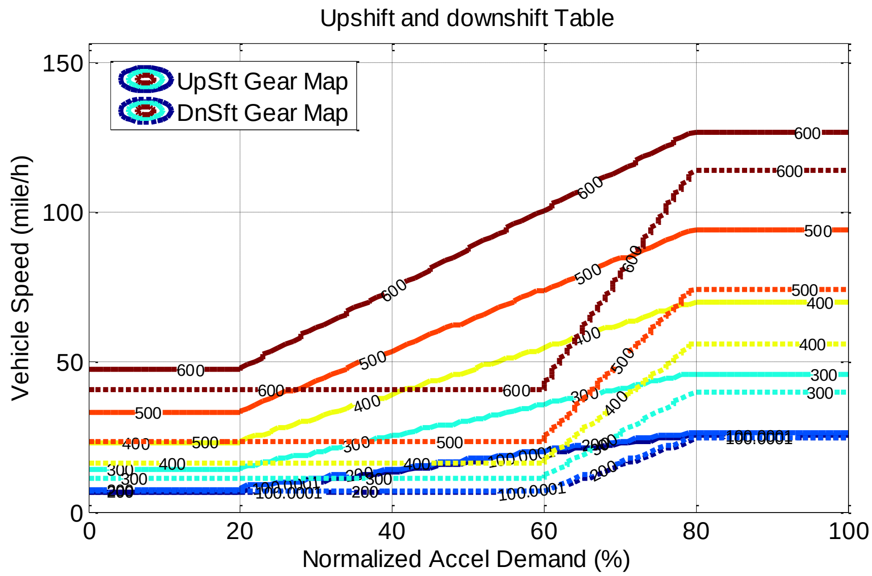


Figure 5.168 6-Speed Automatic Up (plain lines) and Down (dotted lines) Shifting Map

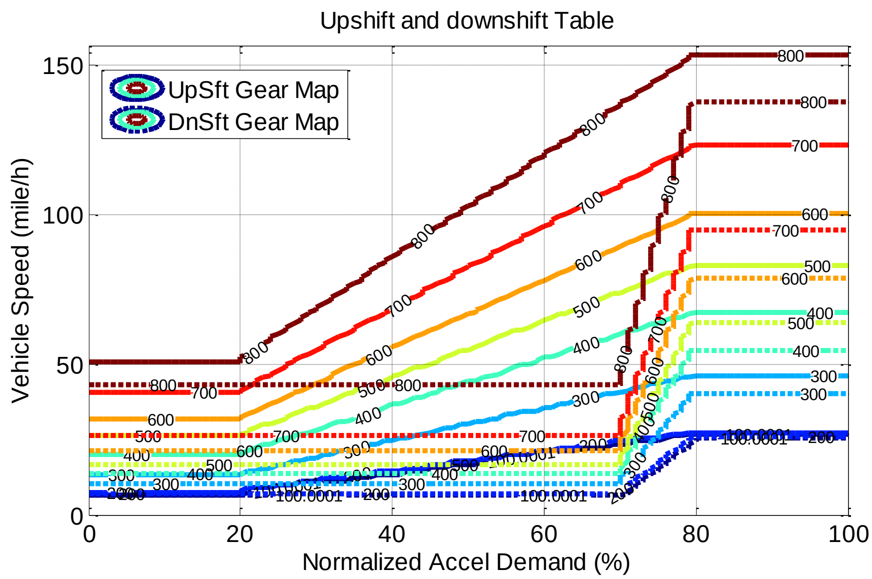


Figure 5.169 8-Speed Automatic Up (plain lines) and Down (dotted lines) Shifting Map

5.4.2.2.3.2 Torque Converter Lock-up Assumptions

A torque converter is a hydrodynamic fluid coupling used to transfer rotating power from a prime mover, such as an internal combustion engine, to a rotating driven load. It is composed of an impeller (drive element); a turbine (driven component); and a stator, which assist the torque converter function. The torque converter is filled with oil and transmits the engine torque by means of the flowing force of the oil. The device compensates for speed differences between the engine and the other drivetrain components and is therefore ideally suited for start-up function.

The torque converter is modeled as two separate rigid bodies when the coupling is unlocked and as one rigid body when the coupling is locked. The downstream portion of the torque converter unit is treated as being rigidly connected to the drivetrain. Therefore, there is only one degree of dynamic freedom, and the model has only one integrator. This integrator is reset when the coupling is locked, which corresponds to the loss of the degree of dynamic freedom. Figure 5.170 shows the efficiency of the torque converter used for the study.

The effective inertias are propagated downstream until the point where actual integration takes place. When the coupling is unlocked, the engine inertia is propagated up to the coupling input, where it is used for calculating the rate of change of the input speed of the coupling. When the coupling is locked, the engine inertia is propagated all the way to the wheels.

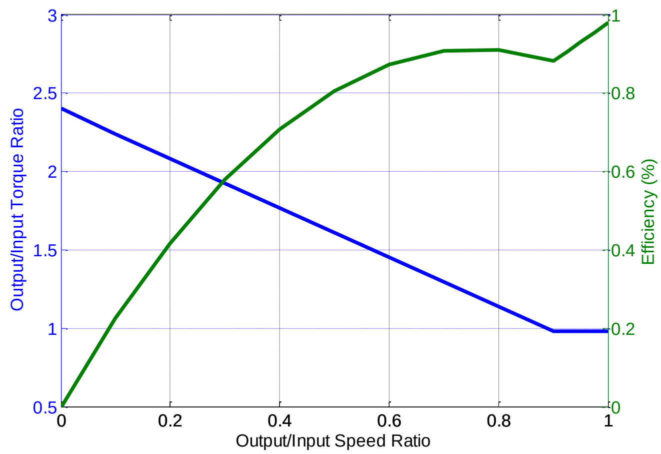


Figure 5.170 Torque Converter Efficiency Example

Figure 5.171 describes the conditions under which the torque converter will be locked. The same algorithm is used to represent current torque converter lockup logic, as well as future aggressive lockup logic. The torque converter is used as a start-up device in the first gear, with very low slip (torque ratio of 0.95) at higher speeds, in the first gear. Recent trends in torque converter technology suggest operation in locked or controlled slip mode, in the 2nd and higher gears. In general, the torque converter is in controlled slip or mechanically locked based on vehicle speed and pedal position, for each gear apart from the 1st. In order to suggest advances in torque converter technology, it was assumed that the torque converter would be in a mechanically locked state for the 2nd and higher gears. This approach has been applied to all transmissions with 6 gears or more.

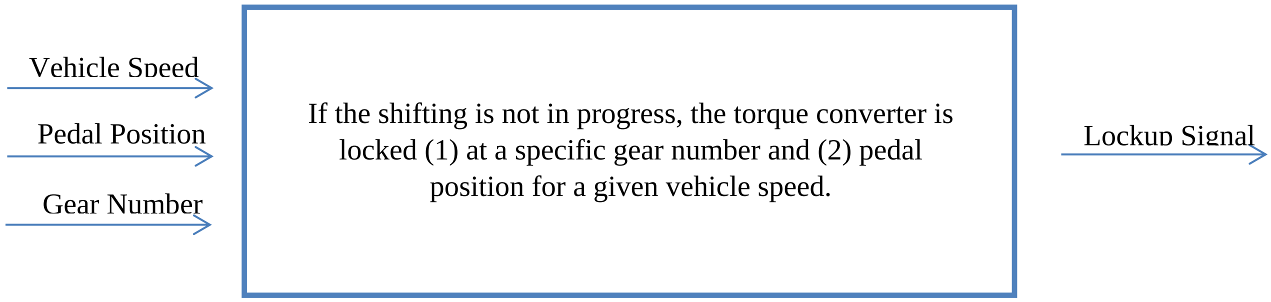


Figure 5.171 Torque Converter Lockup Control Algorithm

5.4.2.2.3.3 Fuel Cut-off Algorithm

Engine fuel cut-off control algorithms used in the study have been developed on the basis of vehicle test data collected at Argonne's Advanced Powertrain Research Facility. The fuel cut-off controller is implemented for gasoline and diesel engines through analysis as shown in Figure 5.172 Engine Fuel Cut-off Analysis Based on Test Data (data source APRF). In Autonomie, engine control and plant blocks are organized for idle fuel rate and fuel off conditions. Engine fuel is cut off under the following conditions:

Vehicle is actively braking, for a certain minimum time.

Engine speed is above a minimum threshold (e.g. 1000 RPM).

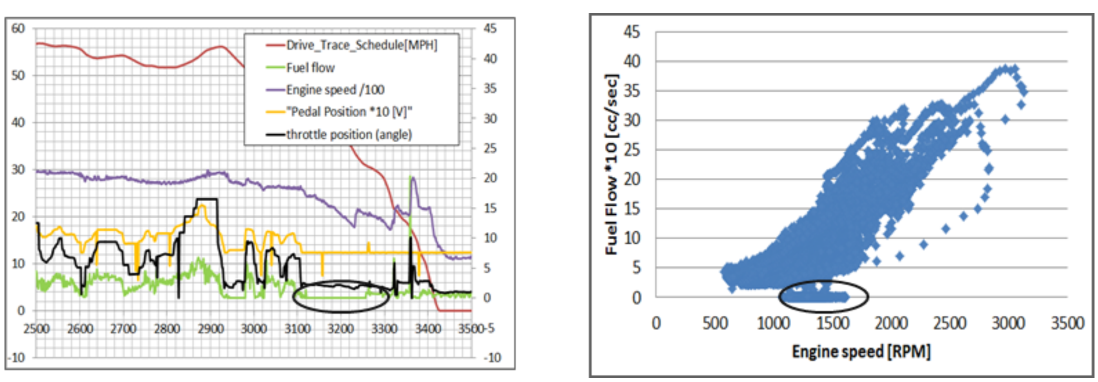


Figure 5.172 Engine Fuel Cut-off Analysis Based on Test Data (data source APRF)

5.4.2.2.3.4 Vehicle Level Control for Electrified Powertrains

The task of achieving fuel savings with a hybrid architecture depends on the vehicle performance requirements and the type of powertrain selected as well as the component sizes and technology, the vehicle control strategy, and the driving cycle. The overall vehicle-level control strategy is critical to minimize energy consumption while maintaining acceptable drive quality. Figure 5.173 illustrates a simple acceleration, cruising and braking cycle for a full HEV, demonstrating the best usage of different power sources based on the vehicle's power demand. During small accelerations, only the energy storage power is used (EV mode) and during braking, some of the energy is absorbed and stored. The engine does not start to operate during low power demands, owing to its poor efficiency compared to the electrical system. The engine is only used during medium and high power demands, where its efficiency is higher.

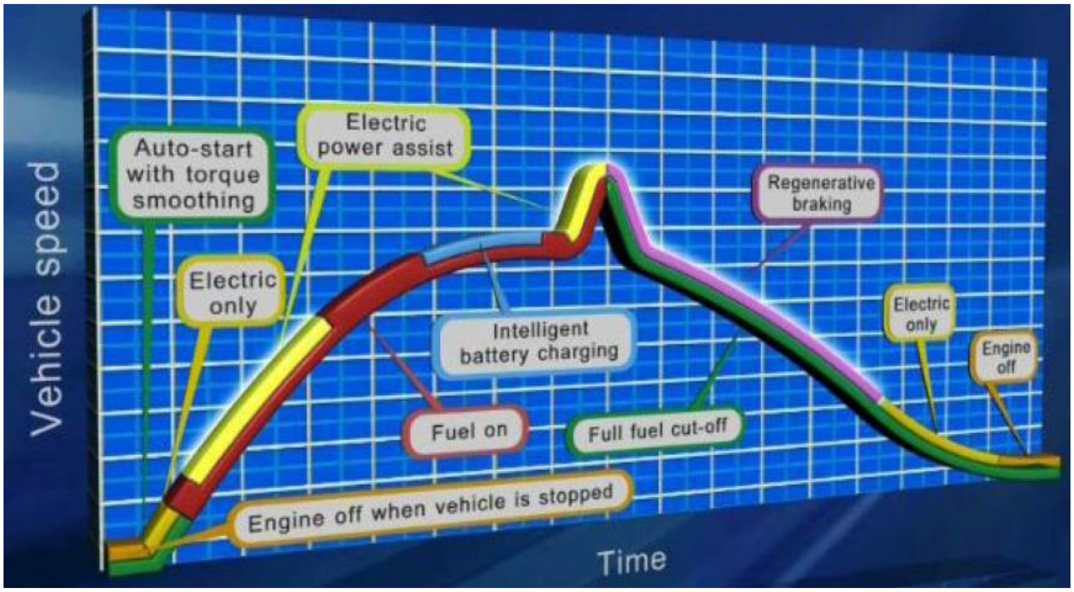


Figure 5.173 Hybrid Electric Vehicle Principles [source: www.gm.com]

While different vehicle-level control strategy approaches have been studied for electric drive vehicles (e.g., rule based, dynamic programming, instantaneous optimization), the vast majority of current and future electric drive vehicles are using and expected to use rule-based control strategies. The vehicle level control strategies logics used in the study will be described below.

It is important to note that while the control algorithms have been developed based on extensive vehicle test data, the calibration parameters used for the study were adapted to the component technologies and performance characteristics (i.e., power, energy, and efficiency) of each individual vehicle.

Micro and Mild HEV

The vehicle-level control strategies of the micro- and mild (i.e., BISG and CISG) micro-HEVs are similar in many aspects due to the low peak power and energy available from the energy storage system.

For the micro HEV case, the engine is turned off as soon as the vehicle is fully stopped and restarted as soon as the brake pedal is released. No regenerative braking is considered for that powertrain.

For the mild HEV cases, the engine is turned off as soon as the vehicle is fully stopped. However, since some regenerative braking energy is recovered, the vehicle is propelled by the electric machine during vehicle launch, allowing the engine to be restarted later.

Single-mode power split HEV

The vehicle-level control strategy algorithm of a single-mode power split HEV was based on the Toyota Prius APRF test data analysis. The control logic implemented can be divided into three areas: engine-on condition, battery SOC control, and engine operating condition. Each algorithm is described below.

The operation of the engine determines the mode, such as pure electric vehicle mode or HEV mode. The engine is simply turned on when the driver's power demand exceeds a predefined threshold. As shown in Figure 5.174, the engine is turned on early if the SOC is low, which means that the system is changed from PEV mode to HEV mode to manage the battery SOC.

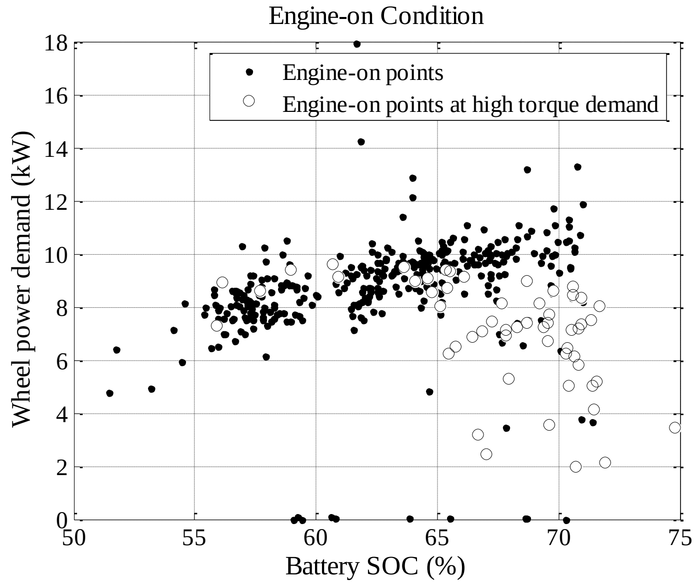


Figure 5.174 Engine-On Condition – 2010 Prius Example Based on 25 Test Cycles (data source APRF)

The engine is turned off when the vehicle decelerates and is below a certain vehicle speed.

The desired output power of the battery is highly related to the energy management strategy. When the vehicle is in HEV mode, the battery power is determined by the current SOC, as shown in Figure 5.175. The overall trend shows that the energy management strategy tries to bring the SOC back to a regular value around 60 percent. Both the engine on/off control and the battery power control are robust approaches to manage the SOC in the appropriate range for an input-split hybrid. If the SOC is low, the engine is turned on early, and the power split ratio is determined to restore the SOC to its target value so that the SOC can be safely managed without charge depletion. In summary, the battery SOC is controlled by raising (low SOC) or lowering (high SOC) the engine power demand required to meet the vehicle speed trace.

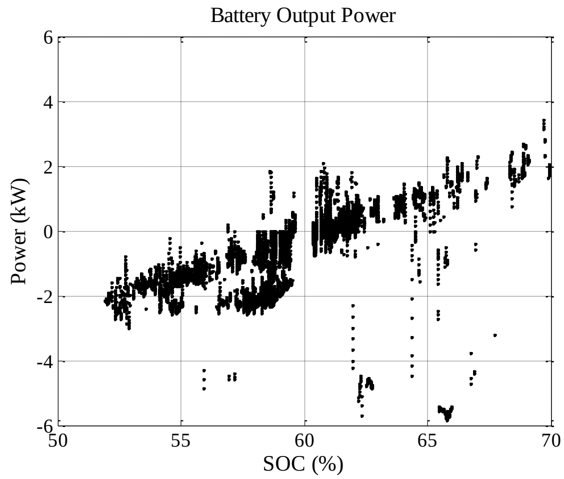


Figure 5.175 SOC Regulation Algorithm – 2010 Prius Example Based on 25 Test Cycles (data source APRF)

For engine operation control, the two previously described control concepts determine the power split ratio. The concepts do not, however, generate the target speed or torque of the engine because the power split system could have infinite control targets that produce the same power. Therefore, an additional algorithm is needed to determine the engine speed operating points according to the engine power, as shown in Figure 5.176. An engine operating line is defined on the basis of the best efficiency curve to select the optimum engine speed for a specific engine power demand.

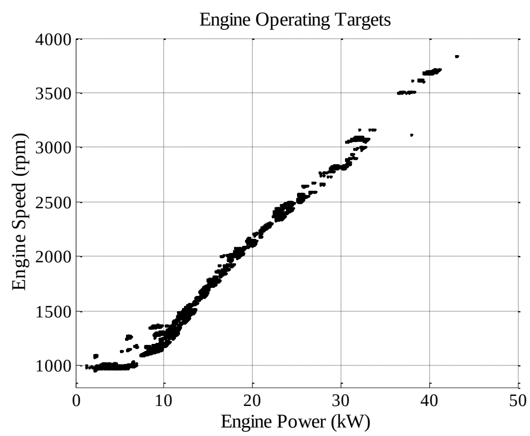


Figure 5.176 Example of Engine Operating Target – 2010 Prius Example Based on 25 Test Cycles (data source APRF)

In summary, the engine is turned on based on the power demand at the wheel along with the battery SOC. If the engine is turned on, the desired output power of the battery is determined on the basis of the current SOC and the engine should provide appropriate power to drive the vehicle. The engine operating targets are determined by a predefined line, so the controller can produce required torque values for the electric machine and the generator on the basis of the engine speed and torque target.

Pre-transmission HEV

The vehicle-level control strategy logic of a pre-transmission HEV is based on the VW Jetta HEV APRF test data analysis. In the pre-transmission HEV, the engine is a main power source and the electric machine assists the engine according to the vehicle operating conditions and the driver request. Three driving modes are used: EV mode, engine mode, and HEV mode. When the vehicle is driving at low speed or the demanded power is low, the vehicle is operated only by the electric machine in EV mode. During high-speed operation, start-up, or aggressive acceleration, the vehicle is operated by the engine in Engine mode or HEV mode.

The driving mode control strategy is determined by the engine on/off state. When the vehicle drives at low speed, the system is operated only by the electric machine, without engine operation. Figure 5.177 (left panel) shows the vehicle speed and wheel demand torque when the engine is turned on. The right figure shows the operating area of pure electric driving in the same index.

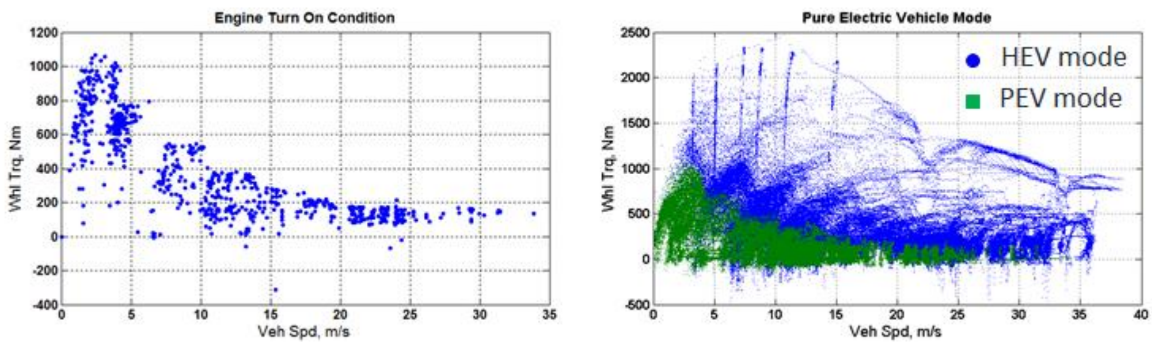


Figure 5.177 Cycles Wheel Torque vs. Vehicle Speed, 2014 Jetta HEV Based on Test Cycles (data source APRF)

In HEV and engine mode, the engine is operated to manage the demanded power at high speed or acceleration. In these modes, the engine is controlled to operate at higher engine thermal efficiency. However, since the range of the multi-gear transmission gear ratio is limited, the electric machine is used to provide additional control of the engine operating points. Therefore, one other important control concept at the vehicle level is how to manage the battery demand power within the appropriate SOC range. Figure 5.178 (left panel) shows the battery SOC target when the engine is turned on. Under the engine on/off condition, the proportional demand power for the battery sustains the SOC level at an appropriate range near specific range. On the right, engine power vs. wheel power is shown for a 2014 Jetta HEV example based on test cycles.

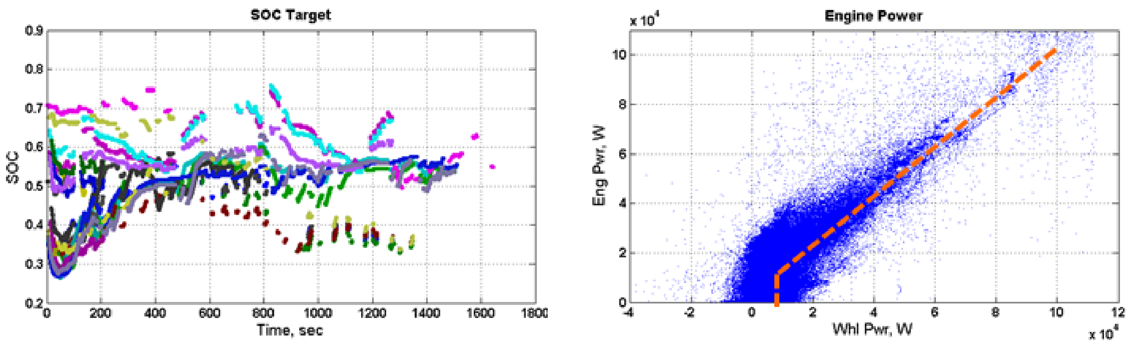


Figure 5.178 SOC vs. Time (left) Engine Power vs. Wheel Power (right) (data source APRF)

Plug-in Hybrid Electric Vehicle - Blended PHEV

The vehicle-level control strategy logic of a single-mode power split blended PHEV was based on the Toyota Prius PHEV APRF test data analysis. The PHEV is able to run with the electric machine only if SOC is high enough and the demand power does not exceed the power limit of the electric machine and the battery. Figure 5.179 shows all points when the engine is turned on.

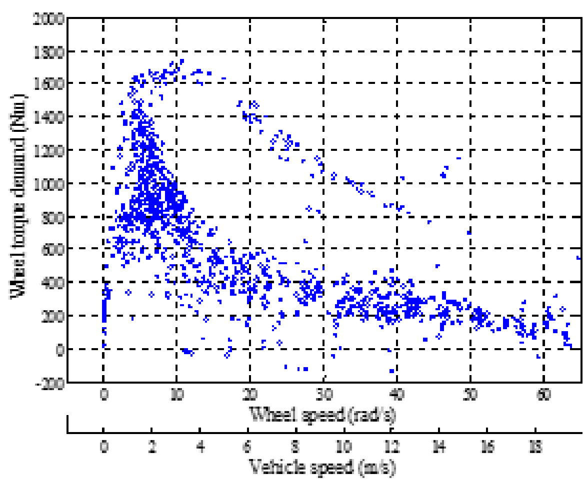


Figure 5.179 2013 Prius PHEV Wheel Speed and Demand Torque, Based on Test Cycles (data source APRF)

Another control strategy logic is necessary to distribute the power between the engine and the battery, which determines the behaviors of SOC on the hybrid driving mode. Figure 5.180 shows the overall control strategy to manage the SOC according to the CD or CS mode.

In Figure 5.180, the points are obtained only during the hybrid driving mode because the battery provides all demand power if the electric machine is the only power source. First, the battery provides no power or constant power under the CD mode if the SOC is greater than 28 percent. The engine is turned on under the CD mode when the battery does not provide all the demand power, and the engine provides all demand power. However, if the vehicle speed exceeds 100 km/h, the battery provides a constant power (here about 10 kW).

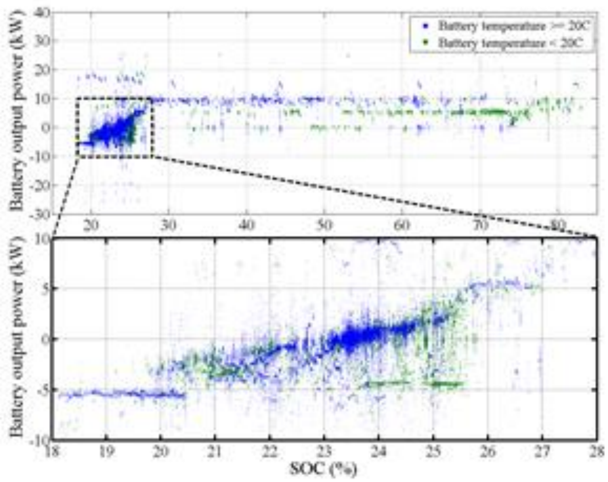


Figure 5.180 2013 Prius PHEV Output Power of the Battery for SOC Balancing Based on Test Cycles (data source APRF)

This control is designed to constantly consume electric energy under the CD mode, so that drivers have consistent experiences during the CD mode. In contrast, the control strategy to manage the SOC in the CS mode is similar to the Prius HEV, where the desired power of the battery decreases as the SOC decreases. Further, rapid recuperation is also observed in the very low SOC range, like below 20 percent, and there is no specific control for the SOC balancing according to the battery temperature just as for the Prius HEV. In Figure 5.181, for a 2013 Toyota Prius PHEV, the power constraints are observed in the regenerative operation because the electric machine must provide the demanded propulsion torque over the constraints until the engine is turned on, whereas the mechanical brake is able to quickly respond to compensate for the required braking torque.

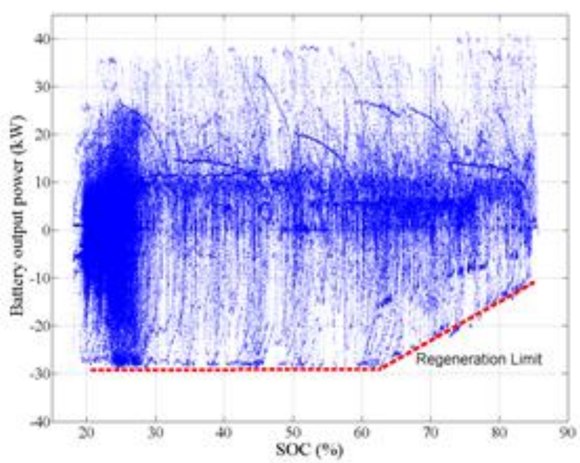


Figure 5.181 2013 Prius PHEV Battery Output Power According to SOC based on Test Cycles (data source APRF)

If the engine is turned on and the desired battery power is calculated according to the strategies in the previous two sections, the desired engine power can be calculated by the demand power and the desired battery power. However, the engine operating target is not fixed because the engine could operate at a number of operating points to produce the same power. Therefore, the operating target of the engine should be controlled as well as a function of temperature. Figure 5.182 shows the two different engine operating targets according to the coolant temperature, which are almost the same as the operating targets of the Prius HEV. The line that can be inductively assumed from the red points in Figure 5.182 shows that the desired torque and speed can be determined if the desired power is given.

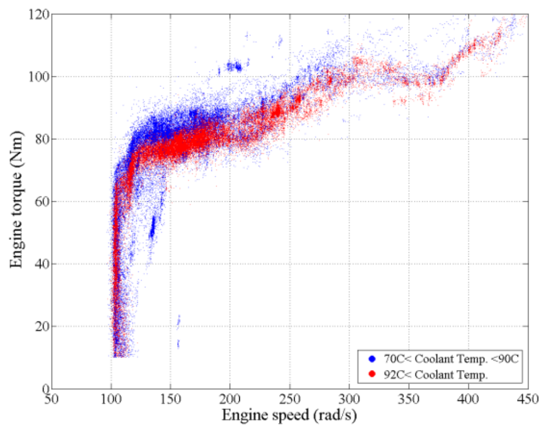


Figure 5.182 2013 Toyota Prius PHEV Engine Operating Target Based on Test Cycles (data source APRF)

Plug-in Hybrid Electric Vehicle - Range Extender PHEV

The vehicle-level control strategy logic of a range extender PHEV was based on the GM Volt Gen 1 PHEV APRF test data analysis. The control implemented can be divided into four areas: engine-on condition, transmission mode, battery SOC control during charge sustain mode, and engine operating condition. If the battery is fully charged, a charge-depleting mode is selected, wherein the battery is the main power source. Since it is considered that all driving should be covered by “EV Drive,” the vehicle is propelled by utilizing stored electric energy. If the battery SOC drops to a predetermined level, a charge-sustaining mode is automatically selected. The vehicle is then propelled by using a combination of the engine and battery while the SOC is maintained.

The engine is turned ON when the driver’s demand power is over a threshold line, as shown in Figure 5.183, where the demand power is determined by the wheel axle torque and current vehicle speed.

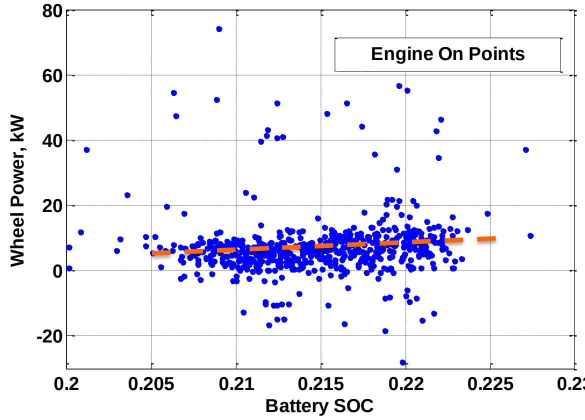


Figure 5.183 Engine On Points – 2011 GM Volt PHEV Example Based on Test Cycles (data source APRF)

The combined electric machine efficiency map and gear spin loss determines the EV drive mode, such as EV1 and EV2. When the EV2 drive is in operation, the most efficient combination of electric machine input speeds can be selected to meet the output speed and torque. With this two-electric machine arrangement, electric machine speeds can be adjusted continuously, for greatest tractive effort or greatest overall efficiency. The EV2 mode is used when the vehicle speed exceeds a predefined threshold and the driver demands light load, as shown in Figure 5.184 in the gearbox (GB) axle torque – vehicle speed domain.

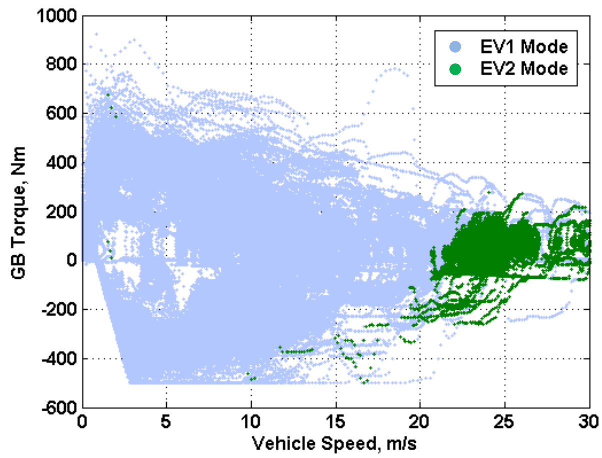


Figure 5.184 EV Operating Mode – 2011 GM Volt PHEV Based on Test Cycles (data source APRF)

In Figure 5.185, the mode selection rule is defined on the basis of the speed ratio, which is defined as the ratio of the ICE input speed to vehicle speed. The power-split mode is used if the speed ratio is low, which means that the system is changed from series mode to power-split mode to avoid low system efficiency. In a high-speed ratio range, the system efficiency of the power-split mode is low because electrical machines have relatively low efficiency. Low system efficiency at a high-speed ratio range can be avoided by propelling the vehicle by using the series mode instead of the split mode. The EV2 drive and split operation offered by the Volt powertrain system provides advantages over the more conventional EV drives and series operation.

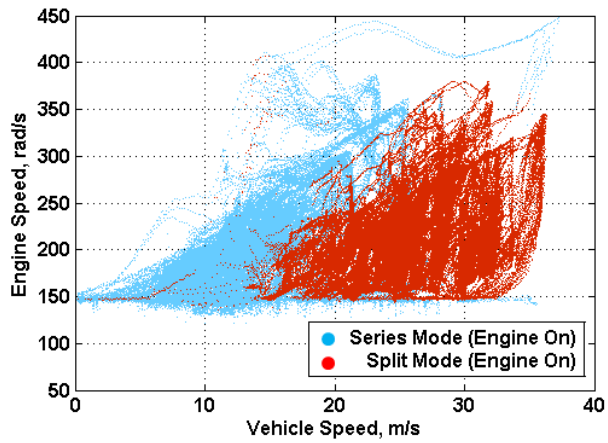


Figure 5.185 HEV Operating Mode – 2011 GM Volt PHEV Based on Test Cycles (data source APRF)

The desired battery power is linked to the energy management strategy. We found that the battery power can be determined by the wheel power demand and the current SOC, as shown in Figure 5.186, when the vehicle is in HEV mode. The results are obtained by analyzing data during HEV mode. Although some points are away from the line, the overall trend shows that the energy management strategy tries to avoid low power operation of the engine and bring the SOC back to a regular range between 21 percent and 22 percent. Both the engine on/off control and the battery power control are robust approaches to manage SOC in the appropriate range. If the SOC is low, the engine is turned on, and the power-split ratio is determined to restore the SOC to a narrow range, so that the SOC can be managed safely without depletion.

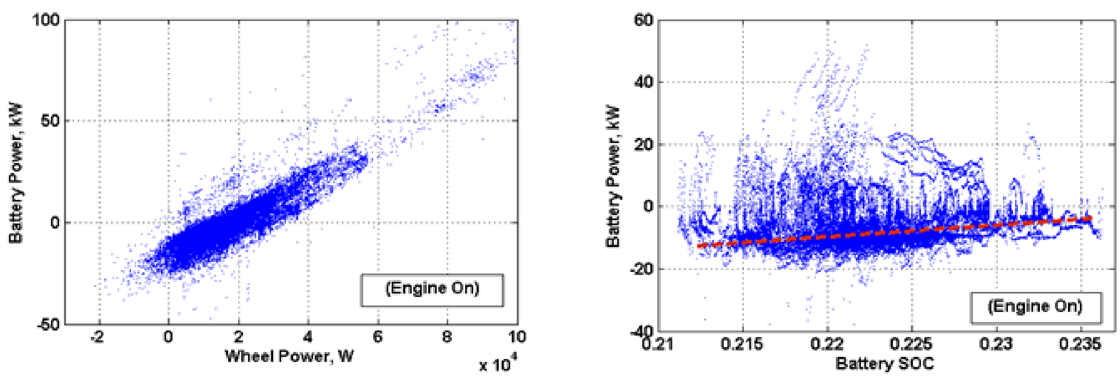


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Figure 5.186 Battery Output Power – 2011 GM Volt PHEV Based on Test Cycles (data source APRF)

The control concepts previously stated are used to determine the transmission mode and the power-split ratio. The concepts do not, however, generate the engine target speed or torque because the series and power-split system can de-couple the engine and wheels speed as long as the output power demand is met, which provides greater flexibility to choose the engine working point to optimize energy consumption. Therefore, an additional control concept to determine the operating target is needed to complete the control strategy, for which engine speed operating points are obtained according to the engine power, as shown Figure 5.187.

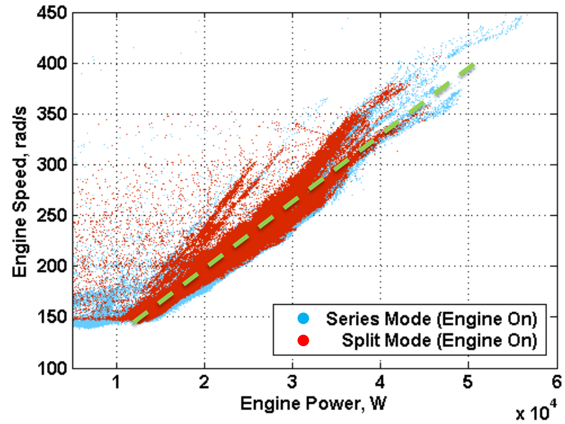

Figure 5.187 Engine Operating Targets – 2011 GM Volt PHEV Based on Test Cycles (data source APRF)

In summary, the engine status is determined on the basis of the power demand or the need for performance. If the engine is turned on, the desired power of the battery is determined on the basis of the current SOC, and then the engine should provide appropriate power to drive the vehicle. Finally, the engine operating targets are determined by a predefined line, and so the controller can produce the required torque values for the electric machine and the generator on the basis of the engine speed and torque target.

Fuel Cell Hybrid Electric Vehicle

Unlike the other vehicle-level controls previously discussed, the algorithm for the fuel cell HEVs was not derived from test data, due to the lack of test vehicles. Instead, dynamic programming was used to define the optimum vehicle-level control algorithms for a fuel cell vehicle. A rule-based control is then implemented to represent the rules issued from the dynamic programming. Overall, owing to the high efficiency of the fuel cell system, energy storage only recuperates energy during deceleration and propels the vehicle under low-load operations — the fuel cell system does not recharge the battery. Unlike electric drive powertrains with an engine, the battery does not smooth the transient demands. An example of fuel cell hybrid operations is shown in Figure 5.188.

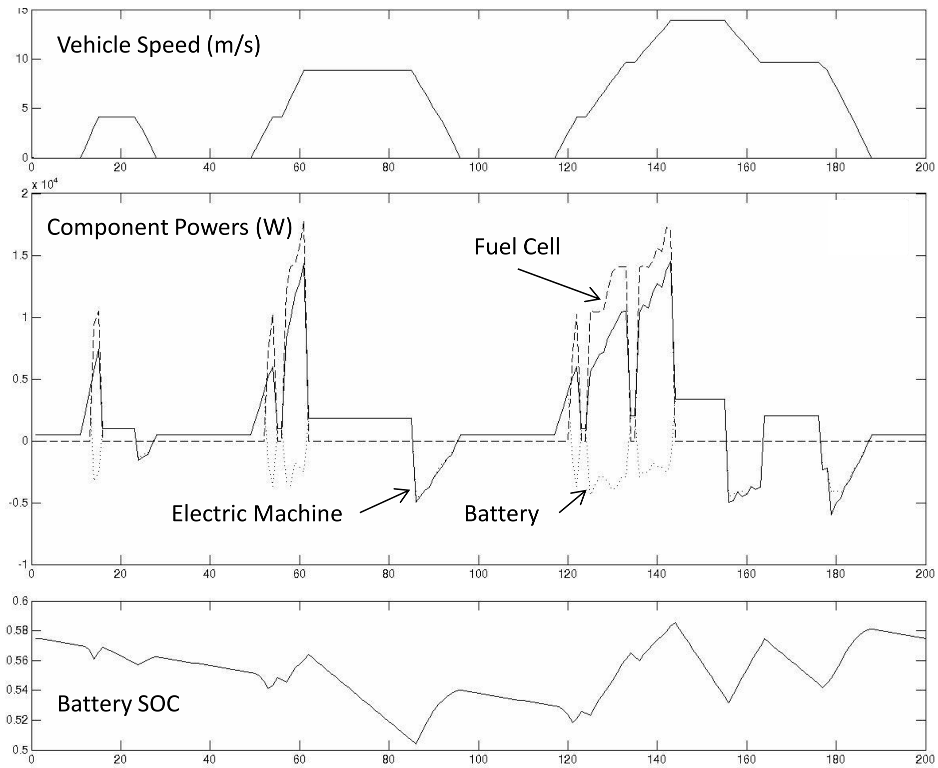

Figure 5.188 Component Operating Conditions of a FCV on the Urban EDC using Dynamic Programming

5.4.2.3 Vehicle Model Validation

5.4.2.3.1 Vehicle Benchmarking

Benchmarking is commonly used by vehicle manufacturers, automotive suppliers, national laboratories, and universities in order to gain a better understanding of how vehicles are engineered and to create large datasets that can be applied in modeling and other analyses. NHTSA has been leveraging the extensive existing vehicle test data collected by Argonne National Laboratory under funding from the US DOE Vehicle Technologies Office.[612] Specific instrumentation lists and test procedures have been developed over the past 20 years to collect sufficient information to be able to develop and validate full vehicle models. Over the coming years, NHTSA intends to benchmark additional vehicles at the APRF to inform the Proposed and Final Determination.

Since its inception in the nineties1, the APRF has been focused technology assessment of advanced technology vehicles for the U.S. Department of Energy and its partners through the generation and analysis of laboratory data. The staff also supports the development of automotive standards through its expertise and public data. The team has tested a large number of vehicles of different types, such as advanced technology conventional vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, battery electric vehicles, and alternative fuel vehicles.

The researchers at the APRF have developed a broad and fundamental expertise in the testing of the next generation of energy-efficient vehicles. Over the last twenty years, many methods of vehicle instrumentation and evaluation have continuously been refined. The instrumentation intends to capture component level information while the powertrain is in the vehicle. This "in-situ" instrumentation and testing approach enables the APRF is capture vehicle level and component level data over dynamic drive cycles as well as specific powertrain mapping tests.

Instrumentation approach

Two levels of instrumentation and testing exist today. The first level (Level-1) involves comprehensive, but non-invasive, instrumentation of a vehicle, leaving the vehicle unmarked after the testing. The second level (Level-2) involves comprehensive invasive instrumentation of a vehicle and its powertrain components, which leaves the vehicle with irreversible alterations, but provides an in-depth assessment of the technology. The goal of the instrumentation is to provide usage information and efficiencies (if possible) of the different powertrain components, operating envelops, and powertrain behavior.

Typically, Argonne receives Level 1 test vehicles on loan; therefore, the vehicles need to leave the test facility in the "as-received" and road worthy condition. This requirement limits instrumentation to sensors that can be easily installed and removed without leaving any damage. The Level 2 benchmark, which included in-depth, testing, and analysis of new and emerging vehicle technologies, is specific to each vehicle. If the vehicle has an internal combustion engine, instrumentation is applied to measure the engine speed, fuel flow and engine oil temperature. For electrified vehicles, a power analyzer is used to record the voltage and current from the high voltage energy storage system. If the vehicle requires charging, the electric power from the grid to the charger is measured. The recording of messages from the vehicle's information buses (diagnostic and broadcast network messages) is another expertise of the APRF staff. The instrumentation is focused to a particular technology, or technologies that enable the increased energy efficiency of a powertrain.

Facility capabilities

The APRF has a 4WD wheel drive chassis dynamometer and 2WD chassis dynamometer. The 4WD chassis dynamometer is in in a thermal chamber to evaluate the powertrain across a range of environmental conditions. The thermal chamber and an air-handling unit with a large refrigeration system that enables vehicle testing from -20°C to 40°C. All temperatures can be evaluated with or without solar emulation lamps providing up to 850 W/m2 of radiant sun energy. Some highlights of the APRF capabilities include: rated to test hydrogen powered vehicles; 5 cycle capable; several emissions measurement systems; and research focused test cell.[613] Figure 5.189 illustrates the two chassis dynamometer test cells available at the APRF.

Figure 5.189 Illustration of testing at 95°F with sun emulation (left) and at 20°F cold ambient temperature (right).

The APRF benchmark program goes well beyond the standard tests performed for EPA certification of fuel economy and emissions. To fully characterize the powertrain and the individual components the instrumented powertrains are tested on a wide range of ambient temperatures, drive cycles, performance tests and vehicle/component mapping tests.

Independent and Public Data

A major goal of the benchmarking activity is to enable petroleum displacement through data dissemination and technology assessment. The data generated from the vehicle testing as well as the analyses are shared through several mechanisms, such as raw data, processed data, presentations and reports.

The independent and public data is a foundation enabling the development of rigorous and technology neutral codes and standards. The data also serves to develop and validate several modeling and simulation tools within the DOE system (i.e., Autonomie) as well as outside (i.e., EPA Alpha model, University modeling, and economic models). These activities in turn impact the modification of test plans and instrumentation for current and future test vehicles. Partners in the testing include U.S. manufacturers and suppliers, through the U.S. Council for Automotive Research. Many of the research activities of the DOE rely on the benchmark laboratory and fleet testing results to make progress towards their own goals. Figure 5.190 details some of these DOE research activities and partners.

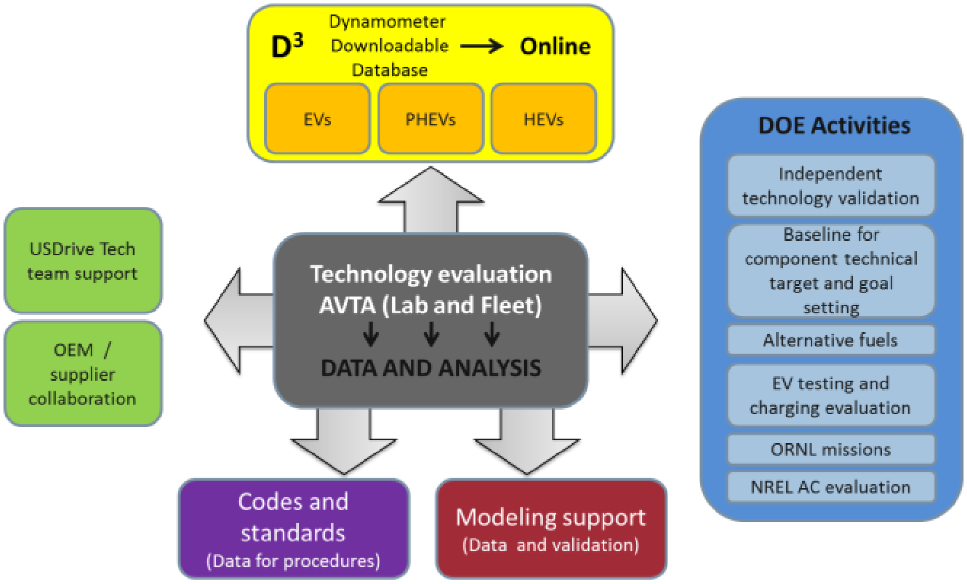

Figure 5.190 Data Dissemination and Project Partners.

Downloadable Dynamometer Database (D3)

An additional avenue for data distribution is Argonne's Downloadable Dynamometer Database (D3).[614] The D3 website provides access to a subset of data and reports.

D3 is a public web portal of highly detailed accurate public and independent vehicle test data, of critical utility in the research community. This web-based portal to Argonne vehicle test data is designed to provide access to dynamometer data that are typically too expensive for most research institutions to generate. Shared data is intended to enhance the understanding of system-level interactions of advanced vehicle technologies for researchers, students, and professionals engaged in energy-efficient vehicle research, development, or education. Figure 5.191 shows the structure and content of the database.

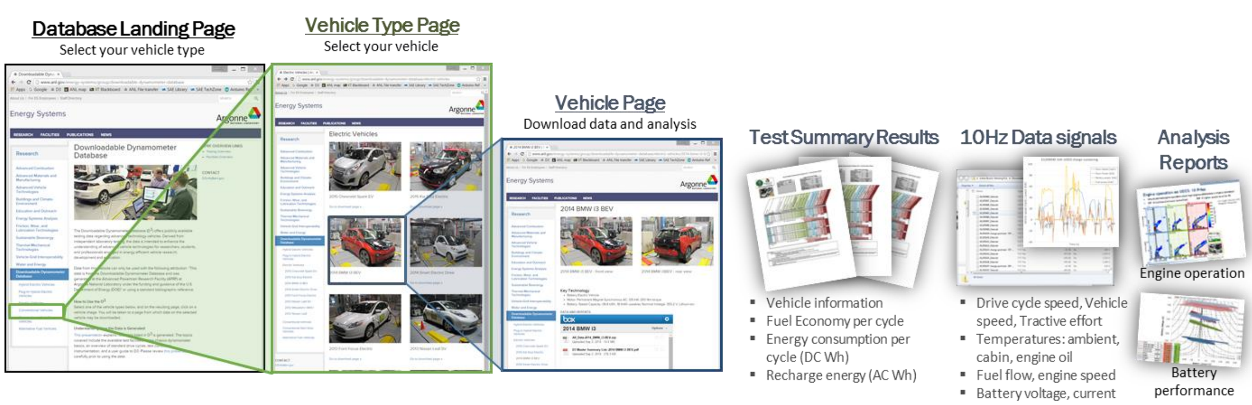

Figure 5.191 Map of Downloadable Dynamometer Database.

5.4.2.3.2 Vehicle Validation Examples

Argonne has been validating the Autonomie vehicle models with vehicle test data for more than 15 years. Test data were collected at the Argonne National Laboratory APRF from more than 60 vehicles, spanning model years 2000-2015. A large number of signals were collected on each vehicle with specific focus on model development and validation. While sensors were different across vehicles, they included: torque sensors (axles); components speeds; coolant flow sensors; coolant component temperatures; exhaust temperatures; emissions; fast CAN data; scan tool data; power analyzer on many nodes; dynamometer loads and speeds; and direct fuel measurement. These readings were all integrated into one data acquisition system. Some additional parameters were then estimated based on measured data and other advanced technology vehicles. After each individual model was independently validated, vehicle system models were developed and the validation quality was quantified using normalized cross correlation power (NCCP).JJJJ Vehicles were tested over a large number of cycles and runs. For example, the MY2010 Toyota Prius HEV was run on 11 separate cycles for a total of 26 tests.[KKKK]

Autonomie vehicle models have been validated within test to test repeatability for a wide range of technologies and powertrain configurations. The following section highlights some of the validation performed using Argonne APRF vehicle test data. While much work has been performed at Argonne under DOE VTO funding, NHTSA is currently evaluating the ability to perform additional vehicle benchmarking activities on specific vehicles, focusing on conventional powertrains.

NHTSA is also very much aware that subtle differences between modeled and physical shift schedules can impact vehicle energy consumption. Some of these differences can be due to drive quality limitations amongst other constraints. While numerous constraints have been already taken into account (i.e., shift frequency), NHTSA welcomes any feedback that would contribute to improving the accuracy of the shifting algorithm, especially for future technologies that are not currently in the market.

5.4.2.3.2.1 Transmission Shifting Algorithm

As discussed in Section 5.4.2.2.3.1, a generic shifting algorithm has been developed, continuously improved and validated over the past 15 years. When new transmission technologies are introduced in the market, that algorithm is regularly validated with the latest test data. This section highlights how the algorithm logic was modified when 8 speed automatic transmissions were introduced. Preliminary analysis led to the development of a new calibration and algorithm for 8 speed transmissions as the initial algorithm developed and validated for 6 speed transmissions did not provide sufficient accuracy.

Figure 5.192 shows the simulation results of the vehicle speed, the engine speed, and the engine torque in UDDS compared with testing results for both shifting algorithms.

Initial shifting initializer (simulation 1),New algorithm and calibration (simulation 2)

[JJJJ] See SAE 2011-01-0881, “Test Correlation Framework for HEV System Model,” Ford Motor Company

[KKKK] The Prius was evaluated on the following cycles: UDDS, LA92, NEDC, JC08, NYCC, SC03, Accels, cycle 505, Highway, US06, and SS.

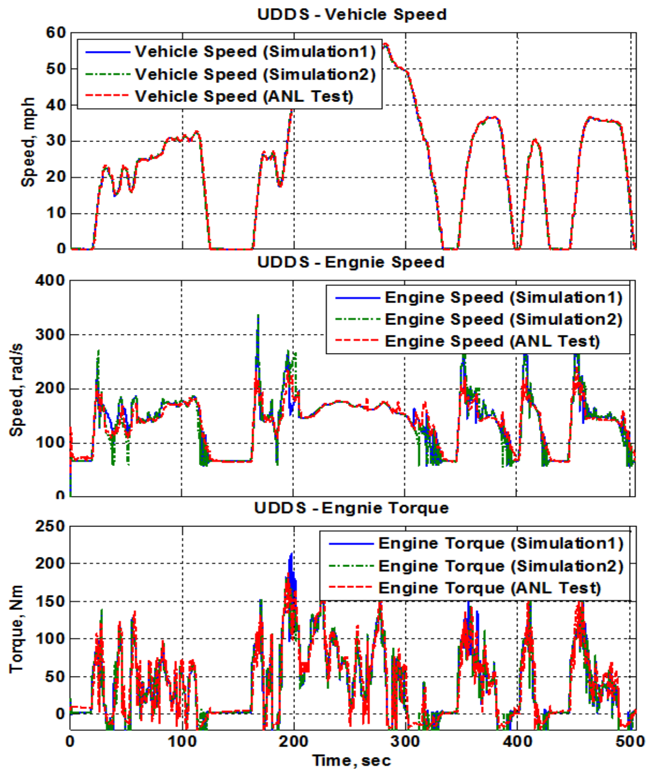

Figure 5.192 2013 Sonata 6ATX Simulation and Testing Results on UDDS (0–505 s) (data source APRF)

In Figure 5.193, the gear numbers over the UDDS (0-505 s) are compared with the test data for two transmission types (6 speed and 8 speed). The first is a 2013 Sonata conventional 6ATX (left) and the second is a 2013 Chrysler 300 8ATX (right). Both simulations show closed shifting performance with the test results, but the results of simulation with the new algorithm show higher accuracy than those of the current algorithm, especially for the eight speed transmission.

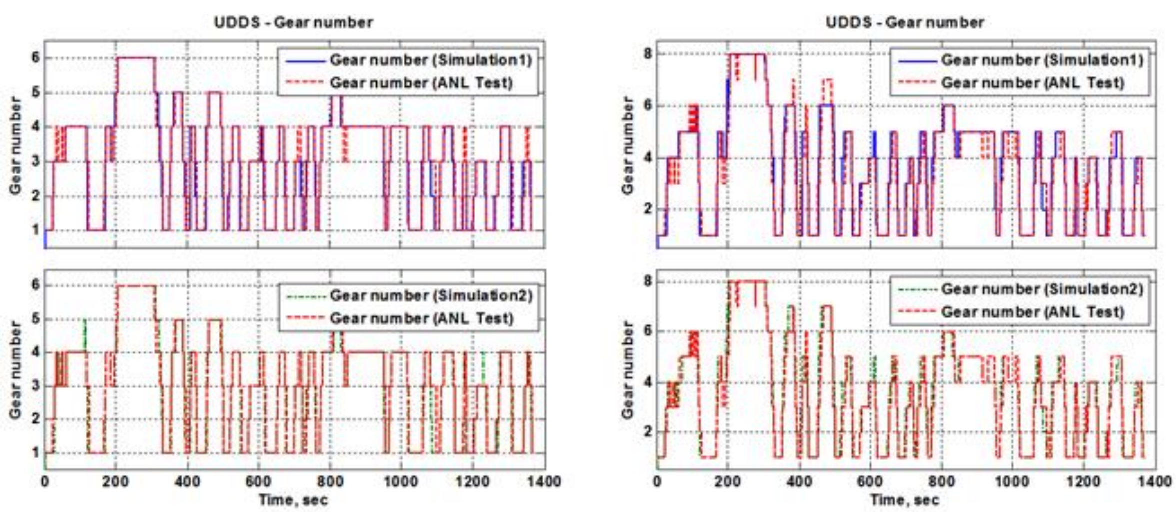

Figure 5.193 Simulation and Testing Results for 6ATX (left) and 8ATX (right) (test data source APRF)

In Figure 5.194, additional simulation results over the NEDC are compared with test data. In this case, a conventional 2012 Fusion with a 6ATX transmission (right) is compared with a 2013 Chrysler 8 ATX (left).

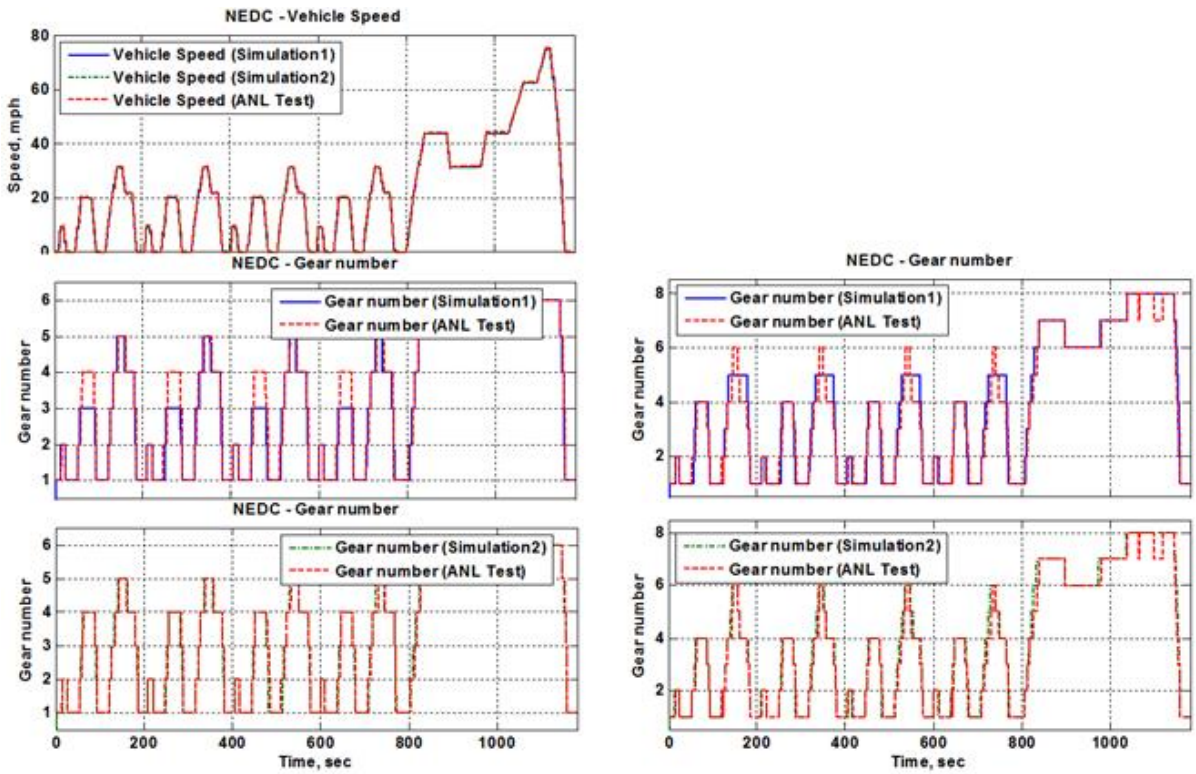

Figure 5.194 Comparison of Simulation and Test Results over the NEDC (test data source APRF)

The CVT model and shifting control strategy developed in Autonomie were validated by comparing the simulation results with the experimental results from Argonne ANL's APRF for multiple vehicles. Figure 5.195 shows the validation results for the target HEV system on the UDDS (city driving on left) and HWFET (highway driving on the right) cycles for the 2012 Honda Civic CVT. The CVT shift dynamic model was validated by comparing the CVT gear ratios: the simulation result for the CVT gear ratio agreed well with the experimental result. The battery was charged or discharged according to the driving mode control strategy. The simulated vehicle speed, gear ratio, engine torque and battery SOC are comparable with the experimental results, demonstrating the validity of the simulation model and control strategy.

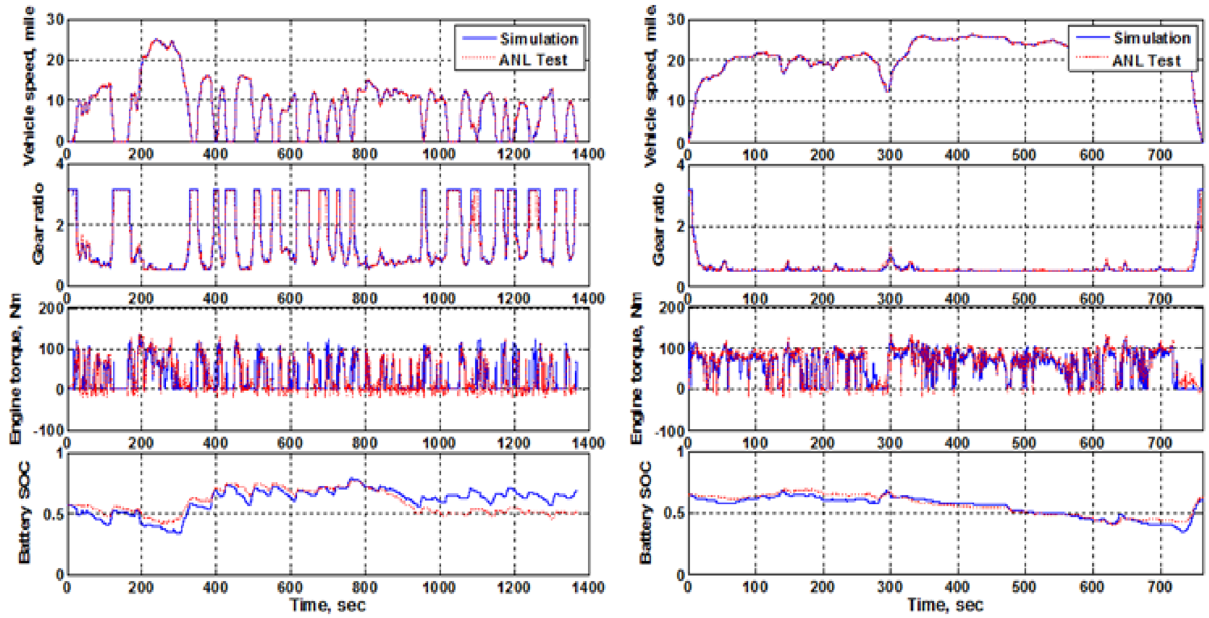

Figure 5.195 Simulation and Test Results Compared for a Honda Civic HEV (test data source APRF)

5.4.2.3.2.2 Powersplit HEV

The power-split HEV model was validated under different thermal conditions. An example of a comparison between the simulation results and the test data for engine operating points is shown in Figure 5.196 for the 2010 Toyota Prius HEV. In Figure 5.196 (left), the engine operating points obtained from simulation results are close to the test data, especially for engine ON/OFF conditions. In addition, the energy consumption and the SOC behavior are also close to the test data.

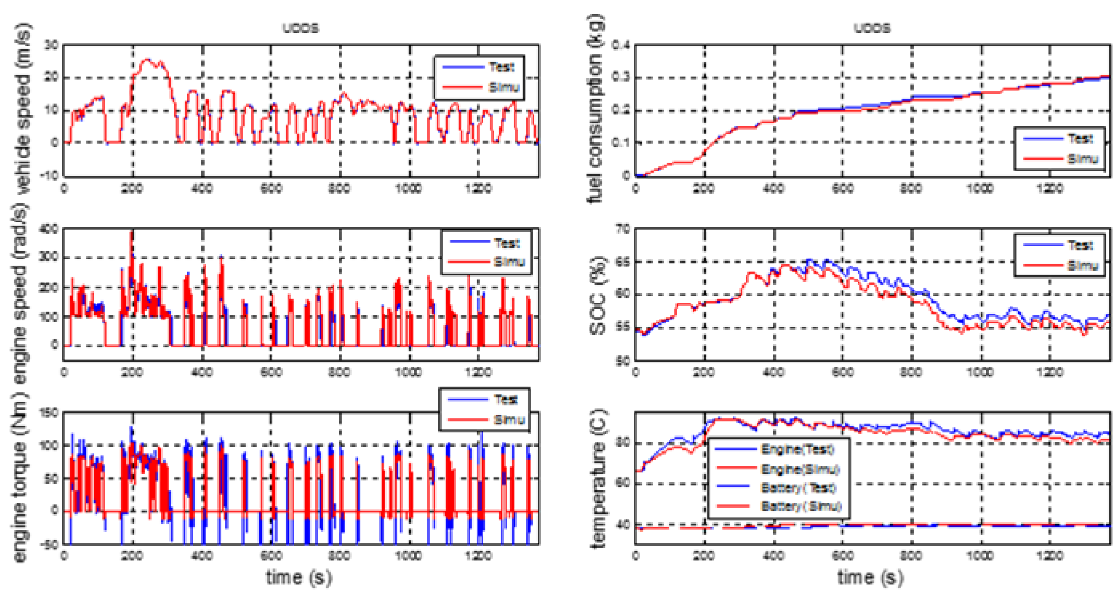

Figure 5.196 Simulation and Testing Results over the UDDS for 2010 Toyota Prius HEV (test data source APRF)

5.4.2.3.3 Pre-transmission HEV

The pre-transmission HEV control logic was validated using Argonne's APRF test data from the 2013 Jetta DCT Hybrid. Comparing the simulation results for the vehicle speed, gear number, and battery SOC on the UDDS cycle with test results, as shown in Figure 5.197, showed good correlation.

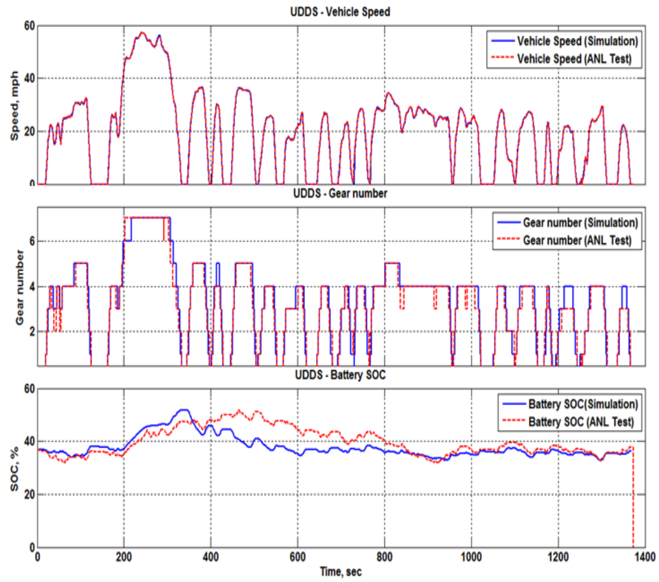

Figure 5.197 Simulation and Testing Results over the UDDS for 2013 Jetta DCT HEV (test data source APRF)

5.4.2.3.3.1 Range Extender PHEV

The range extender PHEV model was validated under different thermal conditions using Argonne's APRF test data from the Gen 1GM Volt. The vehicle speed, component speed, and component torque under normal ambient temperature were successfully compared with the testing results shown in Figure 5.198.

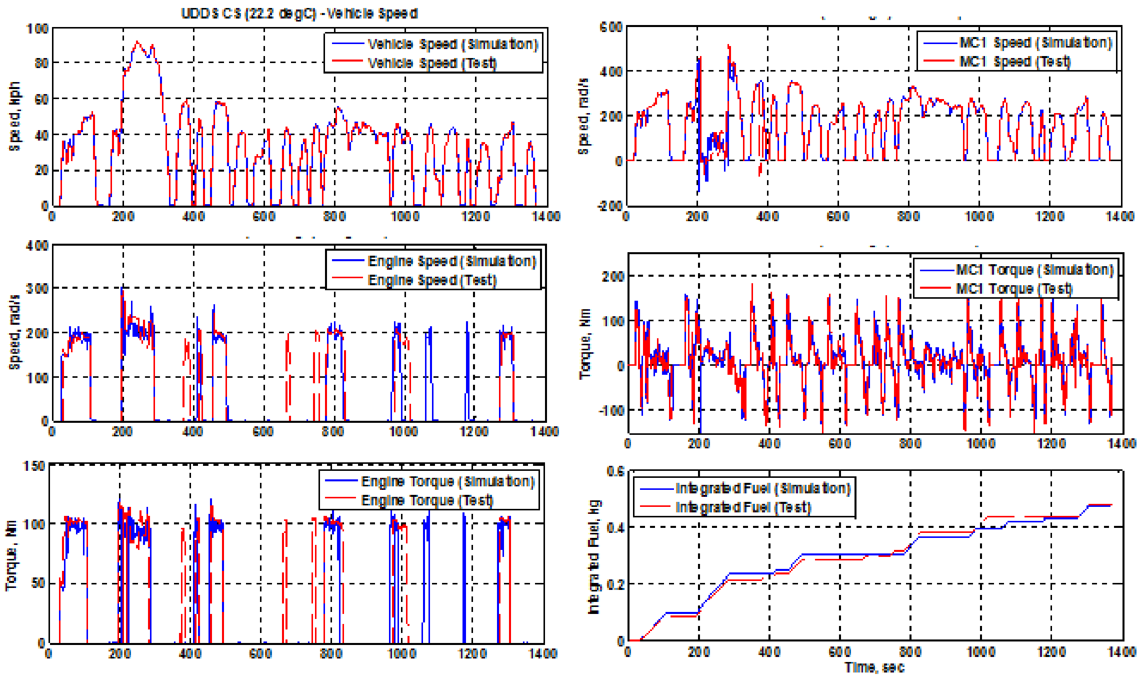

Figure 5.198 Simulation and Testing Results over the UDDS for 2011 GM Volt PHEV (test data source APRF)

In Figure 5.199, the simulated SOC for a 2011 GM Volt PHEV over the UDDS matches well with the testing results during the first 200-seconds, since the controller tends to maintain the engine turned on to warm up the engine, and so the results of simulation show an increase in the SOC at the start of the engine. In addition, the simulation results show that the pattern of the coolant temperature is similar to that from test under normal ambient temperature.

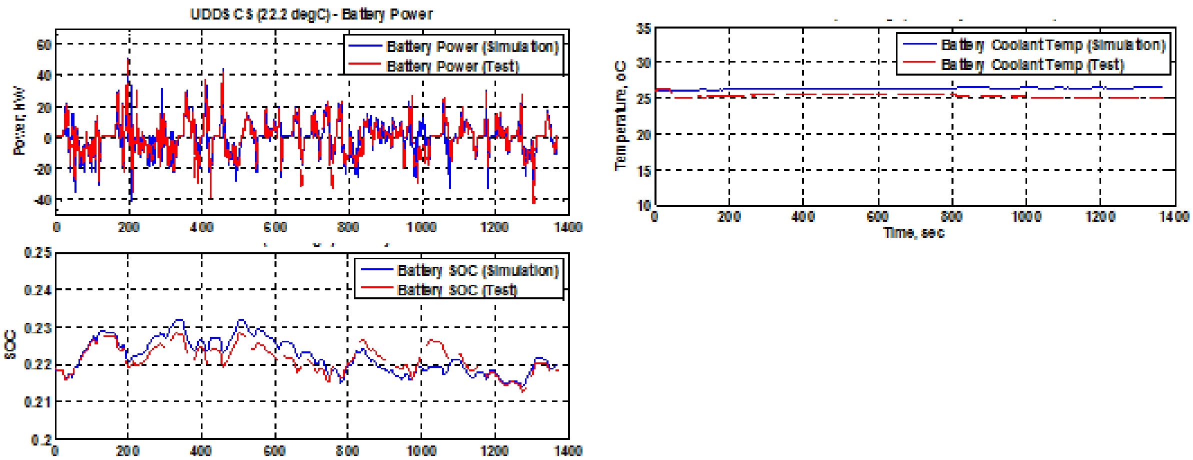

Figure 5.199 Simulation and Testing Results for a 2011 GM Volt PHEV (test data source APRF)

5.4.2.4 Simulation Modeling Study Overview

It is widely acknowledged that full-scale physics-based vehicle simulation modeling is the most thorough approach for estimating future benefits of a package of new technologies. This is especially important for quantifying the efficiency of individual technologies and their synergies with other, especially for those that do not currently exist in the fleet or as prototypes. Developing and executing tens or hundreds of thousands of constantly changing vehicle packages models in real-time is extremely challenging. While this approach was until recently considered generally not practical to implement, the process developed by Argonne in collaboration with NHTSA and the Volpe Center does just exactly that. This approach offers multiple advantages, including the ability to apply varying levels of technologies across the vehicle fleet to account for the full range of vehicle attributes and performance requirements.

As part of rulemakings, the objective of the modeling described in this section is to simulate all of the possible technology combinations in the Volpe model and eliminate the use of synergy factors. The result of this work is a comprehensive understanding of the impact of combined vehicle technologies on energy consumption. To achieve this objective, individual vehicles were simulated to represent every combination of vehicle, powertrain, and component technologies considered for the assessment. The sequential addition of these technologies to the five vehicle classes currently considered results in 140,000 unique vehicle combinations. In addition, powertrain sizing algorithms needed to be run in Autonomie to ensure similar vehicle performances, resulting in over one million simulations.

GT POWER simulation modeling of engine technologies was conducted by IAV Automotive Engineering, Inc. (IAV). GT-Power is a commercially available engine simulation tool with detailed cylinder model and combustion analysis. GT-POWER is used to predict engine performance quantities such as power, torque, airflow, volumetric efficiency, fuel consumption, turbocharger performance and matching and pumping losses, and other parameters. Engine maps resulting from this analysis were then used by ANL in Autonomie.

The current vehicle system simulations included:

- 5 vehicles Classes (Compact, Midsize, Small SUV, Midsize SUV, Pickup)
- 14 engine technologies

- 11 electrification levels (conventional is equivalent to no electrification level)
- 9 transmissions technologies (applied to Low Electrification Level Vehicles only)
- 6 Light Weighting levels
- 3 Rolling Resistance levels
- 3 Aerodynamics levels

NHTSA is planning to simulate all the vehicle classes considered in the Volpe model, including high performance vehicles in the near future. In addition, NHTSA is considering adding new component technologies based on feedback from the Draft TAR and on-going and future benchmarking activities.

The process developed includes the following steps as shown in Figure 5.149:

1) Collect/develop all the technology assumptions
2) Create fuel maps for engine technologies.
3) Develop a process to automatically create the vehicle models.
4) Size the individual vehicles to all meet the similar vehicle technical specifications (note that some vehicles inherit component and energy from previous decision tree steps).
5) Simulate each vehicle model on the standard driving cycles.
6) Create a database with all the required input for the Volpe model.
7) Create post-processing tool to validate the database content.

Since this process has to be performed in an acceptable amount of time, distributed computing was extensively used for vehicle sizing and simulation

The remaining subsections of this chapter describe each step of the analysis methodology.

5.4.2.5 Selection of Technologies for Modeling[LLLL]

Table 5.218 lists the engine, transmission, and vehicle technologies simulated in this study.

Table 5.218 Vehicle and Powertrain Technologies Evaluated

Engine Technologies	Drivetrain Technologies
Variable Valve Timing	6-Speed Manual Transmission
Variable Valve Lift	7-Speed Manual Transmission
Stoichiometric gasoline direct injection	6-Speed Automatic Transmission
Cylinder Deactivation	8-Speed Automatic Transmission
High Compression Ratio	Continuously Variable Transmission
Engine Friction Reduction	6-Speed Dual Clutch Transmission
Turbocharging and downsizing	8-Speed Dual Clutch Transmission
Stoichiometric Exhaust Gas Recirculation	Secondary Axle Disconnect
Downspeeding	Stop Start 12 Volt
Cooled EGR	Mild Alternator Regenerative Braking
Miller Cycle	48 Volt Belt ISG
Advanced Diesel	100 Volt Crank ISG
Improved turbocharger efficiency	Strong Hybrid Power Split

[LLLL] Not all of the technologies in the Volpe model decision tree were evaluated by Argonne. Compressed natural gas, liquid natural gas, liquid propane gas, and LGDI were not modeled by Argonne and are not included in Table 5.218.

Injection pressure increase	Strong Hybrid P2
Downspeeding with increased boost pressure	Plug-in Hybrid (30 mile all-electric range)
Closed loop combustion control	Plug-in Hybrid (50 mile all electric range)
Low pressure EGR	Electric Vehicle (200 mile range)
	Fuel Cell Vehicle
Vehicle Technologies	Improved Accessories
Aerodynamic Drag Reduction	Electric Power Steering
Mass Reduction	Electric Water Pump
Improved Tire Rolling Resistance	Electric Cooling Fan
Low Drag Brakes	High Efficiency Alternator

5.4.2.6 Modeling Assumptions

Section 5.2 presented the agencies' joint assessment of the current state of technologies and the advancements that have occurred since the publication of the FRM. As stated earlier, the agencies have reexamined every technology considered in the FRM, as well as assessing some technologies that are currently commercially available but did not play a significant role in the FRM analysis, as well as emerging technology for which enough information is known that it may be included in this Draft TAR. The categories of technologies discussed in Section 5.2 include: engines, transmissions, electrification, aerodynamics, tires, mass reduction, and other vehicle technologies such as improved accessories and low drag brakes. For a descriptions of these technologies, please refer to that section. This section adds information specific to the NHTSA CAFE analysis of engines, transmissions, electrification, aerodynamics, tires, mass reduction, and other vehicle technologies.

5.4.2.6.1 Vehicle Level

Table 5.219 provides the reference specifications used for the five vehicle classes modeled by ANL. The vehicles were sized to meet each vehicle technical specification (for example performance and range for electric vehicles).

Table 5.219 Reference Vehicle Assumptions for all Classes in Autonomie

	Compact Car	**Midsize Car**	**Small SUV**	**Midsize SUV**	**Pickup**
Wheel mass (kg)	85	85	90	95	95
Wheel radius (m)	0.31725	0.31725	0.35925	0.3677	0.38165
Glider mass (kg)	820	1000	1150	1260	1500
Frontal Area (m2)	2.3	2.4	2.8	2.9	3.3
Drag Coefficient	0.32	0.31	0.36	0.37	0.45
Rolling resistance	0.0075	0.008	0.0084	0.0084	0.009
Electrical Base Acc Load (W)	240	240	240	240	240
EXTRA: Electrical Acc Load for cooling for EV & PHEV 30&40 (W)	220	220	220	220	220
Fuel Tank Size for Conventional (gal)	12	17	17	22	26
Fuel Tank Size for HEV/PHEVs (gal)	10	13	13	17	20
Fuel Tank size for Fuel Cell	320 miles	320 miles	320 miles	320 miles	320 miles

Autonomie has multiple driver and chassis models that can either use vehicle dynamometer coefficient or the aerodynamic equations. The first option is usually only selected when performing vehicle validation. The aerodynamic equations, leveraging Cd, FA, and Crr, were used to perform all simulations.

While only five vehicle classes were simulated by ANL, the Volpe model includes additional vehicle classes. As a result, effectiveness results from the two non-modeled classes have been defined based on results from the five modeled classes. In the next round of simulations, all the vehicle classes required by the Volpe model will be simulated with Autonomie.

5.4.2.6.2 Gasoline and Diesel Engines

IAV provided wide-open-throttle engine performance values and brake-specific fuel consumption (BSFC) maps for the engine technologies listed in Table 5.218 IAV validated the GTPower model with existing dynamometer measurements for several engines. The models were trained over the entire engine operating range and have predictive combustion capability. This is essential, since the BSFC prediction needs to be accurate while the engine setup is subject to change.

Relevant engine geometries/parameters were measured and modeled with friction/flow losses, heat transfer, and other parameters and calibrated to match measurements. Displacement normalized mechanical friction was modeled as a function of engine speed and specific load. A combustion model was trained to predict fuel heat release rates in response to physical effects such as cylinder geometries, pressure, temperature, turbulence, residual gas concentration and other parameters. A knock correlation based on in-cylinder conditions and fuel octane rating predicts if knock will occur and at what intensity. A combustion stability threshold prediction was trained using covariance of IMEP data and is used for understanding EGR tolerance, especially at low loads. Load controllers were developed for fuel/air path actuators and targeting controllers drive optimal and knock limited combustion phasing just as in a physical engine. Careful modeling practice was used to provide confidence that calibrations will scale and predict reasonable/reliable as parameters are changed throughout the various technology concept studies.

IAV provided 14 engine maps in total: eight of these are naturally aspirated gasoline engines, five are turbocharged gasoline engines, as well as one diesel engine. One naturally aspirated gasoline engine map was developed based on benchmarking of a 2014 SKYACTIV-G 2.0L engine from a Mazda 6 by EPA. Finally, one Atkinson engine map generated using Argonne test data was used for electrified vehicles with power split architecture. Thus, the total number of engine maps used in the study is 16.

For all engines, engine speed, BMEP, brake torque, fuel flow rate, PMEP and FMEP data were provided in a standardized format to Argonne. These channels were provided from 1,000 RPM to the max engine speed and from 0 bar BMEP to full load to provide a full operation map. Fuel flow rates at zero output torque were provided separately from 650 RPM (defined idle) to 6000 RPM. Negative torque data was also provided which included the minimum fueled torque curve from the baseline engine concept; 1) unfueled motoring curves from the baseline concept; and 2) unfueled motoring curve from cylinder deactivation concept at wide open throttle. IAV used gasoline with LHV = 41.3 MJ/kg for the mapping but the naturally aspirated engines were calibrated with 87 (R+M)/2 rating fuel and the turbocharged engines used 93 octane fuel. IAV did not use certification fuel and so ANL adjusted the vehicle fuel economy results to represent certification fuel by using the ratio of the lower heating values of the test and certification fuels. Values for brake specific fuel consumption at different engine loads are shown in Figure 5.200.

IAV Engine 1 is a naturally aspirated PFI 2.0-L gasoline engine with VVT from a MY2013 vehicle. A brake specific fuel consumption (bsfc) engine map was generated from dynamometer testing of the existing engine, which then served as the baseline map for all simulated naturally aspirated engines (Engines 1-8a). Figure 4 shows the 2L, 4-cylinder naturally aspirated PFI with DOHC and dual cam VVT. The engine calibrations were fully optimized for best BSFC and maximum torque.

Each subsequent engine (bsfc map) represents an incremental increase in technology advance over the previous technology. Engines 2-4 add variable valve lift (VVL), direction injection (DI), and cylinder deactivation (deac) sequentially to the base engine map. Engine 5a converts Engine 1 from DOHC to SOHC. Engines 5b, 6a, 7a, and 8a add some friction reduction to Engines 5a, 2, 3, and 4[MMMM]

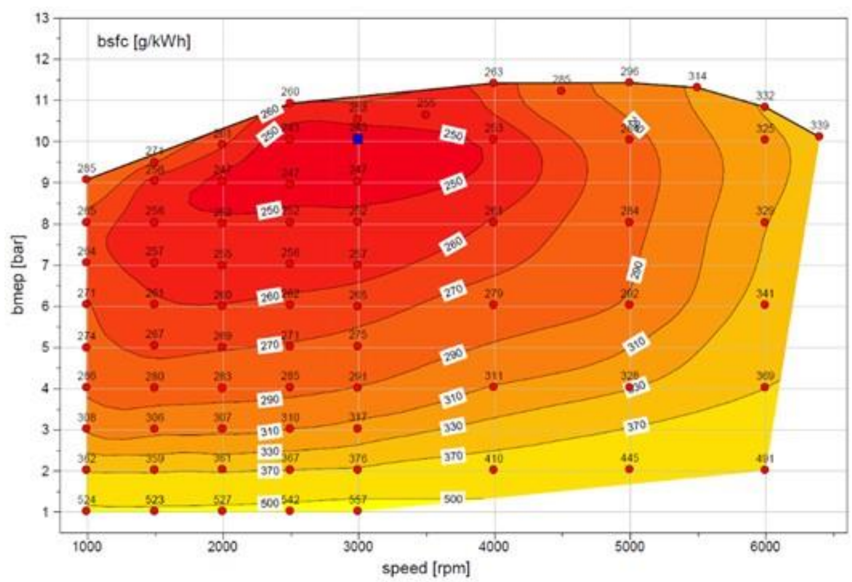

Figure 5.200 IAV Gasoline Engine1 Map

For Engine 2, a VVL system was added to the intake valves to Engine 1. Both valve lift and timing were optimized. This engine allows for reduced pumping work at low loads and more torque at low speeds due to reduced intake duration.

[MMMM] In stage 1, FMEP is reduced by 0.1 bar and in level 2 FMEP is reduced by 25 percent over the entire operating range.

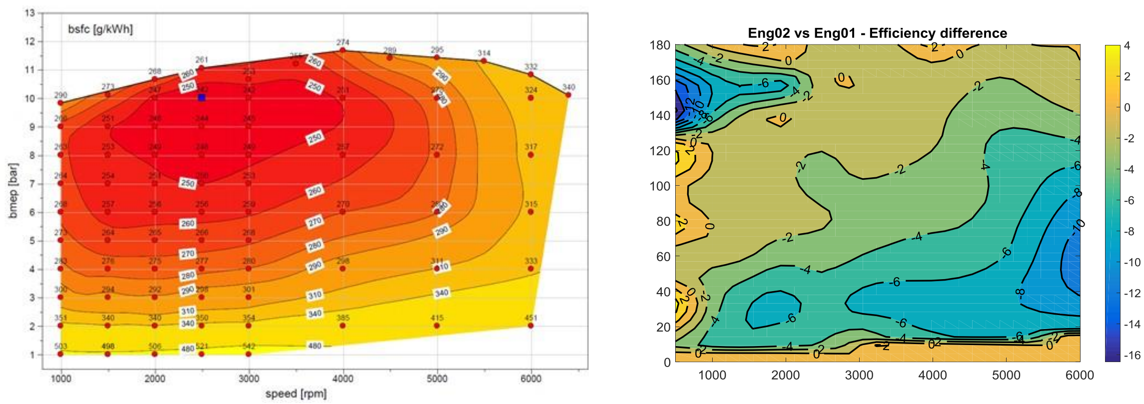

Figure 5.201 IAV Gasoline Engine2 Map (left), Incremental Improvement vs Eng1 (right)

PFI Engine 2 was converted to direct injection to model engine 3. The compression ratio was raised from 10.2 to 11.0 and injection timing optimized. Direct injection provides greater knock tolerance, allowing higher compression ratio and increased efficiency over entire map.

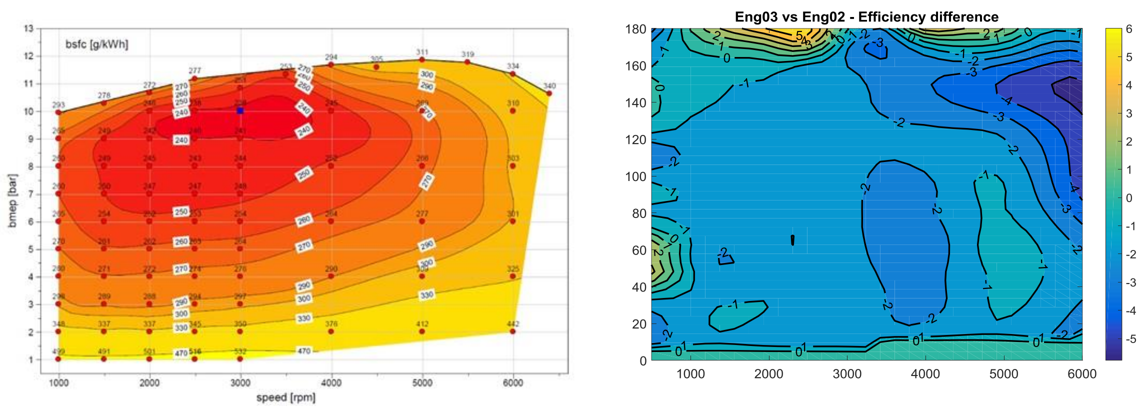

Figure 5.202 IAV Gasoline Engine3 Map (left), Incremental Improvement vs Eng2 (right)

Cylinder deactivation was added to engine 3 to model engine 4. This technology deactivates the intake and exhaust valves and prevents fuel injection into some cylinders during light-load operation. The engine runs temporarily as though it were a smaller engine which substantially reduces pumping losses. For 4 cylinder applications, the engine fires only 2 cylinders at low loads and speeds below 3000 RPM and less than 5 bar BMEP by deactivating valves on 2 cylinders. The main benefit is that the effective load is doubled on 2 cylinders providing less pumping work and higher efficiency.

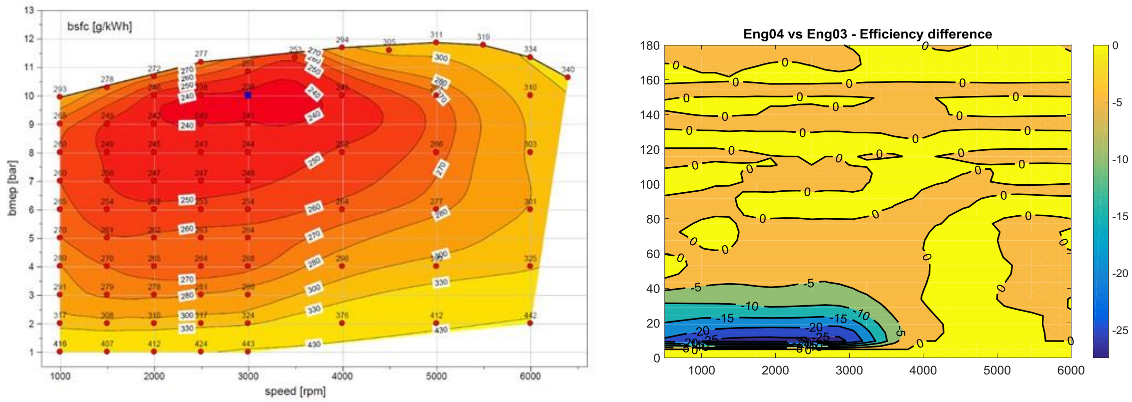

Figure 5.203 IAV Gasoline Engine4 Map (left), Incremental Improvement vs Eng3 (right)

Engine 5b was developed to assess the benefit of reduced friction. Reduction in engine friction can be achieved through low-tension piston rings, roller cam followers, improved material coatings, more optimal thermal management, piston surface treatments, cylinder wall treatments and other improvements in the design of engine components and subsystems that improve engine operation. A SOHC engine with VVT was used and its FMEP reduced by 0.1 bar over its entire operating range. Valve timing was optimized for fixed overlap camshaft.

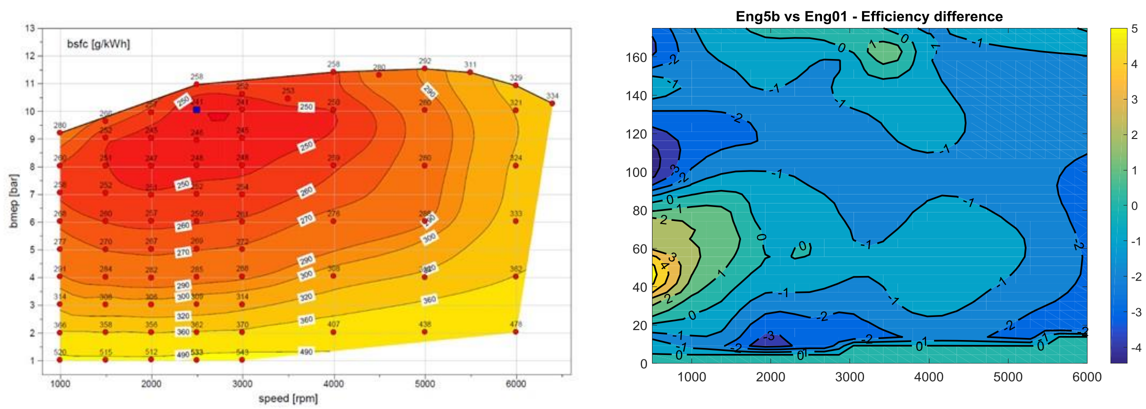

Figure 5.204 IAV Gasoline Engine5b Map (left), Incremental Improvement vs Eng1 (right)

Engine 6a was developed to assess the friction reduction impact on Engine 2. Reduced friction will improve efficiency at all load points as well as raise the full load line.

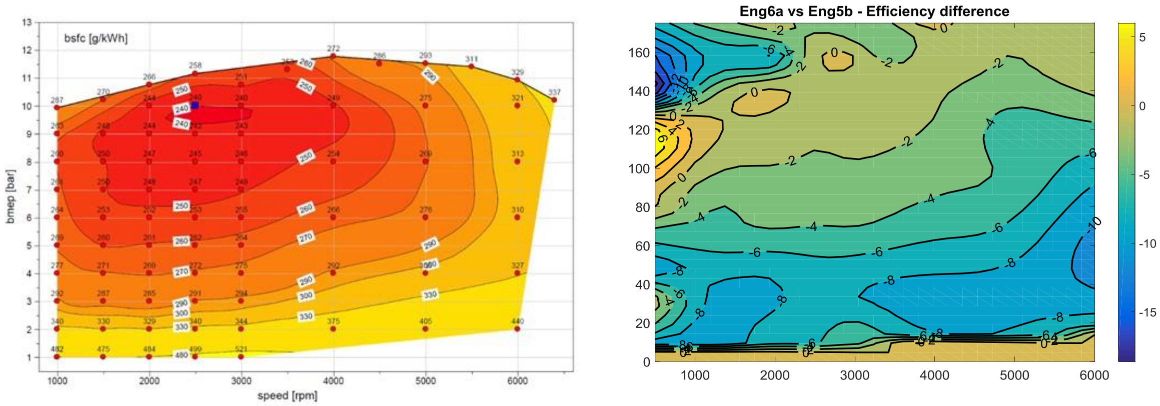

Figure 5.205 IAV Gasoline Engine6a Map (left), Incremental Improvement vs Eng5b (right)

Engine 7a was developed to assess the friction reduction impact on Engine 3.

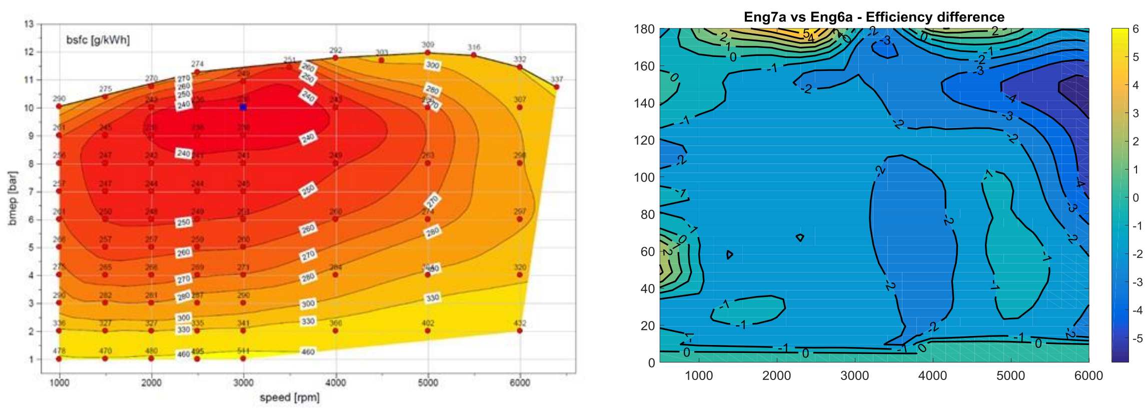

Figure 5.206 IAV Gasoline Engine7a Map (left), Incremental Improvement vs Eng6a (right)

Engine 8a was developed to assess the friction reduction impact on Engine 4.

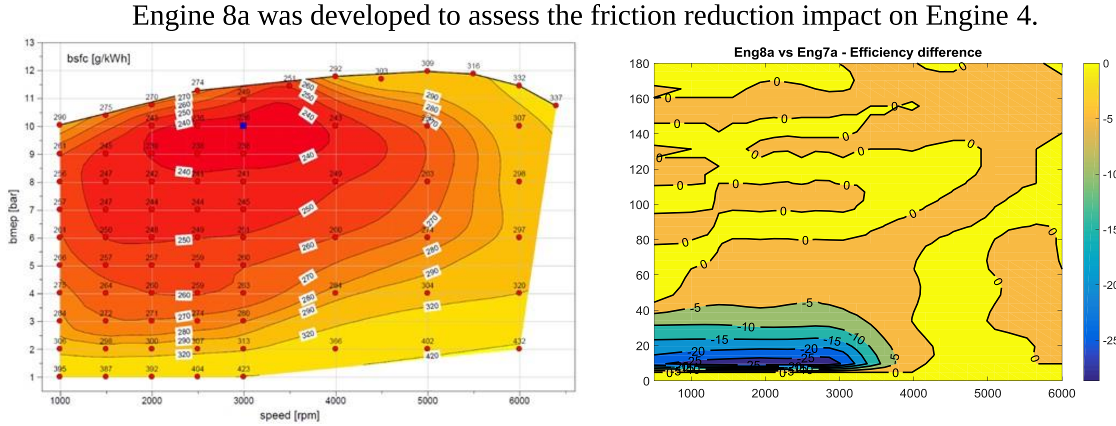

Figure 5.207 IAV Gasoline Engine8a Map (left), Incremental Improvement vs Eng7a (right)

IAV Engine 12 is the base engine for all the simulated turbocharged engines (Engines 13-16) and was also validated using engine dynamometer test data. Turbocharging and downsizing increases the available airflow and specific power level, allowing a reduced engine size while maintaining performance. This reduces pumping losses at lighter loads in comparison to a larger engine. Engine 12 represents a 1.6L, 4 cylinder turbocharged, direct injection DOHC engine with dual cam VVT and intake VVL. A compression ratio of 10.5:1 was used along with side mounted direct fuel injectors and a twin scroll turbocharger. The calibrations were fully optimized for best BSFC. Figure 5.208 shows fuel consumption at given engine speeds and loads.

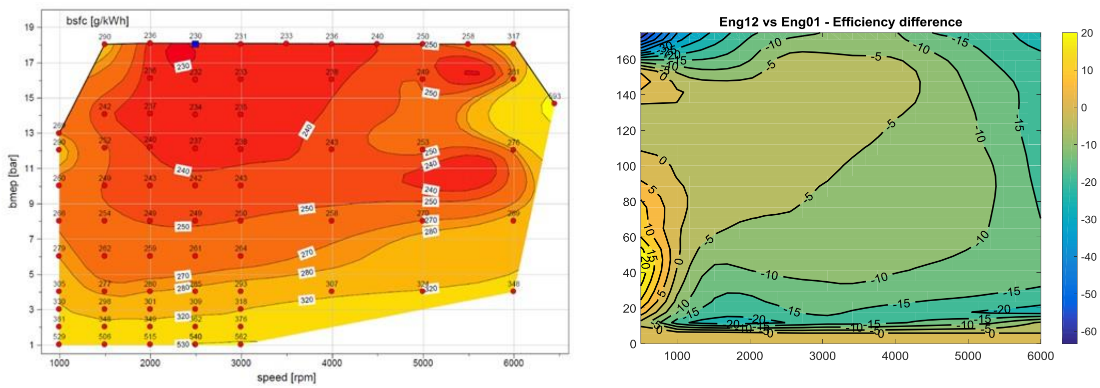

Figure 5.208 IAV Gasoline Engine12 Map (left), Incremental Improvement vs Eng1 (right)

Engine 12 has been further downsized to a 1.2L to represent engine 13. The turbocharger maps scaled to improve torque at low engine speeds. All the turbocharged direct injection engines described below have been developed using 93 octane. NHTSA understands that using such fuel might lead to overestimating the effectiveness of the technology, especially for high BMEP engines. While the engine maps will be updated to represent regular grade octane gasoline, NHTSA does not expect significant effectiveness change on the standard driving cycles as the engines operate at lower loads.

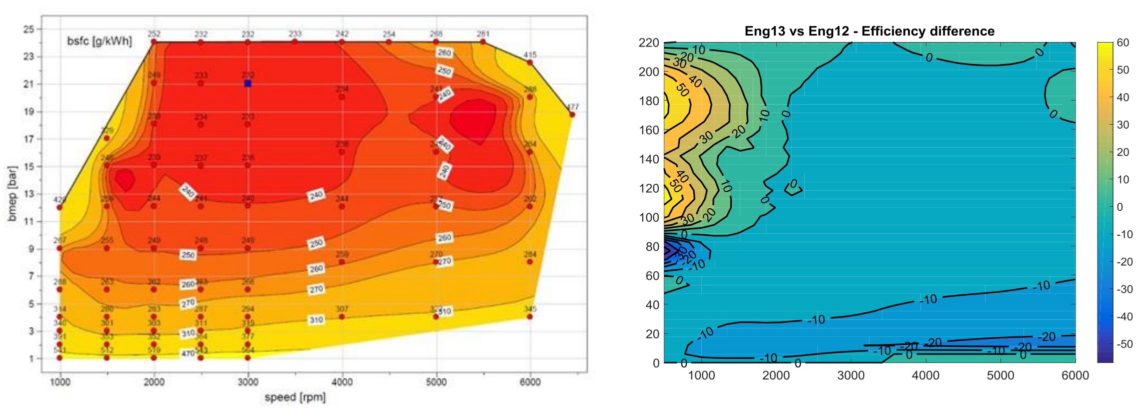

Figure 5.209 IAV Gasoline Engine13 Map (left), Incremental Improvement vs Eng12 (right)

High pressure cooled EGR was added to engine 13 to develop engine 14. Exhaust gas recirculation boost increases the exhaust-gas recirculation used in the combustion process to increase thermal efficiency and reduce pumping losses. Levels of exhaust gas recirculation approach 25 percent by volume in these highly boosted engines (this, in turn raises the boost requirement by approximately 25 percent). Cooled EGR target set points were optimized.

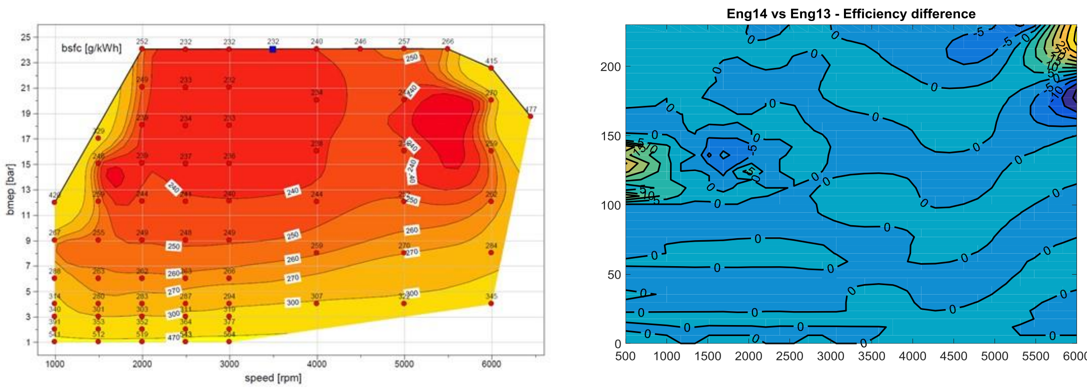

Figure 5.210 IAV Gasoline Engine14 Map (left), Incremental Improvement vs Eng13 (right)

Engine 14 was further downsized to 1.0L to develop Engine 15. Cooled EGR target set points were re-optimized and turbocharger maps were re-scaled. Downsizing with cooled EGR reduces in-cylinder temperatures and knock, and lower the need for enrichment to protect emission control devices.

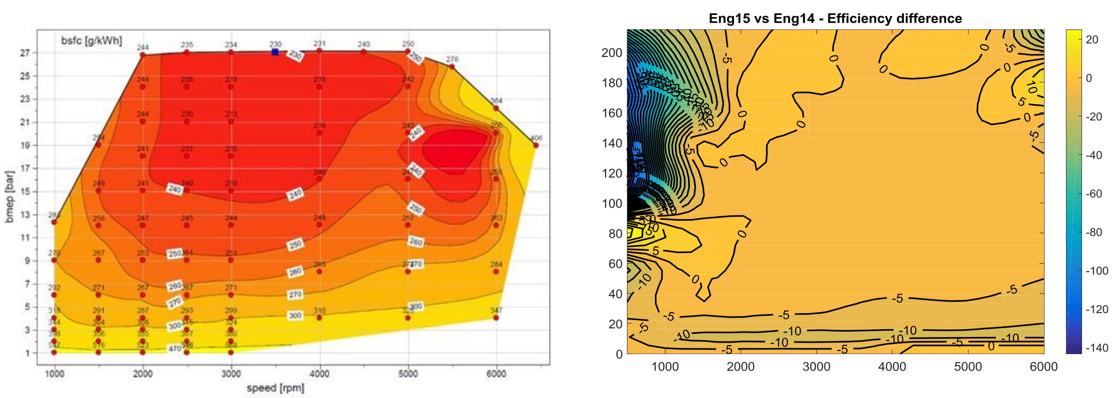

Figure 5.211 IAV Gasoline Engine15 Map (left), Incremental Improvement vs Eng14 (right)

Engine 15 was converter to a 3 cylinder 1.0L concept to develop engine 16. To do so, intake and exhaust piping were scaled to account for larger mass flows through each cylinder and cooled EGR target set points were re-optimized.

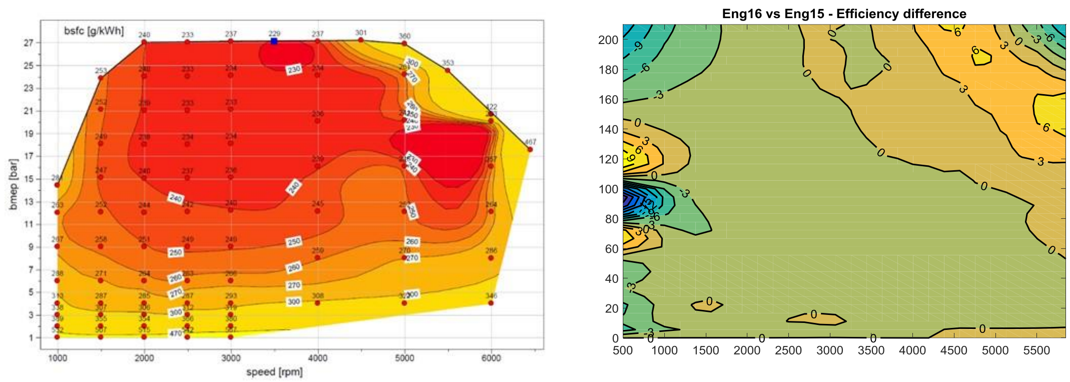

Figure 5.212 IAV Gasoline Engine16 Map (left), Incremental Improvement vs Eng15 (right)

Figure 5.213 shows the engine map for the diesel engine. Diesel engines have several characteristics that give superior fuel efficiency, including reduced pumping losses due to lack of (or greatly reduced) throttling, and a combustion cycle that operates at a higher compression ratio, with a very lean air/fuel mixture, than an equivalent-performance gasoline engine. This technology requires additional enablers, such as NOx trap catalyst after-treatment or selective catalytic reduction NOx after-treatment. For the diesel engine, measured data, including engine speed, BMEP, brake torque, brake power, BSFC channels were provided.

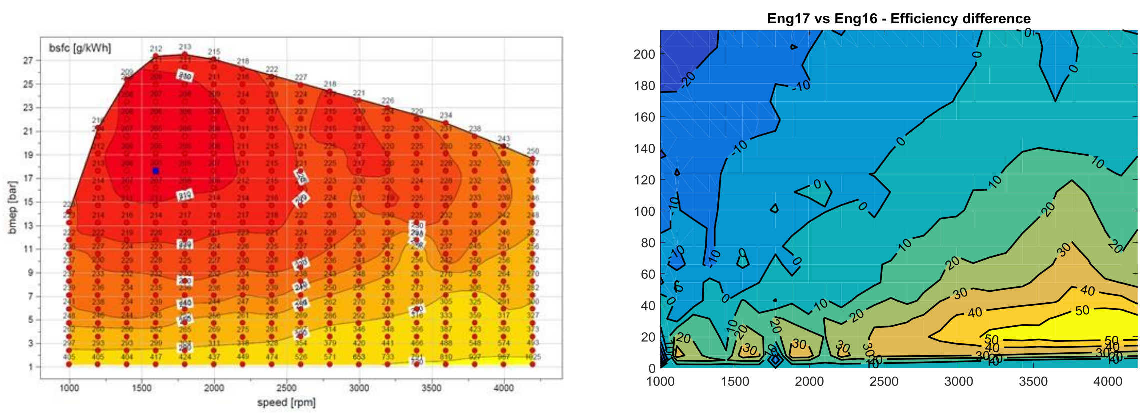

Figure 5.213 Diesel IAV Engine17 Map (left), Incremental Improvement vs Eng16 (right)

The last engine modeled for conventional powertrains was a high compression ratio engine. Higher compression ratio improves piston power stroke while helping to prevent knock. Atkinson cycle engines combine an increase in compression ratio and variable intake camshaft timing. Although producing lower overall power for a given displacement, this engine has specific high efficiency operating points and is capable of significant CO_2 reductions when properly matched to a strong hybrid system. The engine map was developed based on the 2014 SkyActiv 2.0L engine from a Mazda 6 using test data collected by the U.S. EPA and is shown in Figure 5.214.

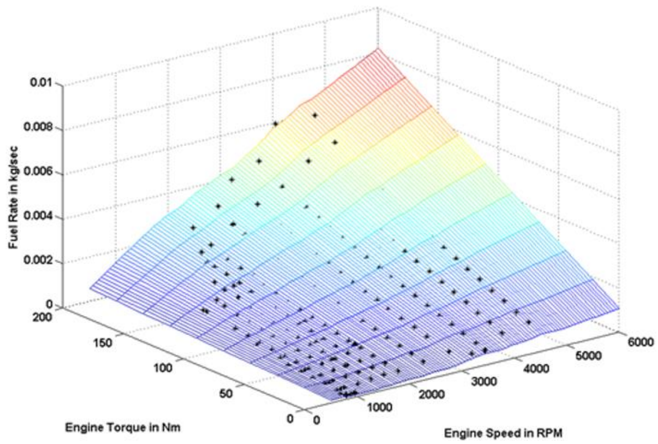

Figure 5.214. High Compression Ratio Engine Map Developed From Dynamometer Test Data

Atkinson engine technology was also used for power split hybrid powertrains. The engine map was developed based on APRF test data and published literature. It is important to note that pre-transmission hybrids as well as multi-mode hybrids have also been simulated. In those cases, all the engine technologies previously described have been considered.

NHTSA is planning to continue to work with IAV to update the existing engine maps for the technologies considered so far as based on feedback and comments received as part of the Draft TAR as well as develop new high fidelity models for additional technologies to represent potential future technologies. NHTSA will ensure that all future engine model development is performed with regular grade octane gasoline. NHTSA will also continue to gather information on the latest engine technologies, both from public and proprietary sources, to compare the effectiveness each of those specific OEM engines with the GTPower models.

5.4.2.7 Description of Engine Technologies Evaluated

This next sections provides NHTSA-specific details on the engine technologies modeled in the gasoline and diesel engines. Please refer to section 5.2 for a general description of variable valve timing and lift, friction reduction, EGR, and developments in the technologies since the publication of the FRM.

5.4.2.7.1 *<u>Friction reduction</u>*

Friction reduction has been shown to offer significant improvements in vehicle fuel consumption. Engines were subjected to two levels of reduction in friction mean effective pressure.

1) A reduction in FMEP by 0.1 bar across the entire engine speed range.
2) An extreme friction reduction (25 percent FMEP) across the entire speed range.

In the Volpe modeling, only the first level of friction reduction has been considered. Predictive friction equation was calibrated from test data used in Engines 1-8b to allow for a smooth and systemic friction study but may under predict FMEP at high loads with late combustion phasing. Map based FMEP lookup compiled from test data was used for Engines 12-16. Due to different methods, we cannot draw direct conclusions on naturally aspirated vs. downsized engine friction.

5.4.2.7.2 Cylinder Deactivation

Cylinder deactivation operates the remaining, firing cylinders at higher BMEP under light load conditions. This moves operation of the remaining cylinders to an area of engine operation with less throttling and thus lower pumping losses and reduced BSFC.

Two separate engine maps are used to model the cylinder deactivation benefits. A logic described below is then used to decide when to use or not the functionality. Due to NVH considerations, cylinder deactivation operation is not performed in several vehicle operation modes, such as vehicle warm-up, low gears, idle, and low engine speed in production vehicles.[NNNN] Cylinder deactivation was disabled under the following vehicle and engine conditions:

1) If the engine is at idle or any speed below 1000 RPM and above 3000 RPM.
2) If the vehicle is in the 1st or the 2nd gear.
3) If the engine load is above half the max BMEP of the engine (and a certain hysteresis is maintained to prevent constant activation and deactivation).

Changes in the transmission shifting calibration (like lugging speed limits) and additional torque converter slippage during cylinder deactivation have not currently been considered.

5.4.2.7.3 Turbocharged Engines

In addition to the naturally aspirated engines, maps for turbo technologies were also developed using GT-Power. With turbo engines, there is a ‘lag’ in torque delivery due to the operation of the turbo charger. This impacts vehicle performance, and vehicle shifting on aggressive cycles. Turbo lag has been modelled in Autonomie for the turbo systems based on principles of a first order delay, where the turbo lag kicks in after the naturally aspirated torque limit of the turbo engines has been reached. Figure 5.215 shows the response of the turbo engine model for a step command.

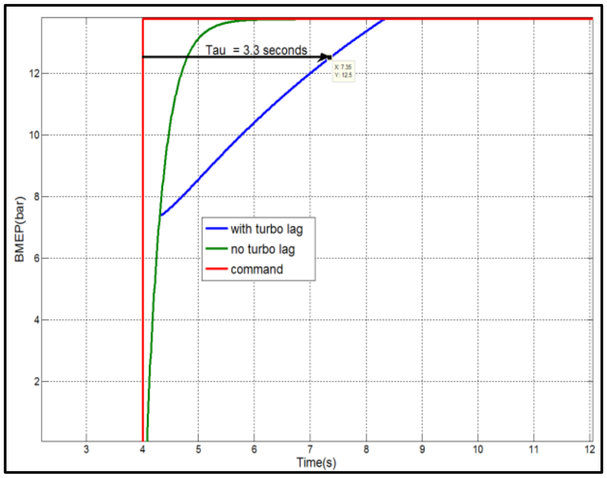

Figure 5.215 Turbo Charged Engine Response for a One Liter Engine

[NNNN] Cold start conditions were not a factor for the simulations since the study assumed “hot start,” for all simulations, with the engine coolant temperature steady around 95 degrees C.

The turbo response varies with engine speed, i.e. at higher speeds, the turbo response is faster due to higher exhaust flow rates. It should be noted that the baseline engine maps (Engine 1 and Engine 12) for the naturally aspirated and the turbo engines were validated with test data. Maximum torque line on boosted engines is adjustable based on boost pressure (Engine 12 especially could have higher torque potential).

5.4.2.8 Transmissions

To represent the current market distribution and trends, NHTSA considered AT, MT, DCT, and CVT transmission technologies in the current assessment.

As was discussed in Section 5.2, above certain values, additional gearing and ratio spread provide minimal additional fuel economy benefits. For this reason, the maximum gear number considered in the present analysis was limited to 8.

Based on the current market distribution, trends and benefit limitations of very high gear numbers, NHTSA, Argonne and Volpe selected the following configurations for use in the Volpe model:

- 5-speed automatic (5AU - baseline vehicle)
- 6-speed automatic (6AU)
- 8-speed automatic (8AU)
- 6-speed dual-clutch (6DCT)
- 8-speed dual-clutch (8DCT)
- Continuously variable (CVT)
- 5-speed manual (5DM)
- 6-speed manual (6DM)
- 7-speed manual (7DM)

Progressive transmission gear ratios have been designed for each transmission type considering trends in gear span and ratios, as well as expected differences in vehicle performance and energy consumption based on the transmission technology. On the basis of a literature review and evaluation of Argonne's APRF chassis dynamometer test data for multiple conventional vehicles, the following criteria were selected for the design of transmission gear ratios, final drive ratios, and shift parameters.

- The vehicle should shift to top gear above a certain vehicle speed (i.e. 45 mph).
- In top gear, the engine should operate at or above a minimum engine speed (i.e. 1,250 rpm) to prevent engine lugging.
- The number of gear shifts for specific transmission on each cycle was defined using APRF vehicle test data. For example, for a 6-speed transmission, on the Urban Dynamometer Driving Schedule cycle, the number of shifts should be around 110 to 120 based on a review of chassis dynamometer test data. Note that this constraint is only evaluate after the simulations and is only used to highlight vehicles with potential drive quality issues.
- Gear span and final drive ratios should be based on industry trends.
- Engine operation will be restricted in the low-speed/high torque region to prevent noise, vibration, and harshness issues and ensure drive quality.
- The span of the 8-speed transmissions is higher than that of the 6-speed transmission.

- The span of the 8-speed DCT is slightly higher than the span of the 8-speed automatic to compensate for the lack of torque multiplication of the torque converter for the automatic transmission.
- The vehicle should be able to meet or exceed Vehicle Technical Specifications (VTSs) related to grade (in first and top gear) and passing performance.

Dual clutch transmissions with torque converters are being introduced in the market. But, based on the 2014 EPA Report on light –duty vehicles, a significant majority of the DCT transmissions in the market today are without the use of a torque converter device.[615] Therefore, in this study, it is assumed that a torque converter is not used with the DCT.

Transmission design parameters that substantially affect engine operation - gearing ratios, ratio spread, and shift control strategy - are all used to optimize the engine operation point, and thus the effectiveness of these transmission parameters depend in large part on the engine it is coupled with. Advanced engines incorporate new technologies, such as variable valve timing and lift, direct injection, and turbocharging and downsizing, which improve overall fuel consumption and broaden the area of high-efficiency operation. With these more advanced engines, the benefits of increasing the number of transmission gears (or using a continually variable transmission) diminish as the efficiency remains relatively constant over a wider area of engine operation. Due to the impact of transmission design, Argonne conducted a review of current transmissions in the market to select the design parameters for the study.

Based on publicly available data, the gear spans, transmission gear ratios, and final drive ratios for several vehicles were reviewed. Table 5.220 lists the minimum and maximum values for gear ratio span, final drive ratio, and engine speed in top gear at 45 mph (indicator of top gear ratio). The table also lists the selected values for the 6-speed transmission. A similar selection was made for the 8-speed case, as well.

Table 5.220 Gear Ratio, Final Drive Information for Sample 6-Speed Automatic Transmission Vehicles

	Minimum Value	Maximum Value	Selected Value for Study
Span	5.6	6.15	6.00
Final Drive	3.2	4.58	3.74
Engine Speed (45 mph)	1,234 RPM	1,604 RPM	1,420 RPM

A gear span of 6 was selected for the 6-speed case, because current trends in transmission technology reflect increasing gear spans, thus driving selection of a span closer to the maximum observed value.

Similarly, span and final drive ratios for the 8-speed AU transmission were chosen, considering available transmissions in the market today as well as the criteria listed above. It should be noted that there are very few compact cars currently in the market with 8-speed transmissions, and most of the available data suggest the use of 8-speed transmissions in the large sedan (and higher) segments, luxury cars, and sports cars. Therefore, the decision on gear span and final drive ratio was made so as to meet the criteria listed above.

Table 5.221 lists the span, final drive ratio, and engine speed at 45 mph for the 6-speed AU, 8-speed AU, and 8-speed DCT transmissions. With a start-stop (BISG) powertrain configuration, the electric machine provides additional torque during vehicle launch, thus aiding in vehicle acceleration and performance. Therefore, it is possible to have a lower final drive ratio than for a conventional powertrain with the same transmission. A very small final drive ratio would result in increased transmission gear ratios to attain the same performance and grade ability requirements, and therefore, an inherent trade-off exists between higher transmission gear ratio and final drive ratio. Finding an optimum trade-off between transmission gear ratio and final drive ratio for the BISG is beyond the scope of this study. Table 5.221 shows gear span, final drive and engine speed in top gear at 45 mph for a 6-speed AU, 8-speed AU, and an 8-speed DCT.

Table 5.221 Comparison of Gear Span, Final Drive and Engine Speed for Three Transmissions

	6-speed AU	8-speed AU	8-speed DCT
Span	6	7.5	7.7
Final Drive	3.7	3.5	3.5
Engine Speed (45 mph)	1,420 RPM	1,290 RPM	1,290 RPM

With the gear span, final drive ratio, and expected engine speed at 45 mph in top gear all preselected, the progressive gear ratios were calculated for each transmission type using the following formula from:

$$i_n = i_z \left[\frac{Span}{\phi_2^{0.5(z-1)(n-1)}}\right]^{\frac{z-n}{z-1}} \quad z \neq 1$$

Where:

z = total number of gears,

n = gear number in consideration for design (varies from 1 to z),

φ_2 = progression factor (independent variable — normally between 1 and 1.2),

i_z = top gear ratio, and

i_n = nth gear ratio.

The independent variable φ_2 can normally take a value between 1 and 1.2 based on industry trends. The selection of φ_2 causes a trade-off between energy consumption and performance. For this study, the independent variable, for each transmission, was chosen so as to minimize the energy consumption over a combined UDDS (Urban) and HWFET (Highway) drive cycle. Figure 5.216 shows the fuel economy and performance (IVM-60 mph) for different values of the independent variable for a UDDS cycle.

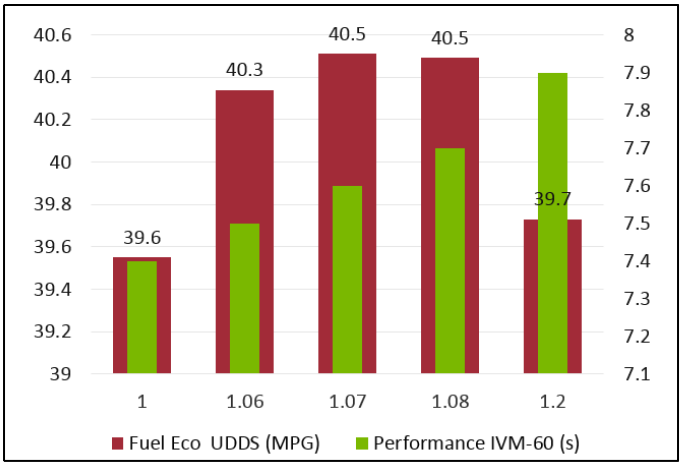

Figure 5.216 Fuel Economy and Performance Variations with Choice of Progression Factor for a 6-Speed Transmission

As shown, a value of 1.07 provides the maximum fuel economy and was therefore chosen to decide the gear ratios of the multi-speed transmissions for the study. Figure 5.217 shows the gear ratios obtained with three different values of φ_2 for a 6-speed transmission.

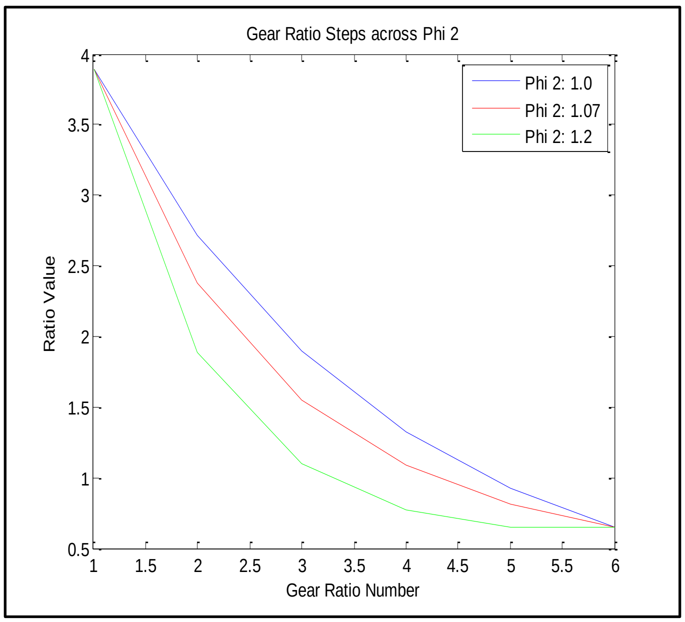

Figure 5.217 Gear Ratios Obtained with Three Values of Progression Factor for a 6-Speed Transmission

A similar process was used for the 8-speed transmissions.

To validate the approach described above for selection of the intermediate gear ratios, the intermediate gear ratios calculated by the algorithm were compared to actual vehicles for two vehicles in the compact class. Gear span, final drive ratio, and top gear ratio were inputs to the equation above. As Figure 5.218 and Figure 5.219 show, with proper selection of the independent variable φ_2, the calculated gear ratios are very close to the actual gear ratios.

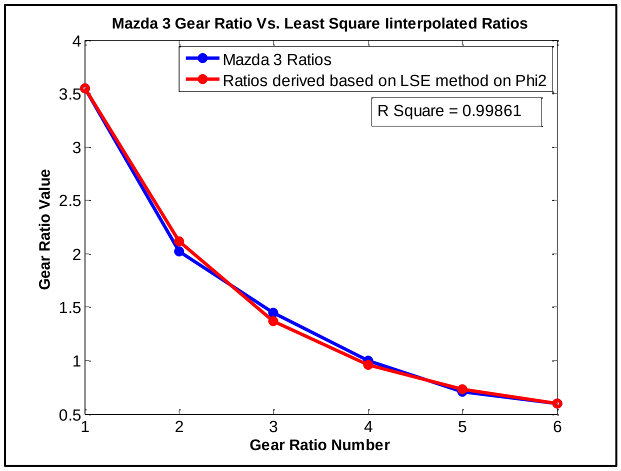

Figure 5.218 Comparison of Actual Gear Ratios and Gear Ratios Calculated

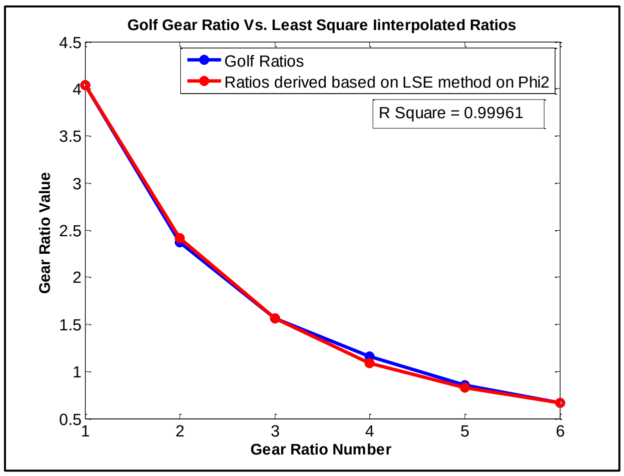

Figure 5.219 Comparison of Actual Gear Ratios and Gear Ratios Calculated

A similar validation was performed with the Ford Focus and the Chevy Cruze. Table 5.222 shows the value of φ_2, which was calculated to minimize the LSE (Least Square Error) between calculated and actual gear ratios for the vehicles, in comparison to the value of φ_2 chosen for the study.

Table 5.222 Progression Ratio for Numerous Vehicles with 6-speed AU

	Ford Focus	Chevy Cruze	Mazda 3	Volkswagen Golf	Study
φ_2	1.09	1.04	1.08	1.08	1.07

Table 5.223 summarizes gear and final drive ratios for the different transmissions evaluated in the study.

Table 5.223 Transmission Attributes

		Gear								Final Drive
		1	2	3	4	5	6	7	8	
5 AU	Gear ratio	3.85	2.3262	1.5039	1.0403	0.77	n/a	n/a	n/a	3.31
	Total gear	12.74	7.70	4.98	3.44	2.55	n/a	n/a	n/a	
5DM	Gear ratio	4.235	2.4985	1.5773	1.0654	0.77	n/a	n/a	n/a	3.31
	Total gear	14.02	8.27	5.22	3.53	2.55	n/a	n/a	n/a	
6AU	Gear ratio	3.9	2.3805	1.5547	1.0865	0.8124	0.65	n/a	n/a	3.74
	Total gear	14.59	8.90	5.81	4.06	3.04	2.43	n/a	n/a	
6DM	Gear ratio	4.225	2.5379	1.6312	1.1218	0.8255	0.65	n/a	n/a	3.74
	Total gear	15.80	9.49	6.10	4.20	3.09	2.43	n/a	n/a	
6DCT	Gear ratio	4.225	2.5379	1.6312	1.1218	0.8255	0.65	n/a	n/a	3.74
	Total gear	15.80	9.49	6.10	4.20	3.09	2.43	n/a	n/a	
7DM	Gear ratio	4.48	2.7351	1.7867	1.2488	0.934	0.7474	0.64	n/a	3.5
	Total gear	16.13	9.85	6.43	4.50	3.36	2.69	2.30	n/a	
8AU	Gear ratio	4.725	2.8923	1.8944	1.3276	0.9956	0.7988	0.6858	0.63	3.5
	Total gear	16.54	10.12	6.63	4.65	3.48	2.80	2.40	2.21	
8DM	Gear ratio	4.914	2.9912	1.9482	1.3577	1.0124	0.8078	0.6897	0.63	3.5
	Total gear	17.20	10.47	6.82	4.75	3.54	2.83	2.41	2.21	
8DCT	Gear ratio	4.914	2.9912	1.9482	1.3577	1.0124	0.8078	0.6897	0.63	3.5
	Total gear	17.20	10.47	6.82	4.75	3.54	2.83	2.41	2.21	

Conventional vehicles were simulated with an automatic transmission, manual transmission, dual clutch transmission, and continuously variable transmission. Power-split HEV and PHEV 20 AER transmissions have a planetary gear set with 78 ring teeth and 30 sun teeth, similar to the Toyota Prius. The PHEV 30 and PHEV50 AER have a planetary gear set with 83 ring teeth and 37 sun teeth, similar to the GM Voltec Gen1. Fuel cell vehicles use a two-speed manual transmission to increase the powertrain efficiency as well as allow them to achieve a maximum vehicle speed of at least 100 mph. BEVs are fixed gear. Table 5.224 gives the characteristics of all transmission used in the study.

Table 5.224 Transmission Peak Efficiency

Peak Efficiency (%): Automatic Trans.	97.5
Peak Efficiency (%): CVT	97.5
Peak Efficiency (%): DCT	98
Peak Efficiency (%): Manual Trans.	98.5
Peak Efficiency (%): Planetary gearset/Voltec Gen1	98
Peak Efficiency (%): Final Drive	98

In the current analysis, similar performance data was used for transmissions (i.e., the 1:1 ratio of the 6 and 8 speed transmissions use the same performance maps). This approach was used to be able to estimate the effectiveness impact of transmissions with higher gear numbers (i.e. increased gear spread) and advanced controls (i.e., earlier torque converter lockup). Benchmarking data collected by EPA and its contractors for a current 6 speed automatic transmission and 8 speed transmission, show that the transmissions currently in the market do not have the same efficiencies since they were designed at different timeframes. As a result, NHTSA has applied a fixed additional effectiveness to represent the benefits of improved efficiency between existing 6 and 8 speed transmissions. Future simulations runs will include multiple efficiency options for each transmission to account for changes in transmission design over time. Additional benchmarking performed by NHTSA and other agencies will also be leverages when they become available to update the transmission technology, assumptions and decision tree steps.

5.4.2.9 Torque Converter

Multiple torque converter performance maps were used for the vehicle simulations depending on the engine maximum input torque. An example of data set is provided in Figure 5.220.

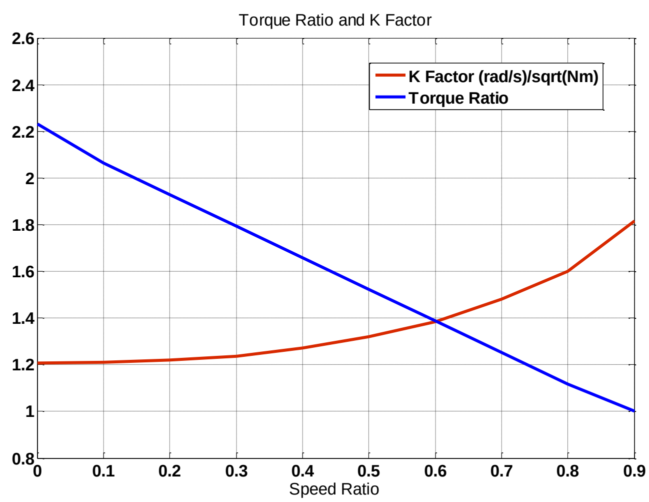

Figure 5.220 Torque Converter Specification Example

5.4.2.10 Electric Machines

Electric machine performance data were provided by Oak Ridge National Laboratory. The performance maps, developed under DOE Vehicle Technologies Office funding, are shown below for:

- micro-HEV, BISG and CISD (Figure 5.221),
- HEV and blended PHEV (Figure 5.222),
- E-REV PHEV (Figure 5.223) and
- BEV and FCHEV (Figure 5.224)
- The performance maps were developed assuming normal temperature operating conditions. Electric machine inverter losses are included in the maps.
- The figures below represent the electric machine peak torque curves. A constant ratio was assumed between the continuous and peak torque curves, as follows:
- 2 for the micro-HEV, BISG, and CISG
- 2 for the electric machine 1 and 1.5 for the electric machine 2 of the power-split HEV and blended PHEV
- 1 for EREV, BEVs, and fuel cell HEV

The electric machine specific weight is 1,080 W/kg and its controller 12,000 W/kg. The peak efficiency is set to 90 percent. This specific weight value was provided by electric machine experts (DOE, OEMs) and was intended to represent the expected state of the technology by 2020. The value may not, however, represent the most optimistic case, and Argonne is planning to update the value based on information from DOE and OEM experts that has recently been received.

The main focus of BISG hybrid vehicles is to capture regenerative braking energy as well as provide minimal assist to the engine during high-transient operating modes. Because the electric machine is linked to the engine through a belt, its power is usually limited. A value of 7 kW was assigned to the BISG for the midsize car.

CISG hybrid vehicles focus on the same areas of improvement as BISG vehicles. However, owing to its position, the electric machine can be larger; consequently, additional benefits can be obtained from regenerative braking and assist in a CISG vehicle than in a BISG vehicle. An electric machine size of 15 kW was selected for the midsize car.

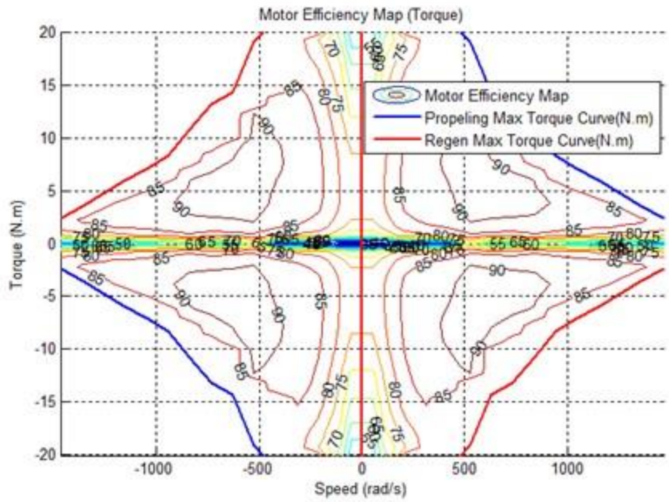

Figure 5.221 Electric Machine Map for Micro- and Mild HEV (data source ORNL)

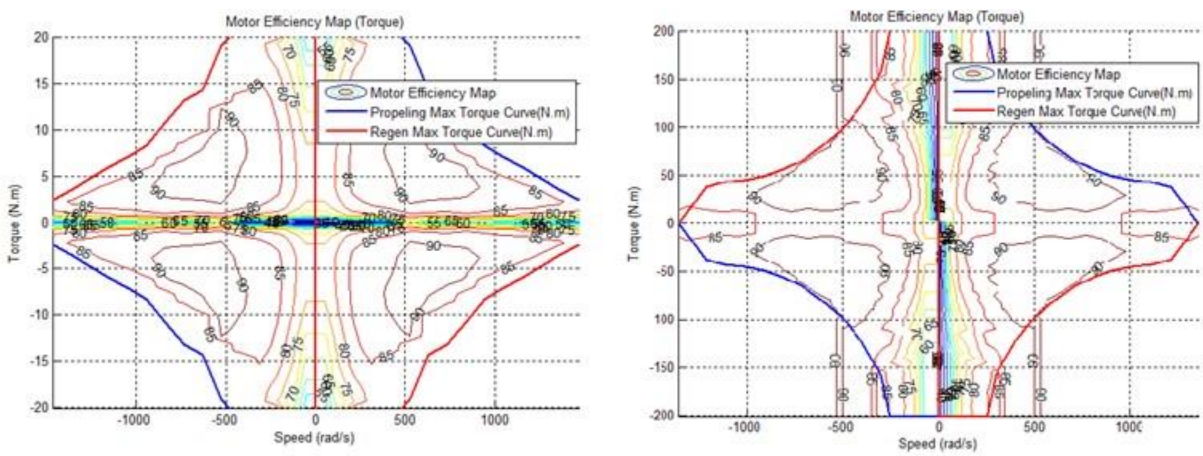

Figure 5.222 Electric Machine Maps for Full HEV and split PHEVs (data source ORNL)

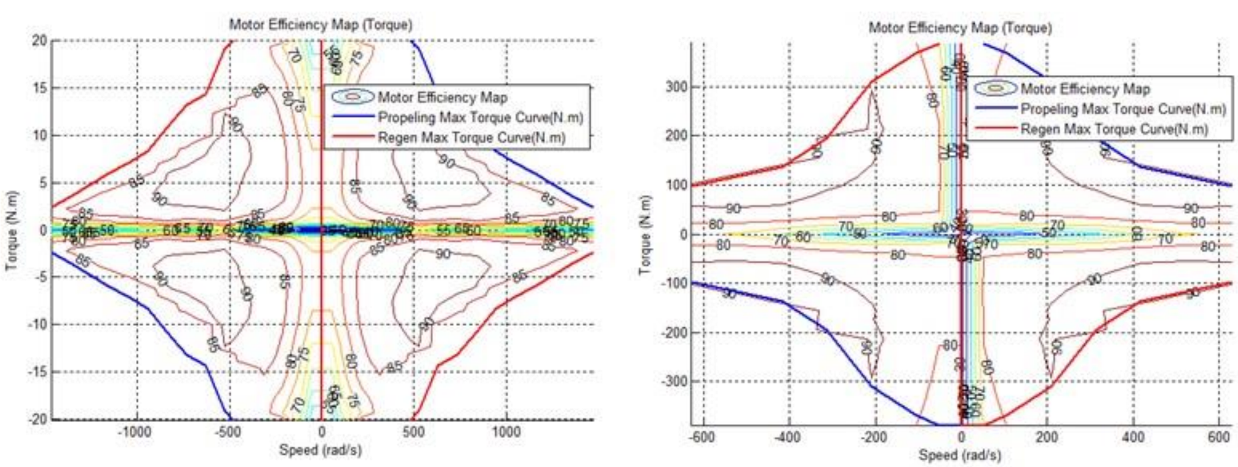

Figure 5.223 Electric Machine Maps for EREV PHEVs (data source ORNL)

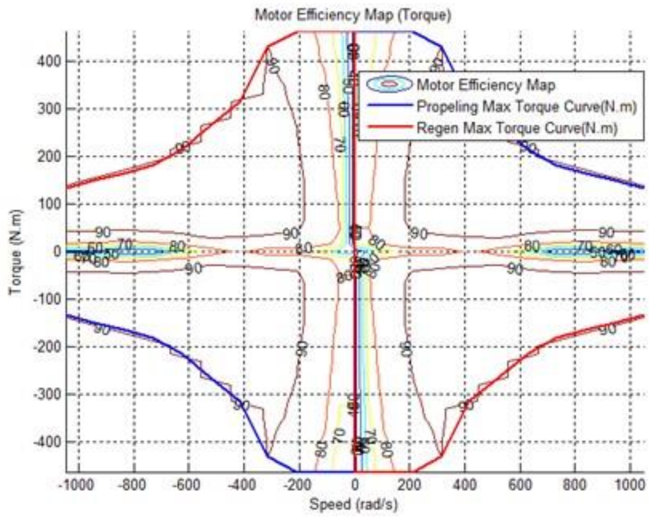

Figure 5.224 Electric Machine Map for BEV and FCHEV (data source ORNL)

The peak electric machine power for the micro-HEVs, BISG and CISG is currently being reviewed by NHTSA and Argonne. The results of this analysis were not available for the last round of vehicle simulations, but will be included in the next runs.

The performance data used as the assumptions will continue to be reviewed and updated if necessary based on the latest information available from benchmarking and publicly available papers and reports.

5.4.2.10.1 *Energy Storage Systems*

The batteries used for the BISG, CISG, HEVs and PHEVs are lithium-ion, while lead acid batteries were used for conventional powertrains. Table 5.225 provides a summary of the battery characteristics and technologies used by each powertrain. Column one of the table lists the powertrain type, column two the battery technology assumed in the modeling, and column three the pack energy densities. ANL designs the battery capacities in Autonomie to meet the voltage targets and range for each PHEV and BEV.

Table 5.225 Reference Battery Characteristics

Powertrain Types	Technology	Reference Cell Capacity (Ah)
Micro-HEV	Lead acid	66
BISG	Li-ion	6
CISG	Li-ion	6
HEV	Li-ion	6

The battery capacity has been selected for each option to allow a nominal pack voltage between 200 V (full HEV case) and 350 V (BEV case) according to literature review. The energy storage pack weights for the PHEVs are based on 92 Wh/kg for PHEVs 30 and 50 AER; and 142 Wh/kg for the BEVs based on battery total energy. The energy storage pack weights for micro-HEV, BISG, CISG, and full HEVs are based on 2000 W/kg. Inputs have been provided by battery experts to represent a 2020 pack production timeframe. These inputs are regularly updated and new values recently received will be used for the next round of simulations.

Different useable state-of-charge ranges during the standard driving cycles under normal temperature conditions have also been selected depending on the powertrain configuration:

- 10 to 20 percent SOC range for micro, mild, and full HEVs.
- 65 percent SOC range for PHEVs
- 90 percent for BEVs.

Over time, batteries lose some of their power and energy capacity. To maintain similar performance at the end of life (EOL) compared with the beginning of life (BOL), an oversize factor was applied while sizing the batteries for power (HEVs) and energy (PHEV). These factors represent the percentage of power and energy that will not be provided by the battery at the EOL compared with the initial power and energy given by the manufacturer. The performance data used to model the other components are based on normal temperature operating conditions. The vehicles are sized with a 20 percent power oversize factor for all hybrid vehicles and energy oversize factors of 30 percent for PHEVs. BEVs 200 AER are not oversized.

The performance data used for the energy storage systems (i.e., Voc, Rint…) represent state-of-the-art technologies. Since most of the current R&D activities focus on battery life and cost and considering the time for new materials to be introduced into the market, it is expected that the battery performance data will remain fairly constant in the near future.

Vehicle test data have shown that, for the drive cycles and test conditions considered, battery cooling does not draw a significant amount of energy, if any at all, for most of the vehicle powertrain architectures. The exception is high energy PHEVs and BEVs, for which an additional constant power draw is used to account for battery cooling. The auxiliary loads in Autonomie vehicle simulations reflect those impacts.

The energy storage system block models the battery pack as a charge reservoir and an equivalent circuit. The equivalent circuit accounts for the circuit parameters of the battery pack as if it were a perfect open-circuit voltage source in series with an internal resistance and 2 RC circuits which represent the polarization time constants. The amount of charge that the energy storage system can hold is taken as constant, and the battery is subject to a minimum voltage limit. The amount of charge required to replenish the battery after discharge is affected by coulombic efficiency. A simple single-node thermal model of the battery is implemented with parallel-flow air cooling.

The voltage is calculated at t=0 as Vout = Voc – Rint * I, with Voc = open-circuit voltage, Rint = internal resistance (two separate sets of values for charge and discharge), and I = internal battery current (accounts for coulombic efficiencies).

5.4.2.10.2 *<u>Fuel Cell Systems</u>*

The fuel cell system is modeled to represent the hydrogen consumption as a function of the produced power as shown in Figure 5.225. The system's peak efficiency is 60 percent, including the balance of plant, and represents normal temperature operating conditions. The system's specific power is 659 W/kg.

The hydrogen storage technology selected is a high-pressure tank with a specific weight of 0.04 kg H2/kg, sized to provide a 320-mile range on the FTP drive cycle.

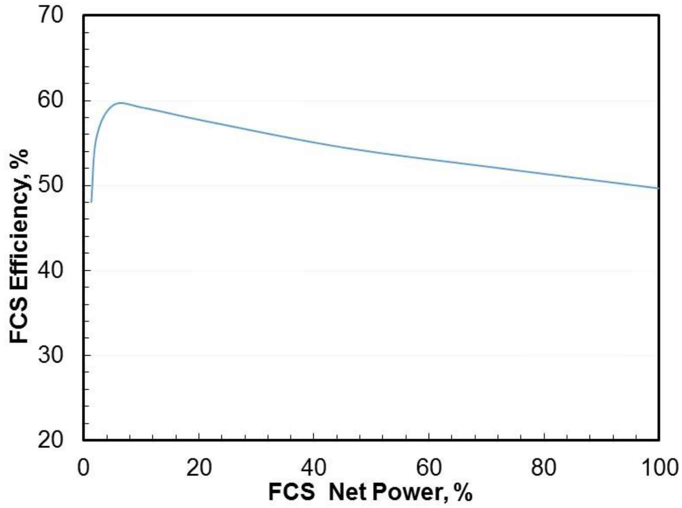

Figure 5.225 Fuel Cell System Efficiency

5.4.2.11 Light-weighting

In the NHTSA analysis, light-weighting assumptions are associated with the glider weight. Its secondary effect (such as downsizing) will be taken into account as part of the vehicle sizing algorithm. The glider percentage mass reduction values selected for the model are:

- 0 percent (reference vehicle)
- 5 percent reduction
- 7.5percent reduction
- 10 percent reduction
- 15 percent reduction
- 20 percent reduction

Only the baseline vehicles and the vehicles with high levels of mass reduction (10, 15 and 20 percent) are sized to meet the vehicle technical specifications. Vehicles with lower levels of mass reduction (5 and 7.5 percent) inherit sizing characteristics (i.e. engine power) from their respective baseline.

5.4.2.12 Rolling Resistance

The following rolling resistance reduction values were selected for the NHTSA CAFE analysis:

- 0 percent (reference vehicle)
- 10 percent reduction
- 20 percent reduction

These values represent a reduction in the coefficient of rolling resistance and were chosen to bound the possible rolling resistance improvements expected in future vehicles. No sizing is performed on this dimension.

5.4.2.13 Aerodynamic

The following aerodynamic reduction values were selected by NHTSA for the CAFE analysis:

- 0 percent (reference vehicle)
- 10 percent reduction
- 20 percent reduction

These values represent a reduction in drag coefficient (Cd) and were chosen to bound the possible rolling resistance improvements expected in future vehicles. No powertrain sizing is performed on this dimension. The reference values were selected after an analysis of the current vehicle characteristics and will be updated based on new information.

5.4.2.14 Accessory Loads

Electrical and mechanical accessory base loads are assumed constant over the drive cycles, with a value of 240 W for conventional, HEV and blended PHEV powertrains. For EREV PHEVs and BEVs, a value of 460W is used. Derived from data from Argonne's Advanced Powertrain Research Facility, these values are used to represent the average accessory load consumed during the standard urban FTP and EPA's Highway Fuel Economy Test (HWFET) drive-cycle testing on a dynamometer. Only the base load accessories are assumed during the simulations, similar to the dynamometer test procedure.

5.4.2.15 Driver

The driver model is based on a look-ahead controller for drive cycle simulations. No anticipation is imposed (0 sec anticipated time) during sizing for acceleration testing, in order to provide realistic vehicle performances.

5.4.2.16 Electrified Powertrains

Interest in electric drive vehicle technologies is growing, and the number of electrified vehicle options available from OEMs is rapidly increasing. This growth represents a shift of focus from market entry and environmental drivers to mainstream, customer-committed development. ANL's assumptions for electrified vehicles are based on the latest assumptions provided by DOE and OEM experts for the 2020 production timeframe. ANL is considering additional modeling based on recent input from DOE and other experts.

Hybrid vehicles combine at least two energy sources, such as an internal combustion engine or fuel cell system with an energy storage system. Electric drive vehicles have the potential to reduce energy consumption in several ways, including the following:

- Regenerative braking: A regenerative brake is an energy mechanism that reduces the vehicle's speed by converting some of its kinetic energy into a storable form of energy for future use instead of dissipating it as heat, as with a conventional friction brake. Regenerative braking can also reduce brake wear and the resulting fine particulate dust.
- Engine shutoff under various driving conditions (e.g., vehicle stopped, low power demand).
- Engine downsizing, which may be possible to accommodate an average load (not a peak load), would reduce the engine and powertrain weight. Higher torque at low

speed from the electric machine also allows the vehicle to achieve the same performance as conventional vehicles with a lower vehicle specific power (W/kg).
- Optimal component operating conditions: For example, the engine can be operated close to its best efficiency line.
- Accessory electrification allows parasitic loads to run on as-needed basis.
- The energy storage systems of PHEVs and battery electric vehicles can also be recharged, further improving fuel displacement.

However, vehicle electrification also have disadvantages that could affect energy consumption, including increased vehicle weight due to additional components.

Two major types of hybrids have been considered for transportation applications: electrical and hydraulic. Since Hydraulic Hybrid Vehicles have been studied almost exclusively for medium- and heavy-duty applications, only HEVs have been considered in the present study.

HEVs combine electric and mechanical power devices. The main components of HEVs that differentiate them from conventional vehicles are the electric machine (motor and generator), energy storage (e.g., battery or ultra-capacitors), and power electronics. The electric machine absorbs braking energy, stores it in the energy storage system, and uses it to meet acceleration and peak power demands.

5.4.2.16.1 *Electrified Powertrain Configurations*

The various HEV powertrain configurations can be classified on the basis of their hybridization degree, as shown in Figure 5.226. The hybridization degree is defined as the percentage of total power that can be delivered electrically. The higher the hybridization degree, the greater is the ability to propel the vehicle using electrical energy.

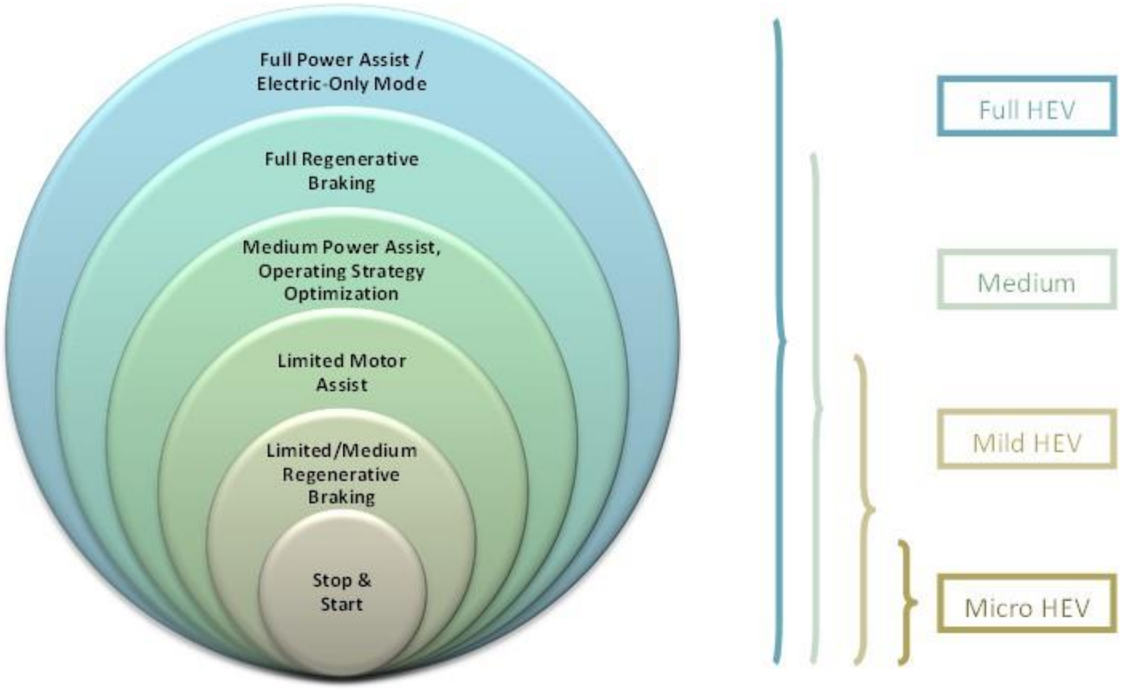

Figure 5.226 Electric Drive Configuration Capabilities

A number of different powertrain architectures have been considered and introduced in the market for different applications. These architectures are usually classified into three categories: series, parallel, and power split. The following sections describe some of the possible powertrain configurations for each architecture.

5.4.2.16.2 Parallel Hybrid Vehicle

In a parallel configuration, the vehicle can be directly propelled by either electrical or mechanical power. Direct connection between the power sources and the wheels leads to lower powertrain losses compared to the pure series configuration. However, since all of the components' speeds are linked to the vehicle's speed, the engine cannot routinely be operated close to its best efficiency curve.

Several subcategories exist within the parallel configuration:

- MHEV: A small electric machine is used to turn the engine off when the vehicle is stopped.

- Starter-alternator: This configuration is based on a small electric machine (usually 5 to 15 kW) located between the engine and the transmission. Because of the low electric-machine power, this configuration is mostly focused on reducing consumption by eliminating idling. While some energy can be recuperated through regenerative braking, most of the negative electric-machine torque available is usually used to absorb the engine's negative torque. Since the electric machine speed is linked to the engine, the vehicle cannot operate in electric mode other than for extremely low speeds (e.g., creep). In addition, the electric machine is used to smooth the engine torque by providing power during high transient events to reduce emissions. The electric machine can be connected to the engine either through a belt or directly on the crankshaft.

- Pre-transmission: This configuration has an electric machine in between the engine and the transmission. The electric machine power ranges from 20 to 50kW for light duty applications, which allows the driver to propel the vehicle in electric-only mode as well as recover energy through regenerative braking. The pre-transmission configuration can take advantage of different gear ratios that allow the electric machine to operate at higher efficiency and provide high torque for a longer operating range. This configuration allows operation in electric mode during low and medium power demands, in addition to the ICE on/off operation. The main challenge for these configurations is being able to maintain a good drive quality because of the engine on/off feature and the high component inertia during shifting events.

- Post-transmission: This configuration shares most of the same capabilities as the pre-transmission. The main difference is the location of the electric machine, which in this case is after the transmission. The post-transmission configuration has the advantage of maximizing the regenerative energy path by avoiding transmission losses, but the electric machine torque must be higher because it cannot take advantage of the transmission torque multiplication.

5.4.2.16.3 Power Split Hybrid Vehicle

As shown in Figure 5.227, power split hybrids combine the best aspects of both series and parallel hybrids to create an extremely efficient system. The most common configuration, called an input split, is composed of a power split device (planetary gear transmission), two electric machines and an engine. Within this architecture, all these elements can operate differently. Indeed, the engine is not always on and the electricity from the generator may go directly to the wheels to help propel the vehicle, or go through an inverter to be stored in the battery. The operational phases for an input split configuration are the following:

- During vehicle launch, when driving, or when the state of charge of the battery is high enough, the ICE is not as efficient as electric drive, so the ICE is turned off and the electric machine alone propels the vehicle.
- During normal operation, the ICE output power is split, with part going to drive the vehicle and part used to generate electricity. The electricity goes either to the electric machine, which assists in propelling the vehicle, or to charge the energy storage system. The generator also acts as a starter for the engine.
- During full-throttle acceleration, the ICE and electric machine both power the vehicle, with the energy storage device (e.g., battery) providing extra energy.
- During deceleration or braking, the electric machine acts as a generator, transforming the kinetic energy of the wheels into electricity to charge the energy storage system.

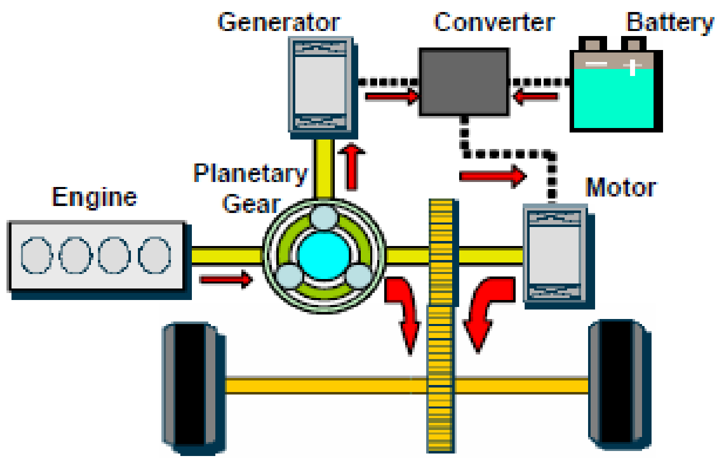

Figure 5.227 Power Split Hybrid Electric Vehicle

Several variations of the power split have been implemented, including single-mode and multi-mode power splits. Examples of single-mode power split hybrids include the Toyota Prius and Ford Fusion Hybrid. An example of a multi-mode power split hybrid is the General Motors Chevrolet Tahoe. It should be noted that there are possible tradeoffs between complexity and energy consumption benefits for multi-mode systems.[616]

5.4.2.16.3.1 Voltec Gen1 Plug-in Hybrid Vehicle

PHEVs differ from HEVs in their ability to recharge the energy storage system through the electric grid. PHEVs energy storage systems have usually a higher total energy compared to HEVs and they also use a larger portion of it (e.g., when most HEVs use 10 to 30 percent of their total battery energy, PHEVs use 60 percent or more of their total energy). Since the vehicle is designed to have a high capacity energy storage, electrochemical batteries are usually used for this application. All the HEV configurations described above can be used as PHEVs. In most cases, because of the desire to propel the vehicle using electrical energy from the energy storage system, the electric machine power is greater for a PHEV compared to an HEV.

ANL used the Gen 1 VOLTEC configuration from General Motors in its simulation to represent a PHEV. Argonne is currently working on developing new vehicles models and sizing algorithms for the three new powertrain configurations recently introduced by GM so that those options can be considered in the next round of simulations in Autonomie.

The VOLTEC GEN1 configuration from General Motors allows different operating modes (e.g. series and parallel, parallel and power split). The VOLTEC GEN1 powertrain architecture, also called the EREV (Extended Range Electric Vehicle), provides four modes of operating, including two that are unique and maximize the powertrain efficiency and performance. The electric transaxle has been specially designed to enable patented operating modes, both to improve the vehicle’s electric driving range when operating as a BEV and to reduce energy consumption when extending the range by operating with an ICE. The EREV powertrain introduces a unique two-electric machine electric-vehicle driving mode that allows both the driving electric machine and the generator to provide tractive effort while simultaneously reducing electric machine speeds and the total associated electric machine losses. For HEV operation, the EREV transaxle uses the same hardware that enables one-electric machine and two-electric machine operation to provide both the completely decoupled action of a pure series hybrid and a more efficient flow of power with decoupled action for driving under light load and at high vehicle speed.

It is important to note that many different variations exist within each configuration (i.e., power-split configurations can be single-mode, two-mode, three-mode, etc.) and between configurations (i.e., several configurations are considered to be a mix of series, parallel and/or power-split). Overall, several hundred configurations are possible for electric-drive vehicles. It is also not uncommon for a specific OEM to use multiple powertrain configurations across its electrified vehicle line up. Recent presentations from General Motors highlighted the fact that, while sharing multiple components, the powertrains from the upcoming Gen2 Volt, Cadillac CTS and Malibu were all different.

In more detail, the Voltec Gen1 system has four different operating modes, as shown in Figure 5.228:

During EV operation:

- One-electric machine EV: The single-speed EV drive power-flow, which provides more tractive effort at lower driving speeds
- Two-electric machine EV: The output power split EV drive power flow, which has greater efficiency than one-electric machine EV at higher speeds and lower loads

During extended-range (ER) operation:

- One-electric machine ER (series): The series ER power flow, which provides more tractive effort at lower driving speeds
- Combined two-electric machine ER (split): The output power split ER power-flow, which has greater efficiency than series at higher speeds and lighter loads

A vehicle-level control strategy was developed on the basis of vehicle test data to properly select each of the operating modes. The logic developed for the power split mode is similar to the one for the input split configuration discussed previously.

For the two-level EV mode, an algorithm has been developed to minimize the losses of both electric machines at every sample time on the basis of each component's efficiency map. For the series mode, the combination of the engine and electric machine losses is also minimized at every sample time. It is important to note that the engine is not operated at its best efficiency point, but rather along its best efficiency line for drive quality and efficiency reasons.

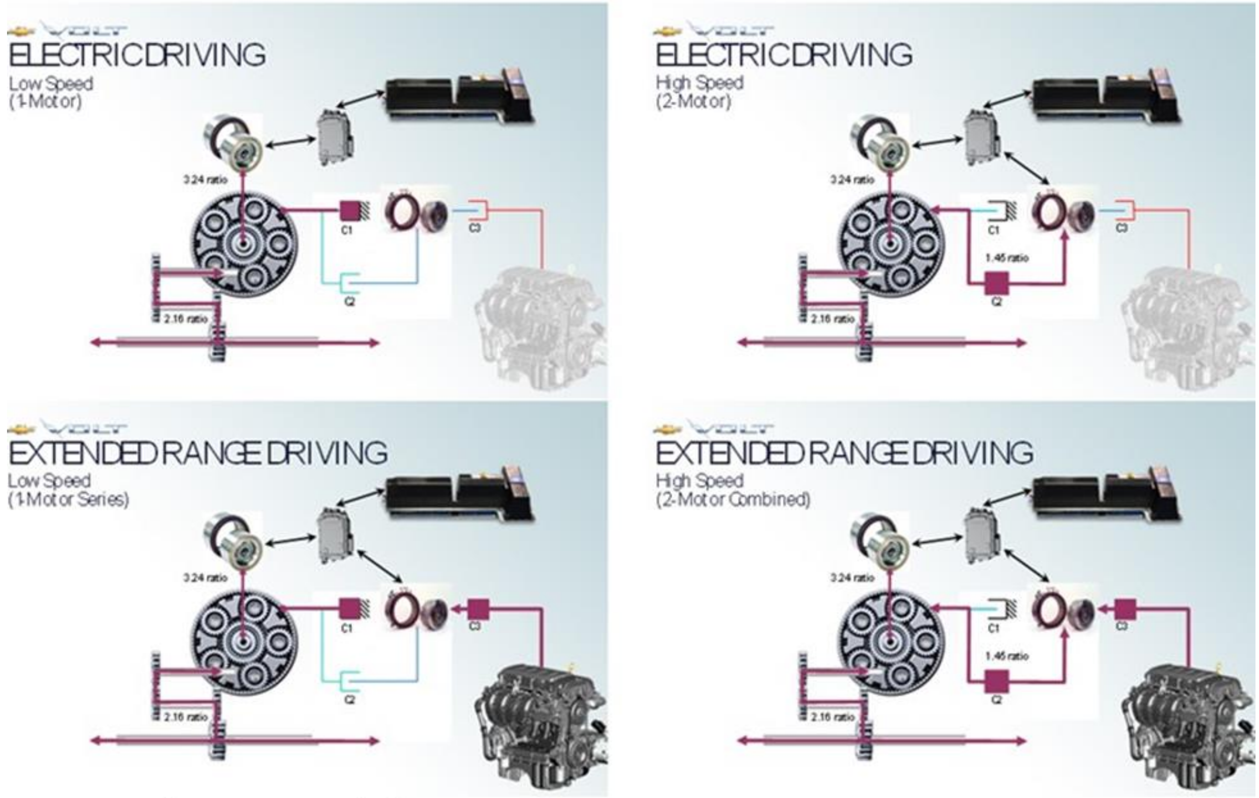

Figure 5.228 Gen1 Voltec Operating Modes [www.gm.com]

5.4.2.16.4 Series Fuel Cell HEV

Currently, for light-duty vehicles, series configurations are essentially considered only for fuel cell applications. The fuel cell system powertrain, described in Figure 5.229, includes a gearbox in addition to the final drive, as well as DC/DC converters for the high-voltage battery and the 12-V accessories.

Because of the fuel cell system high efficiency, the energy storage is not used as the primary power source. The vehicle level control strategy has been developed so that the main function of the battery is to store the regenerative braking energy from the wheel and return it to the system when the vehicle operates at low power demand (low vehicle speed). The battery also provides power during transient operations when the fuel cell is unable to meet driver demand. Component limits, such as maximum speed or torque, are taken into account to ensure the proper behavior of each component. Battery state-of-charge is monitored and regulated so that the battery stays in the defined operating range. The three controller outputs are fuel cell ON/OFF, fuel cell power, and electric machine torque.

The main drawback is that the main components have to be oversized to be able to maintain a uniform performance, leading to higher vehicle weight. Finally, the large number of components and the energy conversion from chemical to mechanical to electrical leads to lower powertrain efficiency.

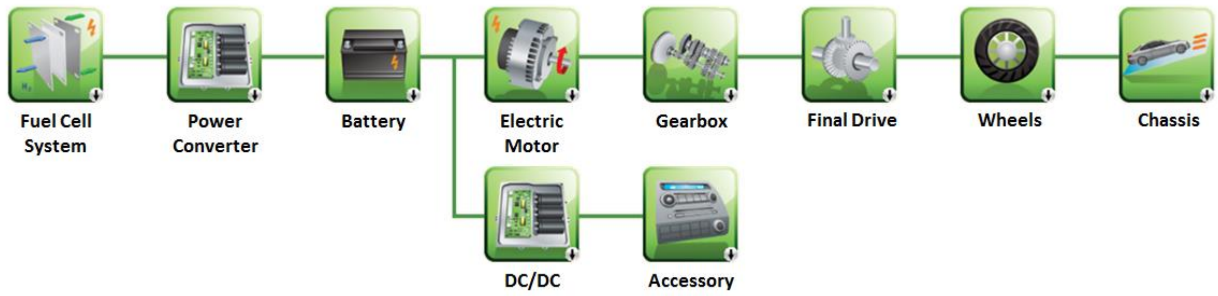

Figure 5.229 Series Fuel Cell Hybrid Electric Vehicle

Several variations of the series configuration have been considered. One of the important considerations in the design of a series HEV is related to the use of a single gear ratio versus a two-speed transmission. Using a single gear ratio usually leads to low maximum vehicle speed and poor performance at high speed due to the low electric machine torque in that operating regime. When applications require better performance at high speeds, a two-speed transmission is considered.

5.4.2.16.5 Powertrain Electrification Selection

The selection of hybridization degree and powertrain configuration is complex, since numerous options exist. On the basis of current production vehicles as well as anticipated near-future trends, the following powertrain configurations were selected for the modeling analysis to match Volpe's requests:

- 12-V micro-hybrid electric vehicle (micro-HEV/start-stop system, no regen braking).
- Belt-integrated starter generator
- Crank-integrated starter generator
- Full hybrid electric vehicle, single-mode power split configuration, fixed ratio
- Full hybrid electric vehicle, Pre-Transmission configuration, 6-speed DCT.
- PHEV, Voltec extended-range electric vehicle (EREV) configuration with 30 AER on the FTP cycle
- PHEV, Voltec EREV configuration, with 50 AER on the FTP drive cycle
- Battery electric vehicle, with 200 AER on the FTP drive cycle
- Fuel cell HEV, series configuration, with 320-mile range on the FTP drive cycle

Note that the AER values are based on unadjusted electrical consumptions on the UDDS driving cycle. Recent announcements by automakers indicate 200 plus mile label ranges are likely. If this is the case, UDDS driving cycle AERs will be closer to 250 miles and if so ANL will update its assumptions for future simulation modeling.

5.4.2.17 Drive Cycles and Vehicle Simulation Conditions

Simulated test procedures followed the current recommendations of the EPA, with the two-cycle test based on the FTP and HFET drive cycles. Combined values are calculated on the basis of a 55 percent city and 45 percent highway cycle using the standard test procedure.

Autonomie includes some temperature models for some powertrains and component technologies, but considering the wider range of options to be considered as part of the study, all the component performance data and controllers are assumed to be operating under warm conditions. As a result, the additional energy consumption due to the FTP cold start has been calculated in post-processing by applying a fuel consumption penalties depending on the assumed warmup strategy. A constant value of 15 percent across all technology options has been applied based on a combination of Argonne APRF test data and analysis of the latest EPA vehicle certifications data as shown in Figure 5.230. No cold start penalty was applied for BEVs.

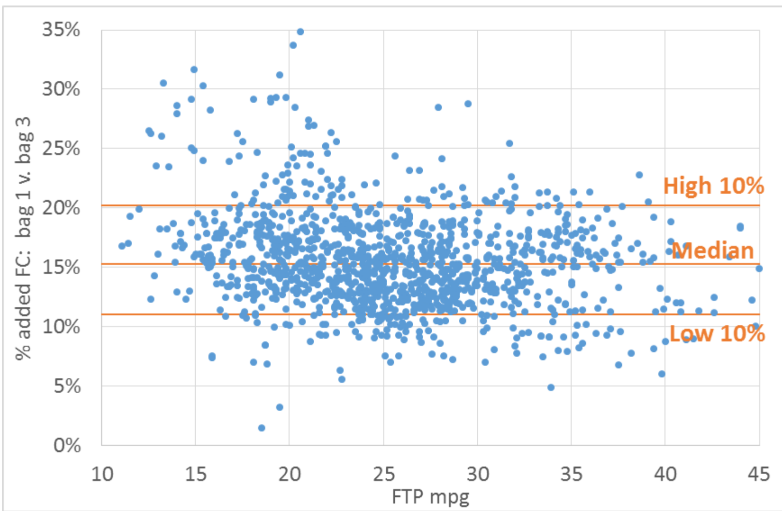

Figure 5.230 Cold Start Penalty between Bag 1 and 3 on the FTP Cycle Based on 2016 EPA Certification Data

5.4.2.18 Vehicle Sizing Process

To compare different vehicle technology-configuration-powertrain combinations, all vehicles to be studied were sized to meet the same requirements:

- Initial vehicle movement to 60 mph <= 9 sec ± 0.1 sec
- Maximum grade (gradeability) of 6 percent at 65 mph at Gross Vehicle Weight (GVW)
- Maximum vehicle speed >100 mph

These requirements are a good representation of the current American automotive market and of American drivers' expectations. The relationship between curb weight and GVW for current technology-configuration-powertrain combinations was modeled and forms the basis for estimating the GVWs of future vehicle scenarios. The following equation has been used to estimate the GVW of future technologies:

GVW (kg) = 1.25 x vehicle test weight (kg) + 193

To compare different vehicle technology-configuration-powertrain combinations, all selected vehicles to be sized are designed to meet the same requirements. Note that not all vehicles are sized but the baseline vehicle (MR0, AERO0, ROLL0) and higher mass reduction level vehicles (MR3, 4, 5 with AERO0, ROLL0).

Improperly sizing the components will lead to differences in energy consumption and will influence the effectiveness results. On this basis, we have developed several automated sizing algorithms to provide a fair comparison between technologies. Algorithms have been defined depending on the powertrain (e.g., conventional, power split, series, electric) and the application (e.g., HEV, PHEV).

All algorithms are based on the same concept: the vehicle is built from the bottom up, meaning each component assumption (e.g., specific power, efficiency) is taken into account to define the entire set of vehicle attributes (e.g., weight). This process is always iterative in the sense that the main component characteristics (e.g., maximum power, vehicle weight) are modified until all vehicle technical specifications are met. The transmission gear span or ratios are currently not modified to be optimized with specific engine technologies as this might also lead to overestimating the effectiveness impact of technologies. On average, the algorithm takes between five and 10 iterations to converge. Figure 5.231 to Figure 5.236 shows the iterative process for each powertrain.

A conventional vehicle is mainly defined by its internal combustion engine; its ability to realize a cycle or acceleration performance is directly linked to its power density. Therefore, the sizing algorithm focuses on calculating the mechanical power needed to meet the requirements. Figure 5.231 illustrates the steps in the sizing process. To begin the sizing process, a default vehicle is created. A simulation is then performed to determine the engine peak power and vehicle mass:

First, the desired power is estimated to meet the grade-ability and acceleration performance requirements, and engine power is updated with the maximum value.

Second, the sizing enters in an acceleration loop to check the performance run initial vehicle movement (IVM) up to 60 mph, and the IVM to 60 mph is recorded. The definition of IVM is that the vehicle must move 1 ft (1/3 m) before the clock starts to record the performance time. This metric provides a more consistent result and removes phenomena that are difficult to model at initial acceleration—such as tire and clutch slip—from consideration.

Finally, the vehicle is run on acceleration performance for passing with its updated parameters. At the end, the time to reach the target (i.e., 0–60 mph and 50–80 mph) are compared with the simulated data. This is the main condition to exit the routine.

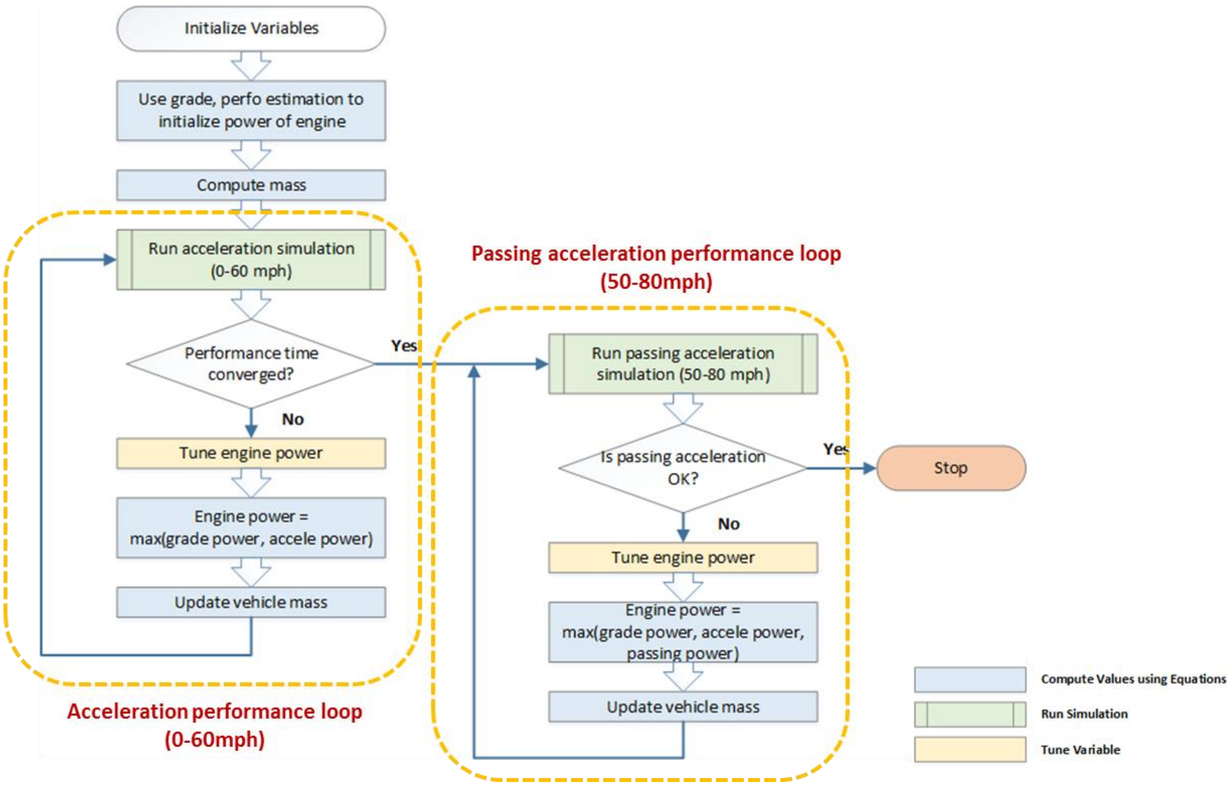

Figure 5.231 Conventional Powertrain Sizing Algorithm

For the hybrid electric vehicles, engine power is sized to meet 70 percent of peak power required to meet the VTS. The battery power is mainly determined to capture all the regenerative energy from the urban dynamometer driving schedule. The electric machine power is sized to meet the grade-ability and performance requirements. Figure 5.232 shows the iterative process used to calculate data for a single power split HEV.

The following procedure is used:

- Battery power is sized to recuperate 100 percent energy through regenerative braking on UDDS.
- Electric machine (EM1) power is sized to recuperate 100 percent energy through regenerative braking on UDDS and to meet the acceleration performance requirement.
- Electric machine (EM2) power is sized as following:
- EM2 peak power is sized to start engine at the top of vehicle speed on UDDS
- EM2 peak power is sized to control engine at the zero of vehicle speed for acceleration performance
- EM2 continuous power is sized to control engine at maximum grade (i.e., engine power fraction going through electro-mechanical power path)

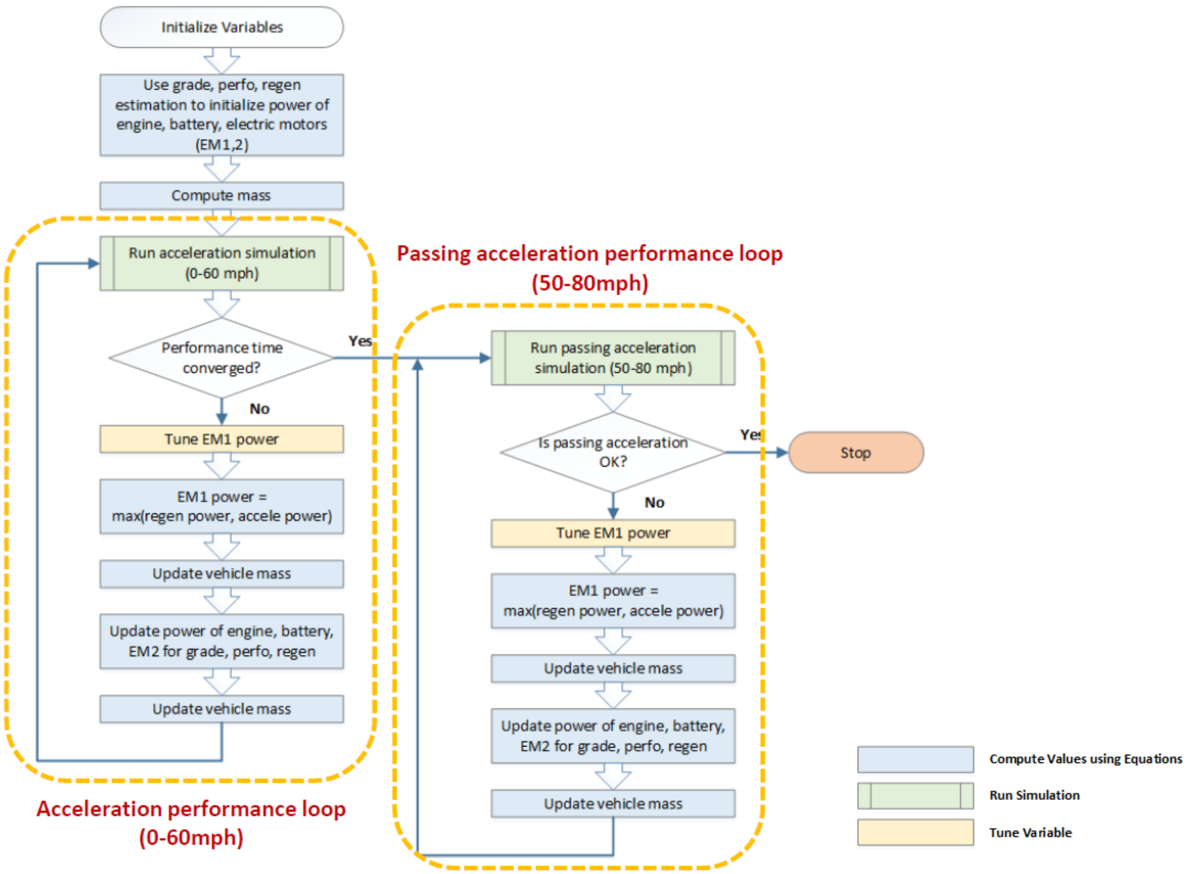

Figure 5.232 Split Hybrid Electric Powertrain Sizing Algorithm

The main algorithm for the single power split powertrain is as follows, and the iterative process is shown in Figure 5.233:

- Battery energy is sized to meet the all-electric range (AER) requirements on UDDS based on unadjusted values. Using the full history of the range attained by the vehicle from each sizing run, the desired range, and the current battery energy, a new estimate was made for the desired battery energy.
- Battery and EM1 powers are sized to be able to follow the UDDS cycle in electric-only mode (this control is only used for the sizing; a blended approach is used to evaluate consumptions) or to meet the acceleration performance requirements.
- Vehicle weight is a function of the engine peak power, electric machines peak power, and battery energy.
- Electric machine (EM2) power is sized the same way as for a single power split HEV.

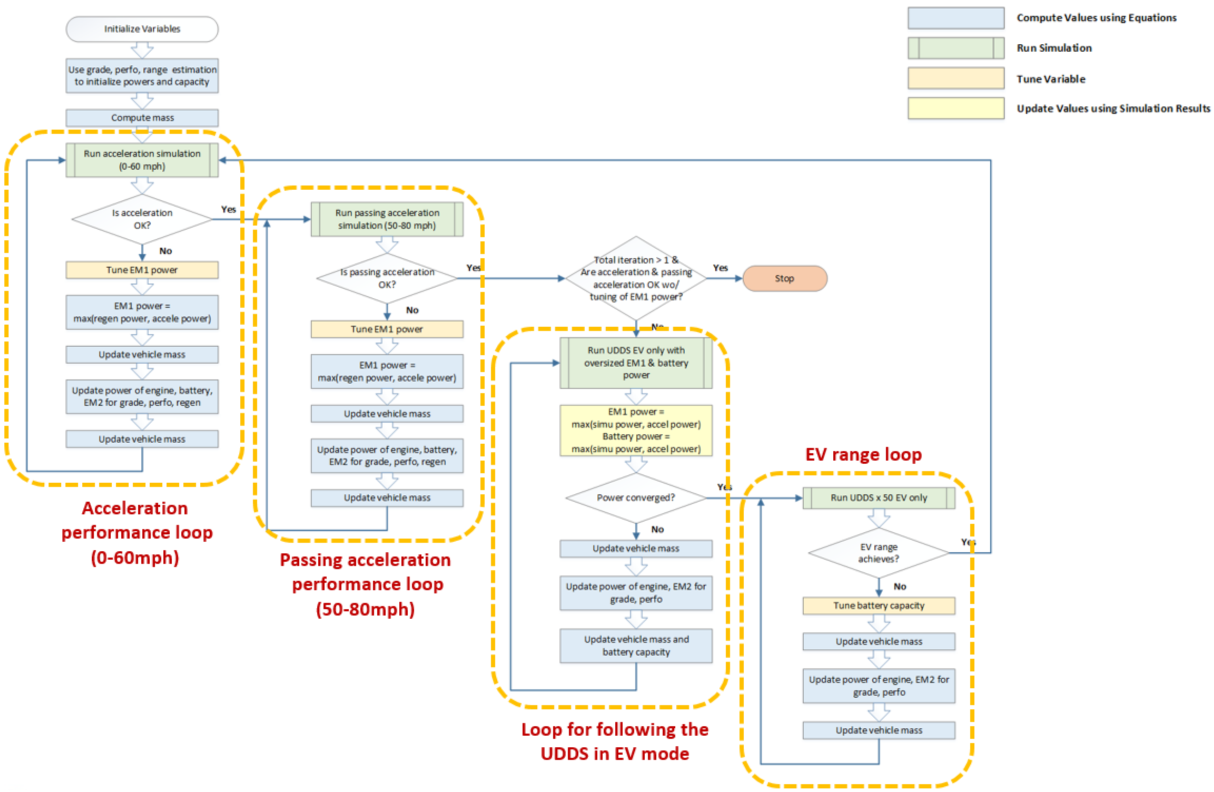

Figure 5.233 Split Plug-in Hybrid Electric Powertrain Sizing Algorithm

The main algorithm for the series-split powertrain is as follows, and the iterative process is shown in Figure 5.234:

- Battery energy is sized to meet AER on UDDS based on unadjusted values.
- Battery and EM1 powers are sized to be able to follow the aggressive US06 drive cycle (duty cycle with aggressive highway driving) in electric-only mode or to meet the acceleration performance requirements.
- Vehicle weight is a function of the engine peak power, electric machines peak power, and battery energy.
- Electric machine (EM2) power is sized to endure the engine peak power as a generator and kick on the engine at top speed on the UDDS.

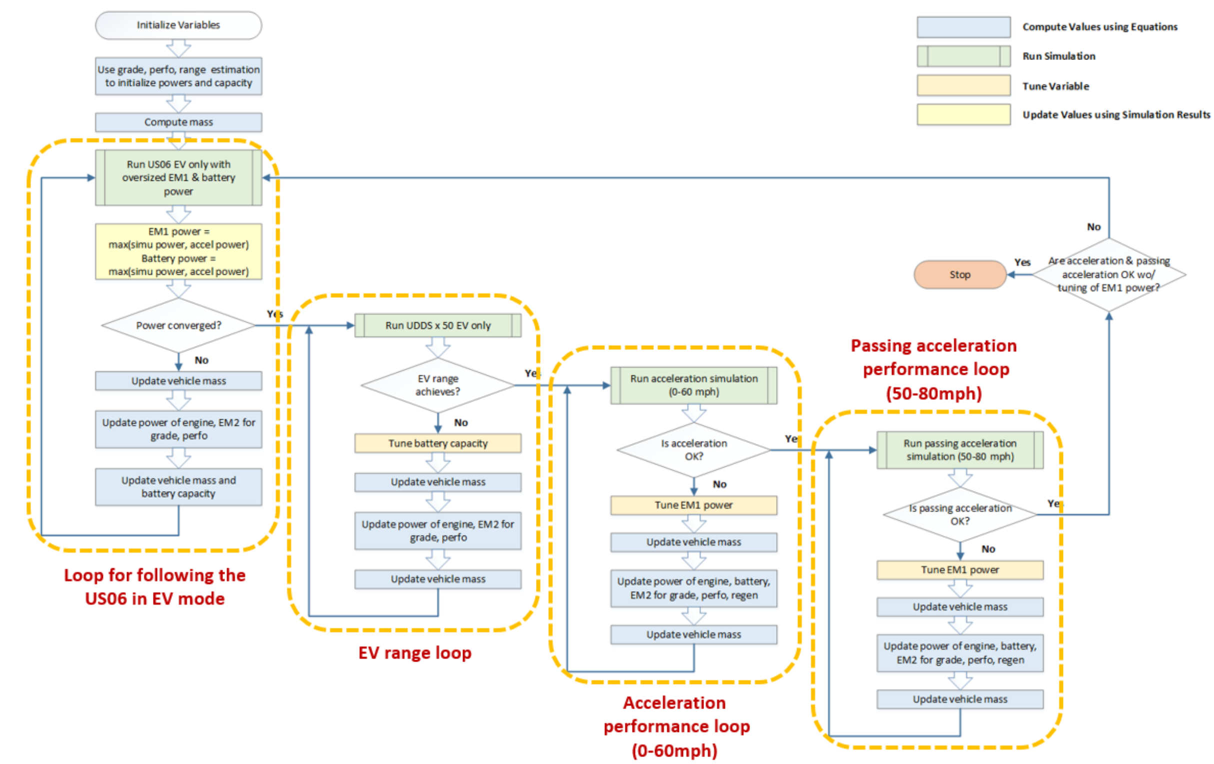

Figure 5.234 Series-Split Hybrid Electric Powertrain Sizing Algorithm

The main algorithm for the single gear BEV powertrain is as follows, and the iterative process is shown in Figure 5.235:

- Battery energy is sized to meet AER on UDDS based on unadjusted values.
- Battery and EM1 powers are sized to be able to follow the aggressive US06 drive cycle (duty cycle with aggressive highway driving) or to meet the acceleration performance requirements.
- Vehicle weight is a function of the electric machine peak power and battery energy.

To be able to maintain the same performance at the end of life as at the beginning of life, an oversize factor is applied while sizing the batteries for both energy (these oversizing factors influence the weight only).

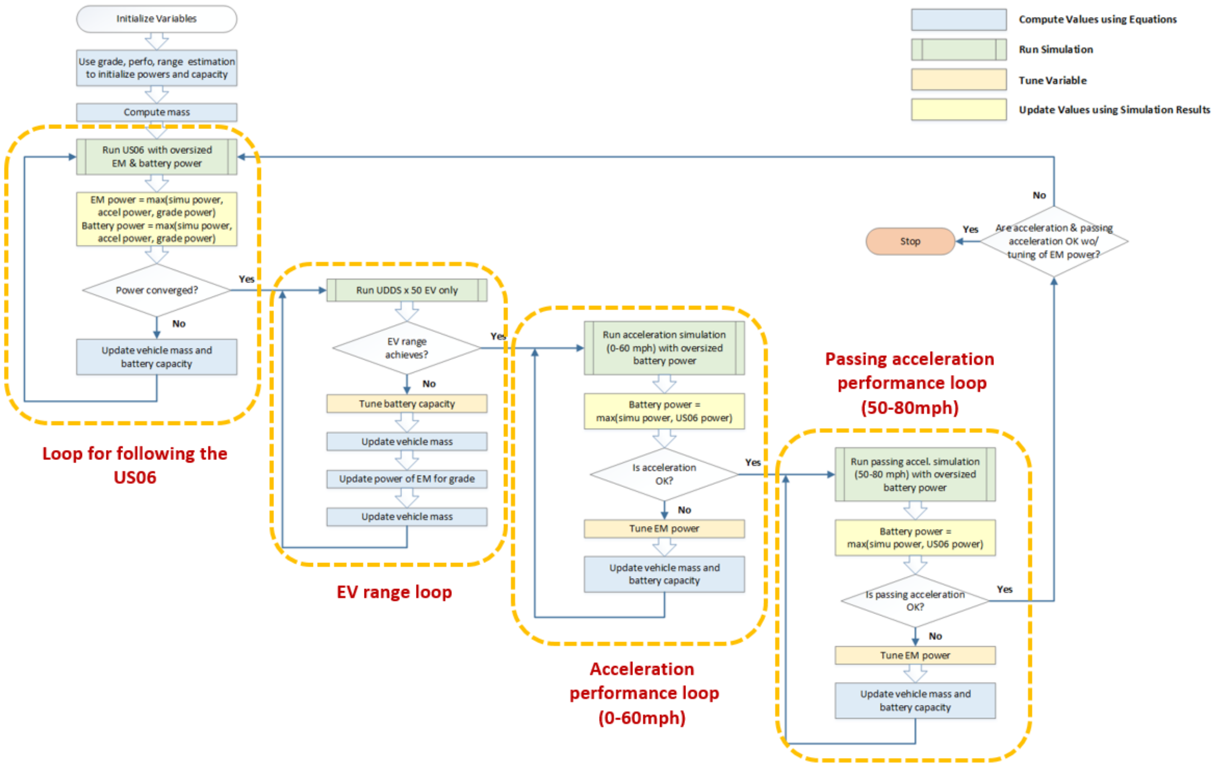

Figure 5.235 Battery Electric Powertrain Sizing Algorithm

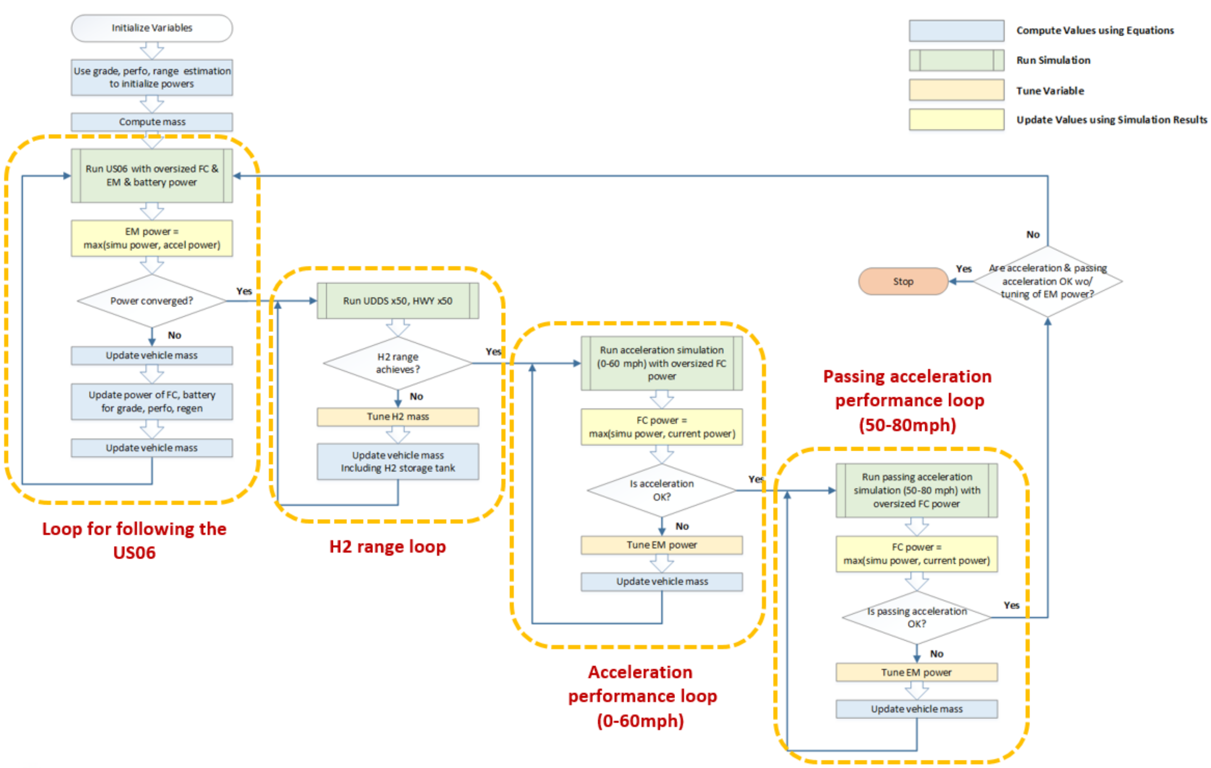

Figure 5.236 Fuel Cell Series Hybrid Electric Powertrain Sizing Algorithm

Since each powertrain and application is different, the rules are specific:

- For HEVs, the electric-machine and battery powers are determined in order to capture all of the regenerative energy from an FTP cycle. The engine and the generator are then sized to meet the gradeability and performance (initial vehicle movement to 60 mph) requirements.
- For PHEV30 and 50s, the main electric-machine and battery powers are sized to be able to follow the aggressive US06 drive cycle (duty cycle with aggressive highway driving) in electric-only mode. The battery's usable energy is defined to follow the FTP drive cycle for 50 miles, depending on the requirements. The genset (engine + generator) or the fuel cell systems are sized to meet the gradeability requirements.
- For BEVs, the electric machine and energy storage systems are sized to meet all of the vehicle technical specifications.

The micro-HEV, BISG, and CISG have sizing results very similar to their conventional counterparts as they all use the same sizing rule except for the electric machine and energy storage systems.

Once the vehicles were sized to meet the same vehicle technical specifications, they were simulated following the appropriate standard driving cycles. It is important to properly store individual results as structured data because they will be reused to support database generation (see Section 11).

5.4.2.19 Autonomie Outputs

Once a simulation is complete, the results are stored in a folder which contains the results for one combination and characterizes one branch/path of the tree. Figure 5.237 shows the folder organization for each individual simulation. Folders can contain up to five directories, depending on the vehicle technology and the type of run performed. Results are divided into directories representing the cycle or procedure simulated. For example, the combined procedure for conventional vehicles has two parts separating the FTP and HFET run, and the PHEV procedure has four parts separating the FTP and HFET runs as well as the charge-sustaining and charge-depleting modes. The last directory is the sizing structure (performance test).

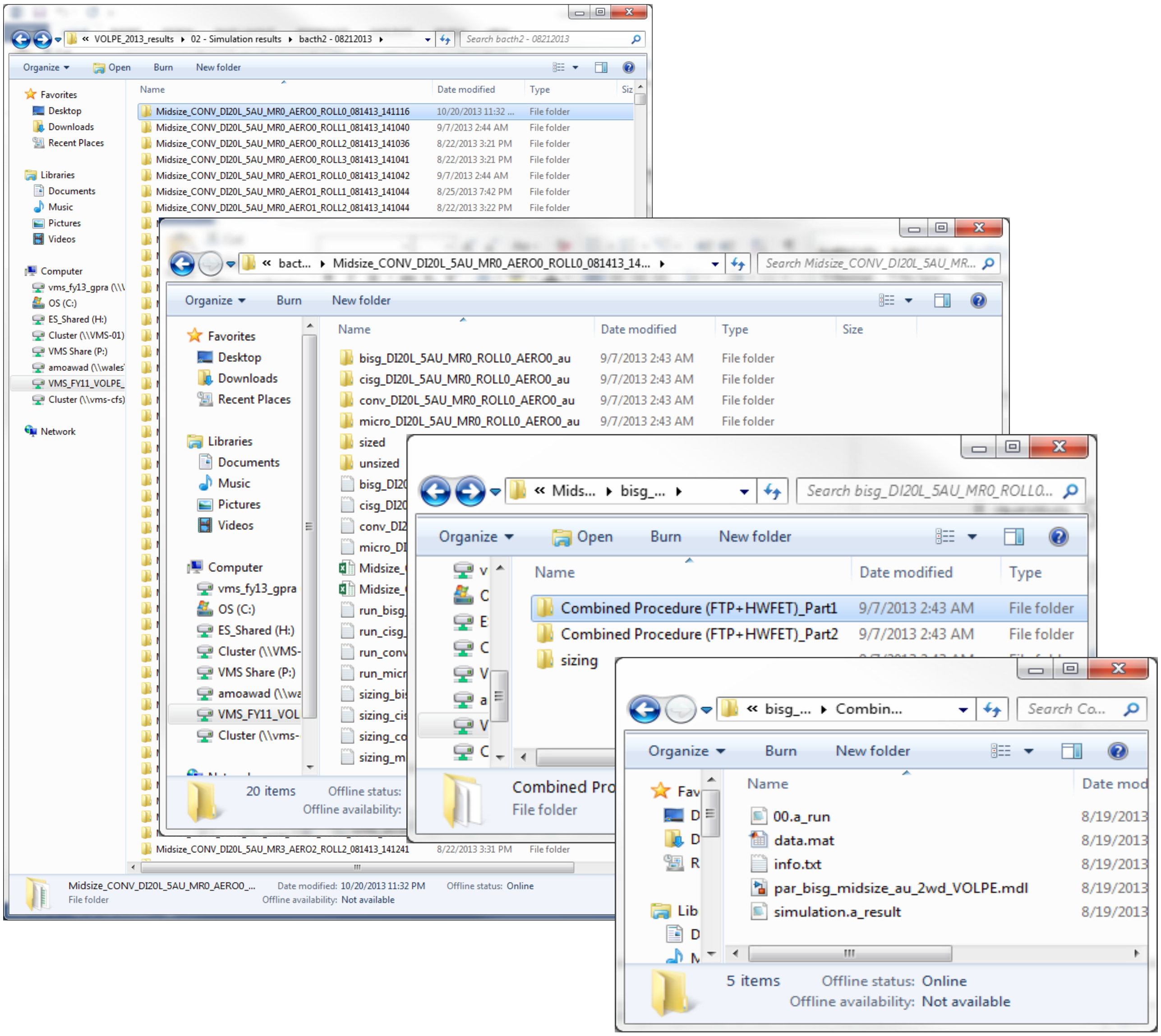

Figure 5.237 Organization of Simulation Results

5.4.2.20 Individual Vehicle Simulation Quality Check

Once the individual simulations are completed, at the results are analyzed both a high level (i.e., vehicle energy consumption) and a low level (i.e., time-based engine power) through Autonomie graphical user interface. An algorithm is also used to automatically flag any potential issues within a simulation (i.e., too many shifting events on a specific cycle).

An exhaustive list of parameters are extracted and checked for each vehicle simulation, including:

- Trace
- Vehicle Weight
- Engine Percentage ON
- Engine Number of Starts
- Engine/Fuel Cell Average Efficiency
- Engine/Fuel Cell Power
- Engine Speed
- Electric Machine Average Efficiency
- Electric Machine Power
- Electric Machine Speed
- Electric Machine Max Current
- Number of Shifts
- Time Fraction in Top Gear
- Battery SOC
- HEV Delta SOC
- Percentage Regeneration Recovered
- Electric Consumption
- Fuel Economy ratios

Distribution plots are generated as part of the report for visual perspectives (Figure 5.238).

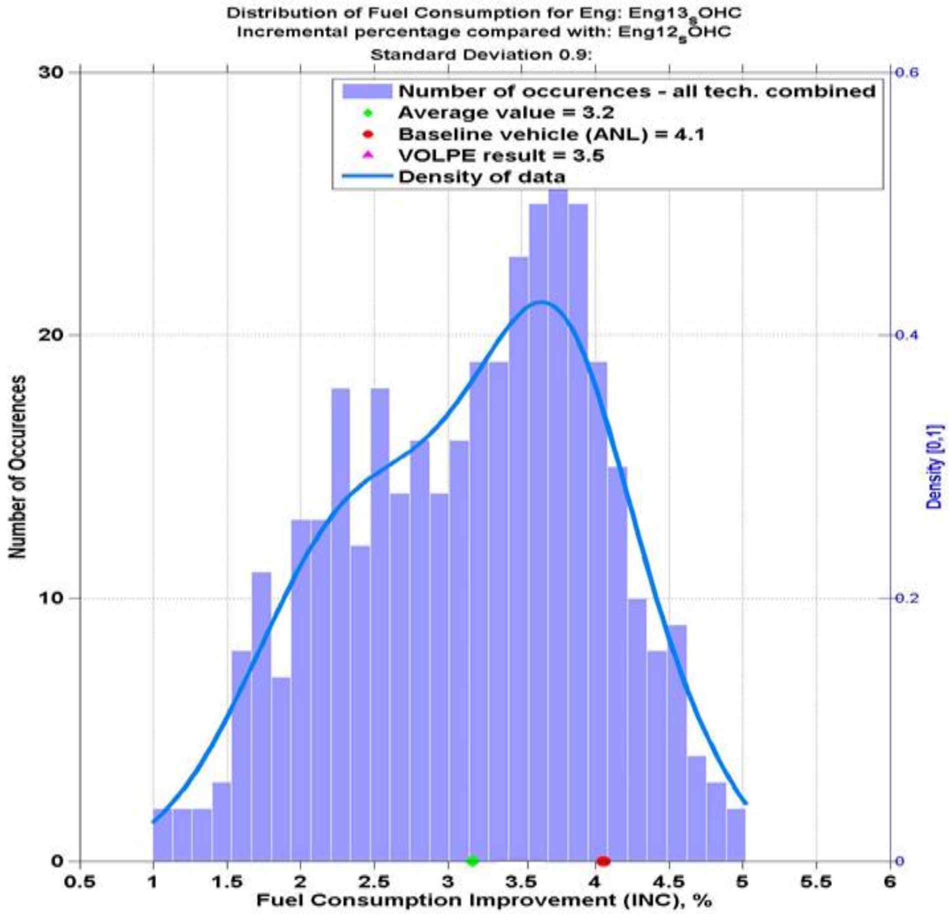

Figure 5.238 Example of QA/QC Distribution Plot

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Chapter 6: Assessment of Consumer Acceptance of Technologies that Reduce Fuel Consumption and GHG Emissions

6.1 Introduction

As part of the midterm evaluation, the agencies committed that, in this Draft TAR, they would examine "Costs, availability, and consumer acceptance of technologies to ensure compliance with the standards, such as vehicle batteries and power electronics, mass reduction, and anticipated trends in these costs."[1] Technologies and costs are examined in Chapter 5 of this document; this chapter reviews consumer acceptance of the technologies being used to meet the standards. With the program in effect since MY2012, this chapter focuses on the evidence to date on consumer acceptance of vehicles subject to the standards.

Chapter 6.2 discusses one potential measure of consumer acceptance, the effects of the standards on vehicle sales; as discussed there, it is difficult, if not impossible, to disentangle the effects of the standards on vehicle sales from the effects of macroeconomic or other conditions on sales. Chapter 6.3 discusses possible reasons why fuel efficient technologies may not be adopted absent the standards, in spite of the observation that fuel savings outweigh upfront costs. Chapter 6.4 discusses preliminary results of an EPA-led analysis of how professional auto reviewers assess the GHG-reducing technologies; in general, the reviews are positive. Finally, Chapter 6.5 reviews evidence related to the effects of the standards on the affordability of new and used vehicles, and suggests the difficulty of identifying and measuring such effects.

6.2 Effects of the Standards on Vehicle Sales

6.2.1 Overview of Vehicle Market

Chapter 3 examines trends in the light-duty vehicle market since the National Program standards went into effect in MY2012.[A] As that chapter shows, vehicle sales have been close to record levels. At the same time that GHG emissions have been dropping, vehicle footprint has increased slightly, horsepower has increased, and weight has been roughly constant. The projections for the car/truck mix used in the 2017-25 rulemaking are close to those being realized through MY2014 (see Chapter 3.1.4).

It is difficult, if not impossible, to separate the effects of the standards on vehicle sales and other characteristics from the impacts of macroeconomic or other forces on the auto market. Figure 6.1 graphs light-duty vehicle production[B] and gross domestic product (GDP) per capita from 2005-2015.[2] As this figure shows, production in the auto industry has had a pattern similar to GDP per capita: production fell with the reduction in economic activity in the 2009 recession, and has increased as the economy has recovered. The American Automotive Policy Council, in citing this recovery, notes that "U.S. auto sales increased by double digits from 2010 to 2014, even though GDP has grown by less than 3 percent each year;"[3] it projects sales to reach or

[A] Note that California's GHG standards began with MY2009 and includes a "deemed to comply" provision with the National Program for MY2012 and subsequent, see Section 1.2.3 for further background.

[B] Vehicle production data represent production volumes delivered for sale in the U.S. market, rather than actual sales data. They include vehicles built overseas imported for sale in the U.S., and exclude vehicles built in the U.S. for export.

exceed 17 million vehicles each year through 2016, and domestic production to go from 5.8 million vehicles in 2009 to 11.5 million or more vehicles through 2016. A number of other factors are also likely to affect new vehicle production and sales, including fuel prices, demographic factors, and vehicle characteristics including but not limited to fuel economy.

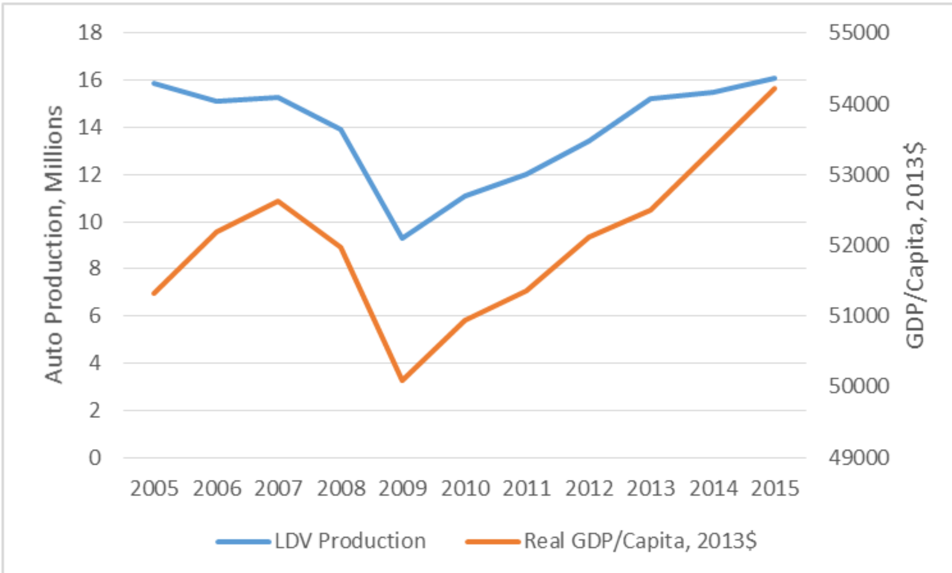

Figure 6.1 Gross Domestic Product Per Capita and Vehicle Production, 2005-2015
Note: Gross Domestic Product per Capita data are from U.S. Bureau of Economic Analysis, Account Code A939RX (Real gross domestic product per capita); LDV production from U.S. EPA 2015.4 2015 production data are projected, not actual, values.

The National Program light-duty vehicle standards, which went into effect in MY2012, are likely to have had some effect on vehicle sales. We have not identified, however, any sound way to separately estimate the effect of the standards on sales. The most solid analysis would involve the ability to compare sales in a place not affected by the standards, with sales in a place identical to the first during the same time period, except where the standards are in effect. Because the standards are national in scope, such a comparison is not possible. Alternatively, it may be possible to examine how sales have changed as the standards have tightened, but it would be necessary to control for all other factors, such as macroeconomic conditions, that affect sales. Perhaps all that can be concluded about the effects of the standards on vehicle sales is that they have clearly not prevented the automobile market from recovering to pre-recession sales levels (indeed, to record sales levels) through 2015.

6.2.2 Consumer Vehicle Choice Modeling and Recent Research

In addition to their effect on overall sales and production, the standards could affect the mix of vehicles sold. Consumer vehicle choice models estimate what vehicles consumers buy based on vehicle and consumer characteristics. In principle, such models could provide a means of examining the effects of the standards on both overall vehicle sales and the mix of vehicles sold. Because the standards are based on the footprints of vehicles, shifts in the mix of vehicles sold do not necessarily affect automakers' ability to meet the standards, but they could affect total GHGs emitted. Whitefoot and Skerlos (2012), for example, use a vehicle choice model combined with producer cost estimates to argue that the footprint-based standard provides some incentive for automakers to increase the size of vehicles in order to face a less stringent standard, and higher GHG emissions.[5,C] As discussed in Chapter 3, the average footprint of vehicles has increased slightly since the standards have been implemented. As with sales, this effect is potentially confounded by a number of factors, such as previous trends, dropping gasoline prices and increasing consumer income that changes the mix of vehicles purchased.

In the 2017-25 LDV GHG RIA (Chapter 8.1.2), EPA provided an extensive discussion of consumer vehicle choice modeling as a way to estimate the effects of GHG/fuel economy standards on vehicle purchase decisions.[6] In that discussion, EPA found that, despite an extensive literature of consumer choice models, few researchers have compared estimates of key model parameters with those of others' models, and there have been few efforts to test the forecasting ability of those models. As a start to addressing this gap in the literature, EPA had commissioned a study of the findings of these models on the role of fuel economy in consumer vehicle purchases and found highly varied results.[7] At the time, EPA concluded that the science of these models was not adequately developed for use in policy-making.

Two recent papers have done some work on the predictive abilities of consumer choice models. Haaf et al. (2014) use data from MY2004-6 vehicles to estimate a number of different econometric models, and test their predictions against MY2007 and 2010 vehicle sales.[8] They conclude that "the models we construct are fairly poor predictors of future shares." They find that a "static" model assuming constant market shares – that is, using current-year market shares rather than a model -- outperformed their estimated models for MY2007, while some attribute-based models predicted better for MY2010. Raynaert (2014) developed a structural model of vehicle supply and demand in Europe, using data from 1998-2007; he then compared red sales-weighted aggregate predictions from the model for MY2011 to actual outcomes.[9] He finds close agreement on aggregate market outcomes: in a period where actual emissions dropped 14 percent, his estimates for emissions differed from the observed values by 2.3 percent. Weight, footprint, and the share of diesel also had discrepancies of 3 percent or less; price/income and horsepower differed by under 10 percent. He implies, without detailed information, that the model nevertheless does not predict market shares or total sales very well. These papers leave questions unanswered about the ability of consumer vehicle choice models to predict sales and fleet mix.

6.2.2.1 EPA's Efforts in Developing and Assessing a Consumer Vehicle Choice Model

As part of its exploration of vehicle choice modeling, EPA commissioned the development of a vehicle choice model from David Greene and Changzheng Liu of Oak Ridge National Laboratory (Greene and Liu 2012).[10] This model, described in the 2017-2025 RIA (Chapter 8.1.2.8), is designed with a straightforward purpose: to estimate, for a predetermined fleet (the reference fleet, described in Chapter 4), the effects of changes in only fuel economy and price on

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[C] While the agencies consider the concept of the Whitefoot and Skerlos analysis to have some potential merits, it is also important to note that, among other things, the authors assumed different inputs than the agencies actually used in the MYs 2012-2016 rule regarding the baseline fleet, the cost and efficacy of potential future technologies, and the relationship between vehicle footprint and fuel economy. Changes in any of the underlying assumptions is likely to lead to different analytical results, and possibly different implications for agency action.

vehicle sales and class mix. The model calculates a sales response to a change in the "effective price" for each vehicle, where the effective price combines any change in up-front cost with a portion of the future fuel savings (see Greene and Liu 2012 for details). That portion of future fuel savings depends on user inputs for factors including the price of fuel, the number of years of fuel savings that a buyer considers (the payback period), and the discount rate. It is intended for use in policy analyses of vehicle GHG/fuel economy regulations, and not to predict changes in the vehicle market associated with macroeconomic shifts or changes in demographic factors. As part of our ongoing study of vehicle choice models, EPA has put the model through a variety of tests intended to understand it better.[11]

One group of tests involved examining the sensitivity of the model to changes in parameters, including the role of fuel economy in consumer purchase decisions, the discount rate, model elasticities, and the initial vehicle fleet.

- First, we examined the effects of a 20 percent improvement in fuel economy[D] for all vehicles; in response, total sales increased about 5 percent, with higher sales increases going for some of the larger, less fuel-efficient vehicles. If poor fuel efficiency would otherwise reduce the interest of buyers in those vehicles, then improving their fuel economy may disproportionately improve their sales.
- Next, we varied the payback period – the number of years of fuel savings that a vehicle buyer might consider in the purchase decision – from 1 to 7 years. Total sales increased by less than 1 percent for every additional year of payback period, suggesting that modeling results are not highly sensitive to this parameter.
- Similarly, varying the discount rate (used to calculate the value of future fuel savings) from 2 to 10 percent changed total sales by less than 1 percent, suggesting insensitivity to this parameter as well.
- When demand elasticities (percent change in sales in response to a one percent change in effective price) for all classes in the model are increased by 50 percent, total sales increase 7 percent, compared to 5 percent in the baseline case; if the elasticity of only one class is changed, total sales are virtually unaffected, though sales in the class that had the elasticity change increased by about 5 percent.
- Finally, we experimented with increasing the number of vehicles in the initial fleet by 50 percent (both uniformly for all vehicles and for one vehicle class at a time), to test sensitivity to assumptions about that baseline fleet. The sales response with a larger fleet to the 20 percent change in fuel economy was approximately proportional: just as sales in the initial case increased 4.9 percent in response to the changes in fuel economy, sales with the larger fleet increased 4.9 percent. Changing the size of individual classes also had very little effect on market shares, because they all increased proportionally.

[D] In the model, sales change in response to an effective price that combines the up-front cost with a share of future fuel savings. Increasing fuel economy thus has the opposite effect of increasing price; the former reduces the effective price, while the latter increases it. We used the 20 percent increase in fuel economy as a fairly large change, especially because it is not offset by any price increase.

In sum, these tests showed that the results of the model are not highly sensitive to any of these parameters. Thus, imprecision in the initial fleet or these other factors is not likely to have a major effect on the model's predictions. It also suggests that the results of changing fuel economy and price in the model may not have large effects on the vehicle fleet. Of course, this series of tests does not provide insight into whether its predictions are accurate.

A second exercise examined the model's ability to predict sales. It should be noted that the model is not intended to predict future sales or fleet mix. To do so would require inclusion of factors such as macroeconomic conditions and demographic shifts that affect sales; EPA's model was not designed to include those factors. As noted above, the model is intended to take as a given the without-standards fleet, and to estimate the effects of changes in price and fuel economy on sales and class shifts, as a way of focusing specifically on the effects of GHG policy on the fleet. For that reason, testing the model by using it to predict sales in a different year is asking more of the model than the purposes for which it was intended. We conducted this test, nevertheless, as an initial attempt to test whether the model's results reflect actual consumer behavior.

In this test, we calibrated the model to MY2008 vehicle sales, calculated the difference in vehicles' fuel economy and price between MY2008 and MY2010 (another year for which we had the specific vehicle data needed for this analysis), used the model to estimate responses to the changes in MY2010 fuel economy and price, and compared the MY2010 predictions to actual MY2010 sales. The model did not predict sales or market shares well. The model predicted an increase in total sales when actual sales decreased. For market shares, similar to the near-term results in Haaf et al. (2014), using actual market shares from MY2008 – i.e., not using a model – had better predictions than using the model. These poor predictions are not surprising, given that MY2010 sales reflect the Great Recession, a significant factor that the model was not designed to address. We do not consider these results a demonstration that the model does not perform well; rather, it indicates the difficulty of testing the predictive abilities of this model as it is designed.

At this point, then, EPA does not plan to use this or another vehicle choice model in its current modeling work. We encourage further research in the validation of these consumer choice models for policy analysis.

6.3 Conceptual Framework for Evaluating Consumer Impacts

As discussed in Chapter 12, the agencies estimate that fuel-saving technologies, in addition to reducing GHG emissions and improving energy security, pay for themselves within a few-year payback period, and thus save consumers money. Despite this, development and uptake of energy efficiency technologies lags behind adoption that might be expected under these circumstances. The implication is that private markets do not provide all the cost-effective energy-saving technologies identified by engineering analysis. The phenomenon is documented in many analyses of energy efficiency, and is termed the "energy paradox" or "energy efficiency gap."[12] A number of hypotheses have been raised for the existence of this gap,[13] as discussed in the 2017-25 LD GHG rulemaking. Some arise from market failures, such as lack of perfect information. Others point to behaviors on the part of consumers and/or firms that appear not to be in their own best interest (behavioral anomalies). Still others point to potential costs of the standards that are not reflected in EPA analyses. On the consumer side, these hypotheses include:

- Consumers might lack the information necessary to estimate the value of future fuel savings, not have a full understanding of this information even when it is presented, or not trust the presented information

- Consumers might be “myopic” and hence undervalue future fuel savings in their purchasing decisions

- Consumers may be accounting for uncertainty in future fuel savings when comparing upfront cost to future returns

- Consumers may consider fuel economy after other vehicle attributes and, as such, not optimize the level of this attribute (instead “satisficing” – that is, selecting a vehicle that is acceptable rather than optimal -- or selecting vehicles that have some sufficient amount of fuel economy)

- Consumers might be especially averse to the short-term losses associated with the higher prices of energy efficient products relative to the long-term gains of future fuel savings (the behavioral phenomenon of “loss aversion”)

- Consumers might associate higher fuel economy with inexpensive, less well designed vehicles

- When buying vehicles, consumers may focus on visible attributes that convey status, such as size, and pay less attention to attributes such as fuel economy that typically do not visibly convey status

- Even if consumers have relevant knowledge, selecting a vehicle is a highly complex undertaking, involving many vehicle characteristics. In the face of such a complicated choice, consumers may use simplified decision rules

- Because consumers differ in how much they drive, they may already sort themselves into vehicles with different, but individually appropriate, levels of fuel economy in ways that an analysis based on an average driver does not identify

- Fuel-saving technologies may impose hidden costs -- adverse effects on other vehicle attributes

If consumers are doing a good job of getting their efficient amount of fuel economy, their willingness to pay for additional fuel savings, revealed in their purchase decisions, should approximately equal expected future fuel savings. A review of the literature sponsored by EPA looked at the range of estimates of the value of fuel economy in consumer purchase decisions in models of consumer vehicle purchase decisions; it found as many studies with undervaluation of fuel economy as there were studies with about-right or overvaluation.[14] The studies used in that review tended to emphasize modeling of vehicle purchase decisions rather than the role of fuel economy in those decisions. Some recent academic research has looked specifically at the question of the value of fuel economy.[15] Busse et al. (2013) and Sallee et al. (2016) find that consumers appear to buy fuel economy that does approximate fuel savings; Allcott and Wozny (2014) find in contrast that the willingness to pay for fuel economy is about 3/4 of the expected future fuel savings. Thus, consumers appear to take fuel economy into account when buying vehicles, but how precisely they do it is not yet clear.

The 2015 National Academies of Sciences report titled, "Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles"[16] also reviewed the literature. Among the studies that NAS reviewed was a 2013 paper by Greene, Evans, and Hiestand, regarding which the NAS Committee stated, "Four nationwide random sample surveys of 1,000 respondents each, conducted between 2004 and 2013, showed that consumers considered fuel economy ratings and future fuel prices to be very uncertain. . . . The surveys also produced consistent evidence that consumer willingness to pay for fuel savings implies average payback periods of 2-3 years" (p. 317). Regarding the overall review of the literature conducted by the NAS Committee, the Committee concludes,

"How markets actually value increases in new vehicle fuel economy is critical to evaluating the costs and benefits of fuel economy and GHG standards. Unfortunately, the scientific literature does not provide a definitive answer at present. . . . In the committee's judgment, there is a good deal of evidence that the market appears to undervalue fuel economy relative to its expected present value, but recent work suggests that there could be many reasons underlying this, and that it may not be true for all consumers. Given the importance of this question to the rationale for regulatory standards and their costs and benefits, an improved understanding of consumer behavior about this issue would be of great value." (p. 318)

The agencies seek comment on consumer willingness-to-pay for fuel economy, including considerations of payback periods on the order of 2-3 years, or more, or less.

Consumers cannot buy technologies that are not produced; some of the gap in energy efficiency may be explained from the producer's side. Two major themes arise on the producer side: the role of market structure and business strategy, and the nature of technological invention and innovation.

- Light-duty vehicle production involves significant fixed costs, and automakers strive to differentiate their products from each other. These observations suggest that automakers, rather than meeting the stylized economic model of perfect competition, can act strategically in how they design and market products. In this context, the fuel economy of a vehicle can become a factor in product differentiation rather than a decision based solely on cost-effectiveness of a fuel-saving technology.[17] Product differentiation carves out corners of the market for different automobile brands. For instance, automakers may emphasize luxury characteristics in some vehicles to attract people with preferences for those characteristics, and they may emphasize cost and fuel economy for people attracted to frugality. By separating products into different market segments, producers both provide consumers with goods targeted for their tastes, and may reduce competition among vehicle models, creating the possibility of greater profits. From the producer perspective, fuel economy is not necessarily closely related to the cost-effectiveness of the technologies to consumers, but rather is one of many factors that manufacturers use to market their models to different consumer groups. As Fischer (2005) points out, this strategy can lead to inefficiencies in the market: an under-supply of fuel economy relative to what is cost-effective to consumers in some segments, and an over-supply of fuel economy in other sectors.[18] The structure of the automobile industry may inefficiently allocate car attributes--fuel economy among them--and help to explain the existence of an energy efficiency gap.

- Chapter 4.1.3 discusses the relationship between technological innovation and the standards, but a shortened discussion is relevant here. In particular, in the absence of standards, automakers are likely to invest in small improvements upon existing technologies ("incremental" technologies) that can be used to improve fuel economy or other vehicle attributes. On the other hand, they may be more hesitant to invest in "major" innovations in the absence of standards, for several reasons.
  - There may be first-mover disadvantages to investing in new technologies. Many manufacturers prefer to observe the market and follow other manufacturers rather than be the first to market with a specific technology. The "first-mover disadvantage" has been recognized in other research where the "first-mover" pays a higher proportion of the costs of developing technology, but loses the long-term advantage when other businesses follow quickly.[19]
  - There could be "dynamic increasing returns" to adopting new technologies, wherein the value of a new technology may depend on how many other companies have adopted the technology -- for instance, creating multiple suppliers for a technology should increase competition, improve quality, and reduce price. This could be due to network effects or learning-by-doing. In a network effects situation, the usefulness of the technology depends on others' adoption of the technology: e.g., a telephone is only useful if other people also have telephones. Learning by doing is the concept that the costs (benefits) of using a particular technology decrease (increase) with use. Both of these incentivize firms to pursue a "wait and see" strategy when it comes to adopting new technologies.[20]
  - There can be synergies when companies work on the same technologies at the same time.[21] Research among multiple parties can be a synergistic process: ideas by one researcher may stimulate new ideas by others, and more and better results occur than if the one researcher operated in isolation.[22,E] Collaboration between automotive companies or automotive suppliers does occur. For example, in 2013, Daimler, Ford, and Nissan teamed up to work on fuel cell vehicles,[23] and Toyota

[E] Powell, Walter W., and Eric Giannella (2010). "Collective Invention and Inventor Networks," Chapter 13 in Handbook of the Economics of Innovation, Volume 1, edited by B. Hall and N. Rosenberg (Elsevier) discuss how a "collective momentum" has led uncoordinated research efforts among a diverse set of players to develop advances in a number of technologies (such as electricity and telephones). They contrast this view of technological innovation with that of proprietary research in corporate laboratories, where the research is part of a corporate strategy. Such momentum may result in part from alignment of economic, social, political, and other goals.

and BMW teamed up to work on battery technology.[24] In 2015 Toyota and Mazda "agreed to form a 'long-term partnership'" to collaborate on numerous advanced technologies, including plug-in hybrid and fuel cell systems.[25] Standards can promote research into low-CO2 technologies that would not take place in the absence of the standards. Because all companies (both auto firms and auto suppliers) have incentives to find better, less expensive ways of meeting the standards, the possibilities for synergistic interactions may increase. Thus, the standards, by focusing all companies on finding more efficient ways of achieving the standards, may lead to better outcomes than if any one company operated on its own.

These potential explanations are relevant, of course, if the efficiency gap exists for vehicles. If the gap does not exist, then there is no need to understand reasons for it. To understand the effects of the standards, EPA has therefore been focusing on the existence of the gap. If the gap exists, then the standards are providing net benefits to vehicle buyers, even if it is unclear why this is happening.[26]

The existence of the gap depends on whether fuel-saving technologies that would not have been used in the absence of the standards provide net benefits to new vehicle buyers even when the externalities associated with the standards are not included. The net benefits calculation involves three components: the technology's effectiveness (which, along with fuel prices and the amount driven, determines the fuel savings);[F] the technology's costs; and whether there are any adverse unintended consequences of the technologies (hidden costs), such as interference with the vehicle's handling or braking.[G] Chapter 5 discusses the technology costs and effectiveness of the technologies that may be used to achieve the standards. The next section describes research that EPA has conducted to assess the existence of potential hidden costs associated with these technologies.

6.4 Consumer Response to Vehicles Subject to the Standards

6.4.1 Recent New Vehicles

6.4.1.1 Sales

One measure of consumer response to the vehicles subject to the standards is the effects of the standards on vehicle sales. As discussed in Chapter 3 and in Chapter 6.1, it is difficult, if not impossible, to separately identify the effects of the standards on vehicles sales from the effects of

[F] Fuel-saving technologies provide different cost savings across consumers, because they drive different amounts under different conditions (which affect miles per gallon). As noted above, if each consumers gets individually optimal fuel economy in a vehicle that meets his/her other needs, then the efficiency gap does not exist even if an analysis done based on an average driver shows potential for increased efficiency.

[G] Note that the agencies' modeling work on technological effectiveness builds in the need to maintain all aspects of vehicle performance. That is, the methodology includes all costs of implementing the technologies to achieve GHG reductions while maintaining all aspects of performance and utility. The agencies thus concluded that adding fuel-saving technologies results in no loss of vehicle utility, and that adding fuel-saving technologies will not preclude future improvements in performance, safety, or other attributes. See generally Chapter 3.2 of 2017-2025 MY TSD, and 77 FR 62714/2. Chapter 4.1.3 and the next sub-chapter further discuss the relationship between the standards and other vehicle attributes.

recovery from recession. It appears that the standards did not prevent recovery of auto sales from the recession, but it is not possible to say whether the standards helped or hindered that recovery.

6.4.1.2 Evaluations from Professional Auto Reviewers

Another way that EPA is examining the effects of the standards on new vehicles is through analysis of the evaluations that professional auto reviewers give to fuel-saving technologies.[27] Auto reviews are a readily available and public source of information about the advantages and disadvantages of new vehicle models. We focused on professional automobile reviews because professional reviewers have experience evaluating vehicle technologies and are expected to identify any potential drawbacks to consumers (i.e., hidden costs) if they exist. Although reviewers may not respond to vehicle technologies in the same way that vehicle owners will, it seems reasonable to expect that, if there are significant problems for particular technologies, reviewers will comment on them.

EPA commissioned RTI International to conduct a content analysis of auto reviews for MY2014 vehicles from six major websites that conduct professional auto reviews: Automobile Magazine, Auto Trader, Car and Driver, Consumer Reports, Edmunds, and Motor Trend.[28] Content analysis is a research technique that breaks text into pre-defined sub-units that can be categorized and analyzed into specified definitional codes.[H] Staff at RTI read each auto review from a professional reviewer (reader reviews or comments were not included in the study) and coded each mention of specific fuel-saving technologies for whether the reviewer evaluated it as positive, negative, or neutral. In addition, they coded mentions of a number of operational characteristics, such as handling, acceleration, and noise. The initial dataset included 1023 reviews. After further review of the data, the final set includes 1,003 separate reviews, containing 3,535 separate evaluations of various fuel-saving technologies.[I]

Table 6.1 shows the results aggregated to the review level.[J] For each technology, positive evaluations exceed negative evaluations. Indeed, in the aggregate, negative evaluations are less than 20 percent of the totals. Even the most negatively reviewed technologies – continuously variable transmissions (51 percent positive) and stop-start (59 percent positive) – have majority positive evaluations. These results suggest that it is possible to implement these technologies without significant hidden costs. The NAS report suggests a similar conclusion: "'It is not technology per se that generates new problems, but rather its integration and execution,' Neal

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[H] There are many descriptions of content analysis and its evolution as a research methodology; see Helfand et al. (2015), footnote 22, for background and citations.

[I] The initial dataset inadvertently contained reviews of 15 vehicles not subject to the standards, primarily medium-duty trucks that had not previously been eliminated. In addition, due to issuance of a notice of violation about the compliance of some Volkswagen diesel engines with emissions standards, we dropped 5 reviews of those vehicles.

[J] Each review could contain mentions of more than one technology, or even multiple mentions of the same technology. The review-level results aggregate all like mentions of a technology in one review. For instance, if a review contains 3 positive mentions of turbocharging, the review-level results count them as 1 positive mention. If the review contains 3 positive mentions and 1 negative mention, at the review level these are counted as 1 positive and 1 negative mention. The data were analyzed both at the level of individual codes, and aggregated to review. With the results very similar, we here focus on the review-level results. See Helfand et al. (2015) for more detail, including code-level results.

Oddes, Director of Product Research and Analysis at J.D. Power, noted (Janes 2013), an observation that could be made for some of the fuel-saving technologies being launched today" (p. 9-21).

Table 6.1 Efficiency Technology's Positive, Negative, or Neutral Evaluations by Auto Reviews

Efficiency Technology Categories		Coding level	Negative		Neutral		Positive		Total
Active Air Dam		Active air dam	-	-	-	-	6	100%	6
Active Grill Shutters		Active grill shutters	-	-	-	-	1	100%	1
Active Ride Height		Active ride height	-	-	1	33%	2	67%	3
Electric Assist or Low Drag Brakes		Electric assist or low drag brakes	1	14%	3	43%	3	43%	7
Lighting - LED		Lighting-LED	1	5%	2	10%	17	85%	20
Low Rolling Resistance Tires		Low rolling resistance tires	4	24%	5	29%	8	47%	17
Mass Reduction		Mass reduction	-	-	9	12%	65	88%	74
Passive Aerodynamics		Passive aerodynamics	4	10%	7	18%	29	73%	40
Powertrain	Engine	Cylinder deactivation	1	3%	4	11%	30	86%	35
		Diesel	7	12%	9	15%	44	73%	60
		Electronic power steering	45	22%	42	20%	121	58%	208
		Full electric	2	9%	6	27%	14	64%	22
		GDI	6	9%	6	9%	54	82%	66
		General Engine	104	16%	95	15%	443	69%	642
		Hybrid	16	23%	10	14%	45	63%	71
		Plug-in hybrid electric	4	14%	6	21%	18	64%	28
		Stop-start	14	27%	7	14%	30	59%	51
		Turbo-charged	20	9%	23	10%	180	81%	223
	General Powertrain	General Powertrain	8	8%	19	18%	78	74%	105
	Transmission	CVT	35	31%	20	18%	57	51%	112
		DCT	16	24%	10	15%	42	62%	68
		General Transmission	30	18%	26	16%	108	66%	164
		High speed automatic	60	14%	81	20%	273	66%	414
		Total	378	16%	391	16%	1,668	68%	2,437

Further evaluation of the data involves looking at correlations between evaluations of each technology and a range of operational characteristics (handling, acceleration, noise, etc.). In particular, this evaluation assesses how the technologies are related to negative evaluations of these characteristics. If the technologies have hidden costs, the research premise is that the technologies should be positively correlated with negative evaluations of operational characteristics. The results do not reveal much evidence of such correlation. When correlations exist, often they are not statistically robust; their statistical significances change depending on what covariates are considered. For instance, seven technologies have at least one statistically significant correlation with the characteristic of acceleration capability in six versions of the model, but only one (continuously variable transmissions) has a statistically significant correlation across all six model versions (its existence is correlated with negative effects on acceleration capability). At the same time, in five of six models, the existence of stop-start technology is significantly associated with reduced probability of negative evaluations of acceleration capability. Indeed, across all characteristics, there are more instances of fuel-saving technologies associated with lower probabilities of negative evaluations of characteristics than with increased negative evaluations. In addition, negative evaluations of characteristics are more likely if the technology itself has a negative evaluation -- in other words, it seems that a bad implementation of the technology is associated with bad characteristics, rather than there being some inherent problem in the technology. If it is possible to implement a technology to avoid hidden costs, as these data suggest, then automakers should be able to improve implementation over time; in such a circumstance, any problems with hidden costs may be temporary.

These findings on the relationship of technologies to hidden costs or hidden benefits have some limitations. They appear sensitive to how the analysis is done, and the magnitudes are often small. Perhaps more importantly, it is not possible to determine whether the technologies themselves cause these effects, or whether these associations are due to the vehicles in which the technologies are installed. For instance, perhaps stop-start was put in vehicles that would have had better acceleration even without it. As a result, this research is not able to disprove the possibility of hidden costs (or benefits). In addition, this research cannot determine what, if any, additional costs may have been incurred to mitigate problems with the technologies. It nevertheless fails to find evidence of systematic hidden costs associated with fuel-saving technologies. The agencies seek comment providing additional evidence related to concerns over hidden costs.

Helfand et al. (2015)[29] provides further detail about the methods and results of this work, including additional limitations. Note that this research examines how professional auto reviewers respond to these technologies, rather than how vehicle buyers respond. If the public tends to be harsher critics than the reviewers, then these results may understate negative consumer response. In addition, reviewers spend much less time with any one vehicle than a vehicle owner; something that a reviewer may not notice in a few hours of test driving may become significant to an owner over time. On the other hand, we expect professional auto reviewers, as experts, to be aware of vehicle characteristics and technologies more than the general public. Thus, consumer response to these technologies may be either more or less critical than reviewer response.

6.4.1.3 Consumer Responses to New Vehicles

Another potential source of information on consumer response to vehicles subject to the GHG and fuel economy standards can come from market research firms that conduct surveys of new vehicle buyers. These surveys, typically conducted a few months after purchase of a new vehicle, ask the buyer's views on a wide range of vehicle attributes. EPA has been pursuing access to one of these survey data sets. Our goal would be to look for associations between the existence of fuel-saving technologies and consumer responses to vehicle attributes: for instance, do consumers rate satisfaction with their vehicles differently for vehicles with stop-start systems relative to those without such systems, controlling for other vehicle characteristics? This research would provide direct insights into consumer attitudes.

EPA is still pursuing access to such a database; results from it are not available for this Draft TAR. If we are successful in gaining access, we intend to use the information to inform the midterm evaluation.

6.4.2 MY2022-25 Vehicles

To date, it seems difficult to find evidence that the standards have posed significant obstacles to consumer acceptance: vehicle sales are very strong, and we have not found evidence of inherent "hidden costs" of the technologies, at the same time that the auto industry as a whole has over-complied with the standards (see Chapter 3.3).[K] As the standards continue to become more stringent, though, there will be both more application of existing technologies to new vehicles, and new or improved technologies are likely to be developed. As discussed in Chapter 4.1.3, these standards themselves may be contributing to innovation that would not have happened in their absence. As a result, it is difficult to extrapolate to future technologies from findings related to existing ones.

There is, of course, uncertainty about which technologies will be necessary to achieve the MY2022-25 standards. In the MY2017-25 rulemaking analysis, EPA projected that the standards could be achieved primarily with gasoline vehicles; it estimated only about 2 percent penetration of plug-in electric vehicles (PEVs), either plug-in hybrid electric vehicles (PHEVs) or all-battery EVs (BEVs).[30] The NAS also expects the spark-ignition gasoline engine to dominate the auto market through, and beyond, 2025.[31] For these vehicles, the effects of the standards on consumer acceptance depend on the costs, effectiveness, and potential tradeoffs or synergies of those technologies with other attributes; there is already an established infrastructure for fuel availability. If the standards can be achieved primarily with greater penetration of existing technologies, we do not have evidence of significant problems for consumer acceptance. On the other hand, if the standards can be achieved only with increased utilization of new technologies, these new technologies could raise the possibility of new challenges.

The role of electrified vehicles in particular in achieving the standards has led to questions about consumer acceptance of those vehicles.[L] Some states,[M] led by California, are requiring greater use of plug-in electric vehicles (PEVs) and fuel cell electric vehicles (FCEVs) for meeting state air quality and greenhouse gas targets, and these vehicles are also included in automaker fleets that are subject to the National Program. If EVs become a more important part of the compliance strategy for the 2022-25 standards, then their unique features -- in particular,

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[K] Design elements of program, such as targeting emissions rather than specific technologies, averaging and banking credits, and allowing credit trades, are expected to have facilitated compliance by providing manufacturers with great flexibility in meeting the standards.

[L] We do not include conventional hybrid-electric vehicles (HEVs) in this discussion. Because they are fueled solely by gasoline and rely on the same infrastructure as other gasoline vehicles, they are part of the gasoline-vehicle market.

[M] Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont have adopted the California Zero Emission Vehicle program.

the need for infrastructure and the associated concerns over vehicle range, as well as differences (many positive) in other attributes -- are likely to have an effect on consumer acceptance.

As noted in the 2017-25 Preamble,[32] the National Program standards are performance-based; there is no mandate under the National Program for any manufacturer to use any particular kind of technology, or for any consumer to choose, any particular kind of vehicle. If the variety of vehicles in the conventional fleet does not shrink, the availability of PEVs should not reduce consumer welfare compared to a fleet with no PEVs: increasing options should not reduce consumer well-being, because other existing options still are available. An individual consumer will buy a PEV only if the price and characteristics of the vehicle make it more attractive to her than other vehicles. Already, many current PEV options are versions of gasoline-only vehicles, for example, the Chevrolet Spark EV, the FIAT 500e, all of Ford's PEV products, and the Volkswagen e-Golf. The forthcoming Hyundai Ioniq will be offered as a conventional hybrid, plug-in hybrid, and all-battery electric vehicle, allowing consumers to choose the degree of electrification best suited to their needs. Similarly, both Volvo and BMW have announced plans to offer plug-in hybrid variants over a wide range of existing and new models.

On the other hand, if the only compliance path available to automakers involves more use of PEVs than markets would normally support (in the absence of government incentives), then achieving the standards may lead automakers and dealers to encourage the market for PEVs by providing incentives for PEV purchase sufficient to meet the standards. This encouragement can come in various forms -- for instance, through marketing and advertising, through sales incentives, or through increased education about PEVs to potential buyers to increase buyer familiarity with the technology. Automakers may also cross-subsidize sales as they have long been able to do to meet fleet average standards; in this case using higher prices on conventional vehicles to support lower prices on PEVs, to increase sales of PEVs relative to gasoline vehicles beyond levels that markets would support in the absence of the standards. Cross-subsidization would be expected to reduce auto industry profits.

If consumers are willing to purchase PEVs (and other low-GHG-emitting vehicles) at prices that provide adequate profits to manufacturers, then consumer acceptance is sufficient to maintain a functioning auto market. As discussed in Section 3.1.5, PEVs are currently estimated to be about 1.1 percent of MY2015 sales. Section 5.2.4 discusses these technologies and the technological advances being made. As that section presents, this market is evolving rapidly, with expected increases in model diversity, vehicle range, decreased costs, and expansion of infrastructure (see Chapter 9). Although PEV range is often cited as a concern for consumer acceptance, it should be noted that PEVs have some desirable characteristics relative to gasoline vehicles, including higher low end torque, potentially higher acceleration, lower operating costs, and the convenience of refueling by plugging in at home.[N,33] Consumer acceptance of these vehicles will depend on the degree of all these factors, plus the differences in attributes, both positive and negative, of PEVs relative to gasoline vehicles. Additionally, many automakers have announced moderately priced BEVs with longer ranges, and various public and/or private initiatives continue to increase investments in public and workplace infrastructure that will further alleviate concerns about range.

[N] The Tesla Model S, an all-electric vehicle, for instance, has regularly been achieving top ratings from standard auto reviewers for its handling and power.

While concerns over range and cost are often cited as primary obstacles to PEV adoption, lack of awareness and understanding of PEVs, perhaps including misunderstanding, itself creates another barrier to adoption.[34] A 2015 survey by the National Renewable Energy Laboratory (NREL) of over 1,000 U.S. households found that less than half of the respondents could name a specific PEV model, despite being available on the market for over four years.[35] Using this same measure, awareness levels were even lower in a 2015 University of California, Davis survey of 5,600 households that purchased a new vehicle after 2008.[36]

The National Academy of Sciences Committee on Overcoming Barriers to Electric-Vehicle Deployment[37] notes that many people consider PEVs, as new technologies, to involve uncertainty and risk compared to gasoline vehicles, and thus are hesitant to consider them. It cites as barriers "the limited variety and availability of PEVs; misunderstandings concerning range of PEVs; difficulties in understanding electricity consumption, calculating fuel costs, and determining charging infrastructure needs; complexities of installing home charging; difficulties in determining the 'greenness' of the vehicle; lack of information on incentives; and lack of knowledge of unique PEV benefits" (p. 47).

Some studies suggest that experience with the technology increases acceptance.[38] Indeed, a survey of PEV drivers in California shows that the vehicle test drive and other PEV drivers to be the two information sources most influential in a consumer's purchase decision. Yet, if people view PEVs as risky and are thus reluctant to try them, then it will be difficult for them to gain experience that would make them more comfortable with the technology.

The NAS Committee discusses the role of auto dealers in helping consumers to understand PEVs. It notes PEV buyers' dissatisfaction with the dealer experience, greater than that of buyers of conventional vehicles.[39] It cites evidence that salespeople are not very knowledgeable about PEVs, and may not get adequate financial incentives for the extra time that PEV buyers may require. Many dealers have no or few PEVs in their stock. At most dealerships the explanation for not having PEVs in stock is "high demand" for the vehicles; the second-most common explanation, in contrast, is a "lack of consumer interest" (p. 52). These problems with consumers' experiences with PEV dealers may contribute to the slow adoption of PEVs in the market.

For a small segment of the public, PEVs already are suitable for their purposes. As the technology of PEVs evolves, especially as range and fueling infrastructure expand, it is likely that a larger segment could find PEVs suitable. As the NAS Committee notes, these issues arise with adoption and diffusion of many new technologies, and are not unique to PEVs. Overcoming these barriers, it argues, will require both public policy incentives and methods to promote consumer experience with them. As noted, some research suggests that some perceived barriers, such as concerns over charging, may become smaller with experience, while some perceived advantages may be strengthened.[40] Thus, consumer acceptance of PEVs may depend, not only on technological advances, but also on the feedback loop associated with other consumers purchasing PEVs.

6.5 Impacts of the Standards on Vehicle Affordability

Because the standards are expected to increase the up-front costs of new vehicles, with the fuel savings that recover those costs coming over time, questions arose in comments on the 2017-25 LD GHG rule about the effects of the standards on affordability. We analyze this question by considering the effects of the standards on lower-income households, on the used vehicle market, on whether access to credit may limit consumers' ability to purchase new vehicles, and on the availability of low-priced vehicles. Further detail may be found in Cassidy et al.[41]

6.5.1 Effects on Lower-Income Households

We begin here by examining the effects of the standards separately for lower- and higher-income households. We consider lower-income households to be those that had after-tax incomes below the weighted median[O] income in a given year, and higher-income households to be those that had after-tax incomes above that threshold. For example, the weighted median in 2013 is $33,371. For this analysis, we use the 2007-2013 Consumer Expenditure Survey (CES), which is conducted annually by the Bureau of Labor Statistics of the U.S. Department of Labor and provides information on the expenditures, income and characteristics of U.S. households, as well as federal poverty levels.[42,P]

The effects of this rule on lower income households depend on its impacts, not only in the new vehicle market, but also in the used vehicle market. Using CES data from 2007-2013, on average, 29 percent of new car buyers were lower income according to our definition.[Q] The 2013 Consumer Expenditure Survey data indicate that lower income households on average spent more in 2013 on gasoline ($2,154) than on vehicles ($670); in addition, they spent more on used vehicles ($362) than on new vehicles ($308). These results are analogous to those that Consumer Federation of America (CFA) provided in comments on the 2017-25 standards. CFA found that households with income less than $20,000 per year in 2010 accounted for 22 percent of households but only 2 percent of money spent on new vehicles; those households spent 7.3 times as much on gasoline as on new car payments.[43] These data suggest that lower income households are more affected by the impact of the rule on the used vehicle market than on the new vehicle market, and that they are more vulnerable to changes in fuel prices than they are to changes in vehicle prices.

6.5.2 Effects on the Used Vehicle Market

The effect of this rule on the used vehicle market will be related to its effects on new vehicle prices, the fuel efficiency of new vehicle models, the fuel efficiency of used vehicles, and the total sales of new vehicles. If the consumer value of fuel savings resulting from improved fuel efficiency outweighs the average increase in new models' prices to potential buyers of new vehicles, sales of new vehicles could rise, and the used vehicle market may increase in volume as

[O] The weighting, from the Bureau of Labor Statistics, corrects for under- or over-representation of certain households in each sample. The weighted median thus reflects the U.S. median rather than the sample median.

[P] The Federal Poverty Level is calculated annually by the Department of Health and Human Services. It varies with household size and for households in Alaska and Hawaii.

[Q] The CES data have many missing data. We present these results on the assumption that omitted information on vehicle purchases is not affected by household income.

new vehicle buyers sell their older vehicles. In this case, used vehicle buyers, including lower-income households, are likely to benefit from the increased inventory of used vehicles. However, if potential buyers value future fuel savings resulting from the increased fuel efficiency of new models at less than the increase in their selling prices, sales of new vehicles may decline, and the used vehicle market may see price increases as people hold onto their vehicles longer.

Jacobsen and van Bentham (2015) look at the effect of fuel prices and fuel standards on the used vehicle market.[44] They argue that the increased price of new vehicles subject to the standards will decrease new vehicle sales, and increase sales and prices in the used vehicle market. As people switch to used vehicles, the greenhouse gas benefits of more efficient new vehicles will be reduced. Their results depend on the standards depressing new vehicle sales.[R] As discussed in Chapter 6.2, we have not identified ways to estimate the effects of the standards on new vehicle sales.

Figure 6.2 presents data from the Consumer Price Index for used[45] and new vehicle.[46] Each series has been adjusted to a year 2013 reference base with underlying prices in 2013$ (using price deflators for GDP[47]) so that numbers on the *y*-axis represent the percentage difference from price levels in 2013 (in 2013$). Used vehicle prices have decreased since 1995, and have varied in a small range between 2008 and 2015. The used car price index closely follows the new car price index, although used car prices have more volatility across all years. Mannheim Consulting indicates that volumes at auto auctions have increased steadily from 2011-2015, with relatively small fluctuations in its value index during that time.[48] These suggest that the increase in new vehicle sales since the recession ended (see Chapter 6.1) has had the expected positive effect on used vehicle volumes; price reflects "strong new vehicle pricing, exceptional credit conditions, higher employment levels, record job stability, and the often overlooked factor of increased dealership operating efficiencies" (Mannheim Consulting, p. 15). The average loan payment for used vehicles, in nominal terms, increased by $6/month between 2014 and 2015;[49] in constant 2013$, the payment is approximately constant, at $350/month. This observation again does not suggest great movement in overall used vehicle prices. Additionally, trends in the new vehicle market, supply of used vehicles, and changing consumer preferences may even result in used prices falling for certain market segments; January 2016 used vehicle prices for compact and luxury cars fell relative to the prior year, while prices for used pickups increased.[50] As with the effects of the standards on new vehicle sales, it is possible that the GHG/fuel economy standards have had some influence on these trends, but their effect is likely swamped by the effects of the economic recovery.

[R] The applicability of their empirical analysis is limited due to their use of pre-2009 data (including cost data from 2002) and a flat (not footprint-based) standard, among other assumptions.

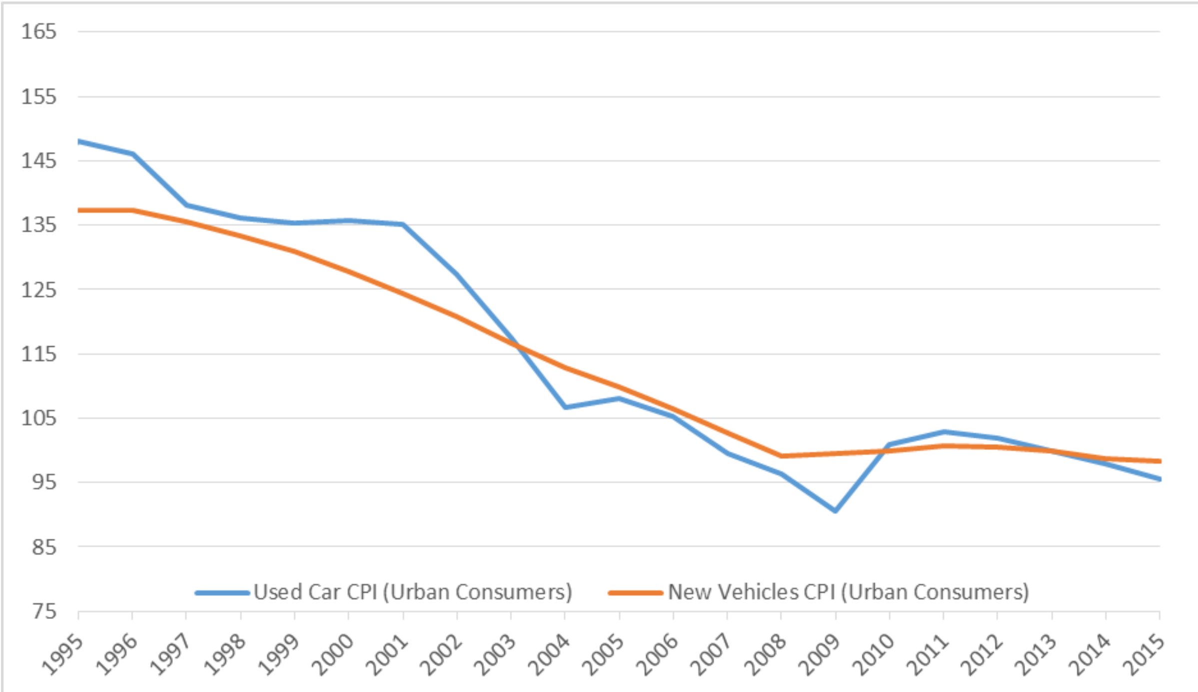

Figure 6.2 Used and New Car Consumer Price Index, 2013=100 (2013$).

A recent Heritage Foundation analysis[51] by Furth and Kreutzer (2016) cites a similar set of price trends to argue that prices of new vehicles are higher by larger amounts (up to $7100) than they would be if they had followed trends before 2009, trends in furnishings and durable household equipment, or trends in vehicle prices in the United Kingdom or in Australia. It implies that the standards created this divergence between the previous trend and current prices. This change in the price trend is unlikely to be due only, or even primarily, to the standards, though. These price trends are based on the vehicles that people are buying, not on a constant vehicle model; that is, if people are switching from less expensive to more expensive vehicles, then price trends would increase, even if the prices of individual vehicles had stayed constant. As discussed in Chapter 3.1.4, fleet mix has been changing during this time, with sales of SUVs and pickup trucks higher than the estimates in the 2012 final rule. For instance, the share of the fleet that is car (sedan) and not car SUV, truck SUV, pickup, or minivan went from 61 percent in MY 2009 to 49 percent in MY 2014.[52] To the extent that the latter vehicles are more expensive than car sedans, the change in sales mix will have affected the trend. Note as well that the price trend changes in 2008, at the start of the Great Recession, before the standards went into effect for MY 2012.[S] Without a good way to separate effects on prices due to the standards from other

[S] Further evidence that these price trends are not due to the standards is found in comparing the trend in the United Kingdom (UK) with the trends in France, Germany, and Italy reported by Furth and Kreutzer (2016). The UK has a fairly steady, steep decrease in prices from 1999 to 2015, while France, Italy, and Germany have much flatter price trends; France and Italy show small decreases followed by a small upturn, while Germany has a steady but small decrease. All these countries are in the European Union, which provides a common set of standards for all countries. If standards alone were driving price trends, then these countries should all see similar trends. Instead, even if the France, Italy, and Germany patterns are similar, the UK pattern is very different. Thus, vehicle standards alone do not seem to be driving price trends.

factors affecting prices, the Furth and Kreutzer (2016) assessment does not provide a sound basis for estimating the effects of the standards on vehicle prices.

The benefits of the standards for buyers of used vehicles will depend on two countervailing effects from the improvement in fuel economy: the increased cost of the used vehicles attributed to fuel-saving technologies, and the savings in fuel costs over time. Depreciation of new vehicle prices reduces the cost of the additional fuel economy for used vehicle buyers. On the other hand, because older vehicles are used less on average than new vehicles, the fuel savings will accrue more slowly. On net, in this current Draft TAR, reduced up-front costs exceed the reduction in fuel savings so that the payback period is shorter for used cars than for new cars; see Chapter 12 for more details.

6.5.3 Effects on Access to Credit

Even though projected fuel savings are expected to outweigh increased vehicle costs, some concerns have been raised about whether higher vehicle prices may exclude prospective consumers from the new vehicle market through effects on consumers' ability to finance vehicles. If lenders focus on the amount of the vehicle loan, the person's current debt, and the person's income when issuing loans, and do not consider the reduced operating costs associated with fuel savings, then the higher up-front costs of the new vehicles subject to the standards could reduce buyers' ability to get loans (holding down payments constant). Thus, if lenders do not take fuel savings into account in providing some loans, households that are borrowing near the limit of their abilities to borrow may either have to change what vehicles they buy (including possibly switching from new to used vehicles), or defer buying vehicles.

The financing market appears to be evolving, apparently in response to consumers buying more expensive vehicles, among other factors. One way that the loan market appears to be evolving is that the available term length of auto loans has increased. The average new car loan in mid-2015 has a record repayment period of 67 months, and 29 percent of loans were for 73-84 months.[53] While interest rates have been low by historic standards since the recession, longer loans typically reduce (or keep constant) the monthly payments that consumers make, though with more payments required and perhaps higher interest rates. Though these longer terms may ease consumers' abilities to buy more expensive vehicles than they otherwise would, they increase the chances that a vehicle owner may end up "under water" -- that is, with a vehicle worth less than the amount that the buyer still owes. In addition, the number of new vehicles being leased has increased, from 19 percent in 2010 to 27 percent in 2015.[54] These changes show an evolving financing market, though why the market is evolving is not clear: it may be that vehicles have become more expensive, or it may be that consumers are choosing more expensive vehicles, or that consumer preferences toward ownership are changing. Any link between these changes and the standards is speculative.

Another market innovation suggests that parts of the loan market take fuel savings into account in the lending decision. Some lenders currently give discounts for loans to purchase more fuel-efficient vehicles.[55] An internet search on the term "green auto loan" produced more than 50 lending institutions that provide reduced loan rates for more fuel-efficient vehicles.[56] A third of credit unions responding to a recent survey offered some type of green auto loan.[57] It seems that some auto loan makers incentivize the financing of more fuel-efficient vehicles.

Comments from the National Automobile Dealers Association (NADA) on the 2017-25 LDV standard[58] argue that an increase in the purchase price of new vehicles would increase the debt-to-income ratio (DTI) of potential buyers beyond a critical threshold, which may prevent these buyers from being eligible for a loan. As discussed in the 2012 FRM,[59] their assessment looked at the number of drivers living in households who would be eligible for a loan of $11,750, but not $14,750. It did not examine households likely to be in the market for new vehicles and was based on inaccurate assumptions about the impacts of the standards on new vehicle prices. Among other assumptions, it implies the disappearance of low-priced new vehicles, a topic discussed below.

Another assumption of the NADA analysis was that the DTI is an impassible obstacle for lending. To determine whether this DTI threshold is rigid, we used CES to identify households with over 36 percent DTI in order to gauge whether exceeding this threshold precludes households from being able to finance a vehicle purchase. We chose this threshold based on guidance from online sources stating that lenders prefer to give loans to consumers who have a DTI under 36 percent.[60] In 2013, the CES data indicated that over 66 percent of households that purchased either a new or used vehicle with a DTI of over 36 percent financed their car purchases. This suggests that it is possible to obtain a loan for a new vehicle even with a DTI over the assumed threshold. Thus, if increases in vehicle prices push some households over the 36 percent DTI, it nevertheless appears possible for them to get loans.

6.5.4 <u>Effects on Low-Priced Cars</u>

Low-priced vehicles may be considered an entry point for people into buying new vehicles instead of used ones; automakers may seek to entice people to buy new vehicles through a low price point, perhaps to build brand loyalty for future, more profitable sales.[61] In comments on the MY2017-25 LD GHG rule, concerns were raised that the standards would increase the cost of low-priced vehicles sufficiently to eliminate this segment. To examine this question, we used Ward's Automotive datasets[62] to explore low-priced new car models over time. Low-priced new models – in particular, those with manufacturer's suggested retail price (MSRP) of less than $15,000 (2013$) for the base version — continue to exist in the automobile market. As shown in Figure 6.3, the number of new car models offered with an MSRP of under $15,000 (2013$) is not large, but automakers to date have been able to preserve the number of offerings in this segment.

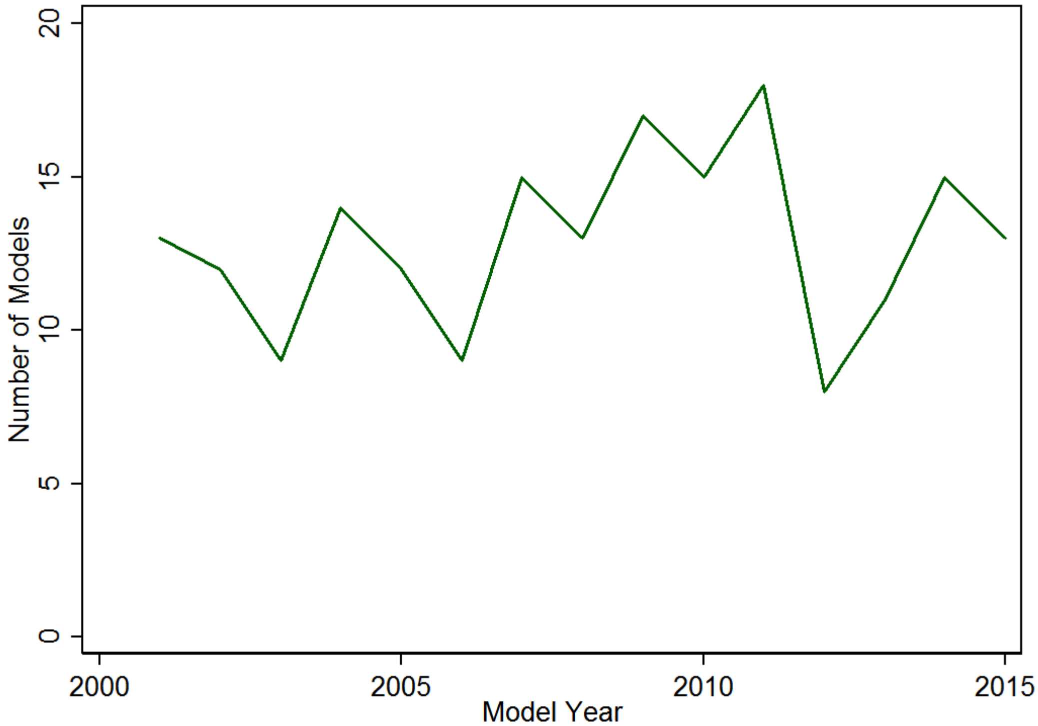

Figure 6.3 Number of <$15,000 Car Models Available, from Ward's Automotive Data

Figure 6.4 shows the MSRP for the least expensive of all new cars available (2013$). During the period 2001-2015, this price has risen, suggesting that the very least expensive new cars have become more expensive.

Figure 6.4 Minimum MSRP of All Car Models Available, from Ward's Automotive Data

Note, however, that the lowest prices were observed in the years surrounding the recession; recent higher prices may be driven, in part, by the strength of the U.S. economy. In the past, not only was the low-priced vehicle segment a way to encourage first-time new vehicle purchasers, but it also tended to include more fuel-efficient vehicles that assisted automakers in achieving CAFE standards.[63] The footprint-based standards, by encouraging improvements in GHG emissions and fuel economy across the vehicle fleet, reduce the need for low-priced vehicles to be a primary means of compliance with the standards. This change in incentives for the marketing of this segment may contribute to the increases in the prices of vehicles previously in this category. In addition, these vehicles may be gaining more content, such as improved entertainment systems and electric windows, if they develop an identity as a desirable market segment without regard to their previous purpose in enabling the sales of less efficient vehicles and compliance with CAFE standards.[64] For instance, the Nissan Versa, the lowest-priced vehicle since MY2011, added Bluetooth, audio controls on the steering wheel, and speed-sensitive volume control in MY2015. It may be that the small, fuel-efficient vehicles previously sold with low prices are evolving to fit consumer demand that prefers content to low prices.

In sum, the low-priced vehicle segment still exists. Whether it continues to exist, and in what form, may depend on the marketing plans of manufacturers: whether benefits are greater from offering basic new vehicles to first-time new-vehicle buyers, or from making small vehicles more attractive by adding more desirable features to them.

6.5.5 <u>Conclusion</u>

It is difficult to assess the effects of the LDV GHG standards on vehicle affordability, due to both challenges in defining affordability, and difficulties in separating the effects of the standards from other market changes. Because lower-income households are likely to buy used vehicles, the effects of the standards on lower-income households depend on its effects in both the new and used vehicles. In the used vehicle market, used vehicle prices do not appear to be increasing. The effects of the standards on access to sufficient financing to purchase a new vehicle may not be large: there continue to be loan discounts for fuel-efficient vehicles, and people with high debt-to-income ratios appear able to get loans. The low-priced vehicle segment still exists, though perhaps in changing form. In sum, if the standards have affected vehicle affordability, those effects do not appear to have been large enough to be obvious in our considerations of the data.

This assessment has focused on the effects of the standards on purchase affordability of vehicles – that is, whether they become more difficult to purchase because of the increase in up-front costs. The vehicles will also become less expensive to operate. The reduced operating costs from fuel savings over time are still expected to exceed the increase in up-front vehicle costs, as a further mitigation of any effects on vehicle affordability.

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Chapter 7: Employment Impacts

7.1 Introduction

The Presidential Memorandum that requested the agencies to develop the National Program sought a program that would "strengthen the [auto] industry and enhance job creation in the United States."[1] Executive Order 13563, "Improving Regulation and Regulatory Review" (January 18, 2011), states, "Our regulatory system must protect public health, welfare, safety, and our environment while promoting economic growth, innovation, competitiveness, and job creation."[2] In addition, the 2017-25 final rule lists "Impacts on employment, including the auto sector" as one of the factors to be considered in this Draft TAR.[3] Although analysis of employment impacts is not part of a cost-benefit analysis (except to the extent that labor costs contribute to costs), EPA is accordingly providing this discussion of the potential employment effects of the standards. This section begins with an overview of employment in the auto industry in recent years, and then discusses estimating the employment effects of the standards. While the 2022-2025 standards may have some effect on employment in the auto sector, this effect is likely to be small enough that it cannot be distinguished from other factors affecting auto sector employment.

7.2 Employment in the Auto Sector in Recent Years

Figure 7.1 shows employment in three segments of the U.S. auto industry from 2005 through 2014: Motor Vehicles; Motor Vehicle Parts; and Automobile Dealers. The Motor Vehicle sector itself, which includes the major manufacturers, employs the fewest people of these three sectors; Motor Vehicle Parts, suppliers to the auto industry, employs roughly two to three times as many people, and the Automobile Dealers sector employs more than the sum of the manufacturing and parts sectors.

As this chart shows, in all three segments, employment was decreasing before the recession began in 2009, and has been increasing in recent years with recovery from the recession. Auto dealers had a smaller percentage decrease than Motor Vehicles or Motor Parts, though all have recovered back to employment levels of 2007-2008 by 2014.

Figure 7.1 includes vehicle sales[A] during this period (see also Chapters 3 and 6.1); it shows a similar overall pattern of decrease followed by increase, though sales have increased more rapidly on a percentage basis than employment since 2009 (see Figure 7.2). The similarities in the patterns for sales and employment suggest, unsurprisingly, that one of the key drivers of employment in auto-related sectors is vehicle production. Indeed, the American Automotive Policy Council cites a prediction from the Center for Automotive Research that auto employment will increase by more than a third from 2011 to 2016, as production of vehicles in the U.S. increases from 5.8 million in 2009 to at least 11.5 million vehicles in 2016,[4] and total sales reached a record high of 17.5 million in 2015.[5] The differences in changes in magnitude for employment compared to sales may be due to a number of factors; one of those factors may be

[A] Vehicle production data represent production volumes delivered for sale in the U.S. market, rather than actual sales data. They include vehicles built overseas imported for sale in the U.S., and exclude vehicles built in the U.S. for export.

changes in the production process and in productivity; another factor might be the GHG/fuel economy standards.

The effects of the standards on employment are difficult to identify. As Chapter 6.1 discusses, it is difficult, if not impossible, to disentangle the effects of the standards on vehicle production (or employment) from changes in other factors, especially the state of the macroeconomy. Figure 7.2 shows the same employment sectors and production as in Figure 7.1, now indexed to show each value as a percent of its value in 2005; it also includes Gross Domestic Product (GDP) per capita.[B] This figure suggests that auto sector production and employment declined earlier and more deeply than the economy as a whole, and rebounded more vigorously.

EPA's Regulatory Impact Analysis for the MY2017-25 light-duty vehicle standards included a discussion of the effects of the standards on employment in the automotive and directly related sectors (e.g., the parts sector) (see Chapter 8.2).[6] It did not quantify the overall net effects of the standards on U.S employment. Nor did it quantify the effects of the standards on vehicle sales, and thus did not quantify the effects of employment changes in these sectors due to changes in vehicle sales. It did provide partial estimates of the effects of increased expenditures on employment in these sectors: some of those increased expenditures would be on labor. Those estimates were provided to suggest the magnitude of employment impacts, even though they were only one pathway through which employment in these sectors would be affected. It estimated increases on the order of 700 to 3,200 jobs in 2017 (p. 8-28) due to those expenditures, with the range dependent on whether the increased expenditures occurred in the light duty vehicle manufacturing sector or the parts sector. Given levels of employment in the auto sector in 2015, this increase would be less than 1 percent of employment in the auto sector, and it does not account for any effects of the standards on vehicle sales. As Figure 7.1 and Figure 7.2 suggest, employment is likely to vary much more than that proportion due to macroeconomic factors. Thus, while the MY2012-16 standards are likely to have had some effect on employment in the auto sector, this effect is likely to have been small enough that it cannot be distinguished from other factors affecting auto sector employment. In addition, the standards are not expected to have had any notable inflationary or recessionary effect.

[B] Graphing in this way facilitates comparison of percentage changes in the data series compared to 2005.

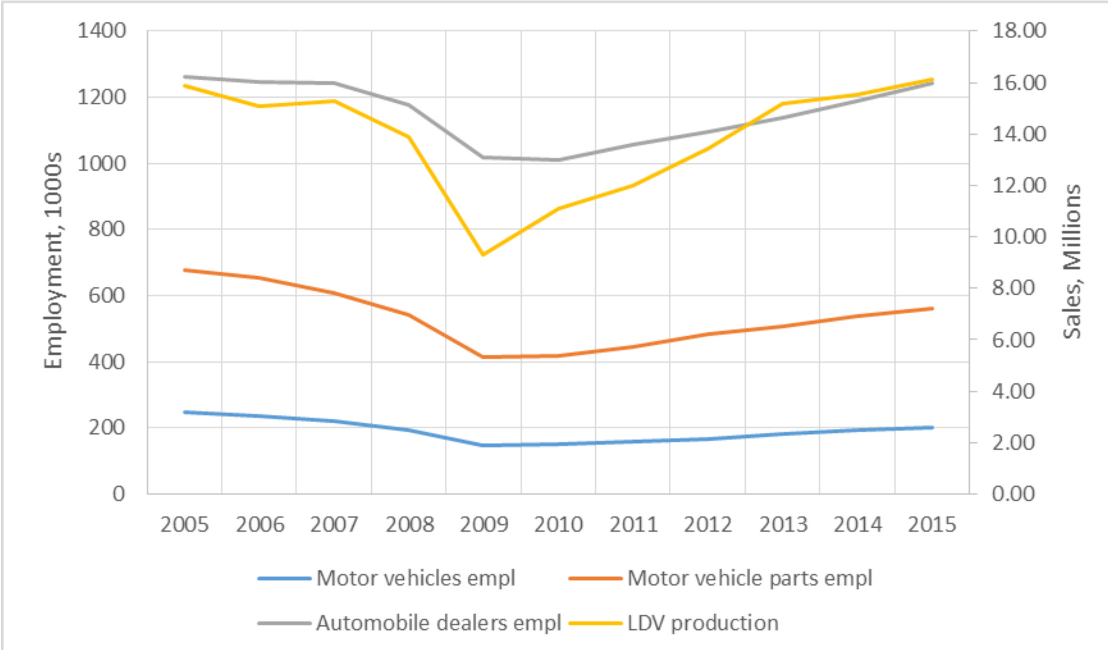

Figure 7.1 Auto Sector Employment and Production[a]

Note: [a] Employment data are from http://www.bls.gov/iag/tgs/iagauto.htm. Production data are for model years, from U.S. EPA 2015.[7] Note that 2015 production data are projected, not actual, values.

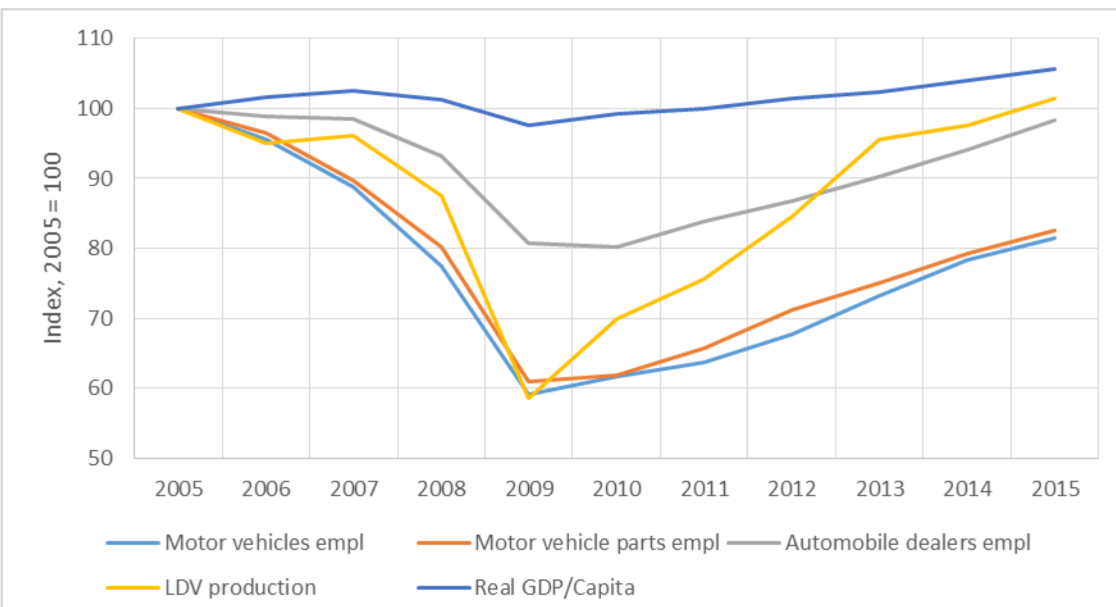

Figure 7.2 Indexed Auto Sector Employment and Production, and Gross Domestic Product (GDP) per Capita,[a] 2005 = 100 for all data series.

Note: [a] Employment data are from http://www.bls.gov/iag/tgs/iagauto.htm. Production data are for model years, from U.S. EPA 2015.[8] Note that 2015 production data are projected, not actual, values. GDP per capita data are found at https://research.stlouisfed.org/fred2/series/A939RX0Q048SBEA/downloaddata.

7.3 Current State of Knowledge of Employment in the Automotive Sector Based on the Peer-Reviewed Literature

As suggested in the previous section, the employment effects of environmental regulation are difficult to disentangle from other economic changes and business decisions that affect employment, over time and across regions and industries. In light of these difficulties, we look to economic theory to provide a constructive framework for approaching these assessments and for better understanding the inherent complexities in such assessments.

If the U.S. economy is at full employment, even a large-scale environmental regulation is unlikely to have a noticeable impact on aggregate net employment.[C] Instead, labor would primarily be reallocated from one productive use to another, and net national employment effects from environmental regulation would be small and transitory (e.g., as workers move from one job to another).[9]

Affected sectors may experience transitory effects as workers change jobs. Some workers may retrain or relocate in anticipation of new requirements or require time to search for new jobs, while shortages in some sectors or regions could bid up wages to attract workers. These adjustment costs can lead to local labor disruptions. Although the net change in the national workforce is expected to be small, localized reductions in employment may adversely impact individuals and communities just as localized increases may have positive impacts.

If the economy is operating at less than full employment, economic theory does not clearly indicate the direction or magnitude of the net impact of environmental regulation on employment; it could cause either a short-run net increase or short-run net decrease.[10] An important research question is how to accommodate unemployment as a structural feature in economic models. This may be important in assessing large-scale regulatory impacts on employment.[11]

Environmental regulation may also affect labor supply. In particular, pollution and other environmental risks may impact labor productivity or employees' ability to work.[12] While the theoretical framework for analyzing labor supply effects is analogous to that for labor demand, it is more difficult to study empirically. There is a small emerging literature described in the next section that uses detailed labor and environmental data to assess these impacts.

7.3.1 Regulatory Effects at the Firm Level

Neoclassical microeconomic theory provides insights into how profit-maximizing firms adjust their use of productive inputs in response to changes in their economic conditions.[13] Berman and Bui (2001, pp. 274-75) model two components that drive changes in firm-level labor demand: output effects and substitution effects.[14],[D] Regulation can affect the profit-maximizing quantity of output by changing the marginal cost of production. If regulation causes marginal cost to

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[C] Full employment is a conceptual target for the economy where everyone who wants to work and is available to do so at prevailing wages is actively employed. The unemployment rate at full employment is not zero.

[D] Berman and Bui also discuss a third component, the impact of regulation on factor prices, but conclude that this effect is unlikely to be important for large competitive factor markets, such as labor and capital. Morgenstern, Pizer and Shih (2002) use a very similar model, but they break the employment effect into three parts: 1) a demand effect; 2) a cost effect; and 3) a factor-shift effect.

increase, it will place upward pressure on output prices, leading to a decrease in the quantity demanded, and resulting in a decrease in production. The output effect describes how, holding labor intensity constant, a decrease in production causes a decrease in labor demand. As noted by Berman and Bui, although many assume that regulation increases marginal cost, it need not be the case. A regulation could induce a firm to upgrade to less polluting and more efficient equipment that lowers marginal production costs, or it may induce use of technologies that may prove popular with buyers or provide positive network externalities (see Chapter 6.3 for discussion of this effect). In such a case, output could increase.

The substitution effect describes how, holding output constant, regulation affects labor-intensity of production. Although increased environmental regulation may increase use of pollution control equipment and energy to operate that equipment, the impact on labor demand is ambiguous. For example, equipment inspection requirements, specialized waste handling, or pollution technologies that alter the production process may affect the number of workers necessary to produce a unit of output. Berman and Bui (2001) model the substitution effect as the effect of regulation on pollution control equipment and expenditures required by the regulation and the corresponding change in labor-intensity of production.

In summary, as output and substitution effects may be positive or negative, theory alone cannot predict the direction of the net effect of regulation on labor demand at the level of the regulated firm. Operating within the bounds of standard economic theory, however, empirical estimation of net employment effects on regulated firms is possible when data and methods of sufficient detail and quality are available. The literature, however, illustrates difficulties with empirical estimation. For example, studies sometimes rely on confidential plant-level employment data from the U.S. Census Bureau, possibly combined with pollution abatement expenditure data that are too dated to be reliably informative. In addition, the most commonly used empirical methods do not permit estimation of net effects.

7.3.2 Regulatory Effects at the Industry Level

The conceptual framework described thus far focused on regulatory effects on plant-level decisions within a regulated industry. Employment impacts at an individual plant do not necessarily represent impacts for the sector as a whole. The approach must be modified when applied at the industry level.

At the industry level, labor demand is more responsive if: (1) the price elasticity of demand for the product is high, (2) other factors of production can be easily substituted for labor, (3) the supply of other factors is highly elastic, or (4) labor costs are a large share of total production costs.[15] For example, if all firms in an industry are faced with the same regulatory compliance costs and product demand is inelastic, then industry output may not change much, and output of individual firms may change slightly.[16] In this case, the output effect may be small, while the substitution effect depends on input substitutability. Suppose, for example, that new equipment for GHG emissions reductions requires labor to install and operate. In this case, the substitution effect may be positive, and with a small output effect, the total effect may be positive. As with potential effects for an individual firm, theory cannot determine the sign or magnitude of industry-level regulatory effects on labor demand. Determining these signs and magnitudes requires additional sector-specific empirical study. For environmental rules, much of the data needed for these empirical studies is not publicly available.

In addition to changes to labor demand in the regulated industry, net employment impacts encompass changes in other related sectors. For example, the standards are expected to increase demand for fuel-saving technologies. This increased demand may increase revenue and employment in the firms supporting this technology. At the same time, the regulated industry is purchasing the equipment, and these costs may impact labor demand at regulated firms. Therefore, it is important to consider the net effect of compliance actions on employment across multiple sectors or industries.

Affected sectors may experience transitory effects as workers change jobs. Some workers may retrain or relocate in anticipation of new requirements or require time to search for new jobs, while shortages in some sectors or regions could bid up wages to attract workers. These adjustment costs can lead to local labor disruptions. Although the net change in the national workforce is expected to be small, localized reductions in employment may adversely impact individuals and communities just as localized increases may have positive impacts.

To summarize, economic theory provides a framework for analyzing the impacts of environmental regulation on employment. The net employment effect incorporates expected employment changes (both positive and negative) in the regulated sector and elsewhere. Labor demand impacts for regulated firms, and also for the regulated industry, can be decomposed into output and substitution effects which may be either negative or positive. Estimation of net employment effects for regulated sectors is possible when data of sufficient detail and quality are available. Finally, economic theory suggests that labor supply effects are also possible. In the next section, we discuss the empirical literature.

7.3.3 Peer-Reviewed Literature

In the labor economics literature there is an extensive body of peer-reviewed empirical work analyzing various aspects of labor demand, relying on the above theoretical framework.[17] This work focuses primarily on the effects of employment policies, e.g. labor taxes, minimum wage, etc.[18] In contrast, the peer-reviewed empirical literature specifically estimating employment effects of environmental regulations is very limited. Several empirical studies, including Berman and Bui (2001),[19] Morgenstern, Pizer and Shih (2002),[20] Gray et al (2014),[21] and Ferris, Shadbegian and Wolverton (2014)[22] suggest that net employment impacts may be zero or slightly positive but small even in the regulated sector. Other research suggests that more highly regulated counties may generate fewer jobs than less regulated ones.[23] However, since these latter studies compare more regulated to less regulated counties, they overstate the net national impact of regulation to the extent that regulation causes plants to locate in one area of the country rather than another. List et al. (2003)[24] find some evidence that this type of geographic relocation may be occurring. Overall, the peer-reviewed literature does not contain evidence that environmental regulation has a large impact on net employment (either negative or positive) in the long run across the whole economy.

Analytic challenges make it very difficult to accurately produce net employment estimates for the whole economy that would appropriately capture the way in which costs, compliance spending, and environmental benefits propagate through the macro-economy. Quantitative estimates are further complicated by the fact that macroeconomic models often have very little sectoral detail and usually assume that the economy is at full employment. EPA is currently in the process of seeking input from an independent expert panel on modeling economy-wide impacts, including employment effects. For more information, see:

http://yosemite.epa.gov/sab/sabproduct.nsf/0/07E67CF77B54734285257BB0004F87ED?OpenDocument.

7.4 Employment Impacts in the Motor Vehicle and Parts Manufacturing Sector

This chapter describes estimated changes in employment in the motor vehicle, trailer, and parts (hence, motor vehicle) manufacturing sectors associated with the MY2022-25 standards. We focus on the motor vehicle manufacturing sector because it is directly regulated by the GHG/fuel economy standards, and because it is likely to bear most of any employment changes due to the standards. We include discussion of effects on the parts manufacturing sector, because the motor vehicle manufacturing sector can either produce parts internally or buy them from an external supplier, and we do not have estimates of the likely breakdown of effort between the two sectors.

We follow the theoretical structure of Berman and Bui [25] of the impacts of regulation in employment in the regulated sectors. In Berman and Bui's (2001, p. 274-75) theoretical model, as described above, the change in a firm's labor demand arising from a change in regulation is decomposed into two main components: output and substitution effects. As the output and substitution effects may be both positive, both negative, or some combination, standard neoclassical theory alone does not point to a definitive net effect of regulation on labor demand at regulated firms.

Following the Berman and Bui framework for the impacts of regulation on employment in the regulated sector, we consider two effects for the motor vehicle sector: the output effect and the substitution effect.

7.4.1 <u>The Output Effect</u>

The output effect measures the effect due to new vehicle sales only. If vehicle sales increase, then more people will be required to assemble vehicles and their components. If vehicle sales decrease, employment associated with these activities will decrease. The effects of the MY2022-25 standards on vehicle sales thus depend on the perceived desirability of the new vehicles relative to other transportation options. On one hand, these standards will increase vehicle costs; by itself, this effect would reduce vehicle sales. In addition, while adverse effects on other vehicle characteristics would also decrease sales, there is currently no evidence of systematic adverse effects of fuel-saving technologies (see Chapter 6.3). On the other hand, these standards will reduce the fuel costs of operating the vehicles; by itself, this effect would increase vehicle sales, especially if potential buyers have an expectation of increasing fuel prices. EPA has not made an estimate of the effects of the standards on vehicles sales (see Chapter 6.1).

7.4.2 <u>The Substitution Effect</u>

The substitution effect includes the impacts due to the changes in technologies needed for vehicles to meet the standards, separate from the effect due to vehicle sales (that is, as though holding output constant). This effect includes both changes in employment due to incorporation of abatement technologies and overall changes in the labor intensity of manufacturing. We here capture these effects using estimates of the historic share of labor as a part of the cost of production, which we then extrapolate to provide future estimates of the share of labor as a cost of production. When these shares are multiplied by the change in the cost of production, they approximate the change in labor associated with the cost increases associated with the standards. We present estimates for this effect to provide a sense of the order of magnitude of expected impacts on employment, which we expect to be small in the automotive sector, and to repeat that regulations may have positive as well as negative effects on employment.

One way to estimate this effect, given the cost estimates for complying with the rule, is to use the ratio of workers to each $1 million of expenditures in that sector. The use of these ratios has both advantages and limitations. It is often possible to estimate these ratios for quite specific sectors of the economy: for instance, it is possible to estimate the average number of workers in the light-duty vehicle manufacturing sector per $1 million spent in the sector, rather than use the ratio from another, more aggregated sector, such as motor vehicle manufacturing. As a result, it is not necessary to extrapolate employment ratios from possibly unrelated sectors. On the other hand, these estimates are averages for the sectors, covering all the activities in those sectors; they may not be representative of the labor required when expenditures are required on specific activities, or when manufacturing processes change sufficiently that labor intensity changes. For instance, the ratio for the motor vehicle manufacturing sector represents the ratio for all vehicle manufacturing, not just for emissions reductions associated with compliance activities. In addition, these estimates do not include changes in sectors that supply these sectors, such as steel or electronics producers. They thus may best be viewed as the effects on employment in the auto sector due to the changes in expenditures in that sector, rather than as an assessment of all employment changes due to these changes in expenditures. In addition, this approach estimates the effects of increased expenditures while holding constant the labor intensity of manufacturing; it does not take into account changes in labor intensity due to changes in the nature of production. This latter effect could either increase or decrease the employment impacts estimated here.[E]

Some of the costs of this rule will be spent directly in the motor vehicle manufacturing sector, but it is also likely that some of the costs will be spent in the motor vehicle parts manufacturing sector. The analysis here draws on estimates of workers per $1 million of expenditures for both of these sectors.

There are several public sources for estimates of employment per $1 million expenditures. The U.S. Bureau of Labor Statistics (BLS) provides its Employment Requirements Matrix (ERM),[26] which provides direct estimates of the employment per $1 million in sales of goods in 202 sectors. The values considered here are for Motor Vehicle Manufacturing (NAICS 3361) and Motor Vehicle Parts Manufacturing (NAICS 3363) for 2014. These values are updated from the 2012 FRM, which used the 2010 ERM data.

The U.S. Census Bureau provides both the Annual Survey of Manufacturers[27] (ASM) and the Economic Census (EC). The ASM is a subset of the Economic Census, based on a sample of establishments; though the Census itself is more complete, it is conducted only every 5 years, while the ASM is annual. Both include more sectoral detail than the BLS ERM: for instance, while the ERM includes the Motor Vehicle Manufacturing sector, the ASM and EC have detail

[E] As noted above, Morgenstern et al. (2002) separate the effect of holding output constant into two effects: the cost effect, which holds labor intensity constant, and the factor shift effect, which estimates those changes in labor intensity.

at the 6-digit NAICS code level (e.g., light truck and utility vehicle manufacturing). While the ERM provides direct estimates of employees/$1 million in expenditures, the ASM and EC separately provide number of employees and value of shipments; the direct employment estimates here are the ratio of those values. The values reported are for Motor Vehicle Manufacturing (NAICS 3361), Automobile and Light Duty Motor Vehicle Manufacturing (NAICS 33611), and Motor Vehicle Parts Manufacturing (NAICS 3363), for 2014 for the ASM and 2012 for the EC. These values are updated from the 2012FRM, which used 2010 values for the ASM, and 2007 values from the EC.

The values used here are adjusted to remove the employment effects of imports through use of a ratio of domestic production to domestic sales of 0.663.[F]

Table 7.1 provides the values, either given (BLS) or calculated (ASM and EC) for employment per $1 million of expenditures in 2014 (2012 for EC), all adjusted to 2013 dollars using the Bureau of Economic Analysis's Implicit GDP Price Deflators.[G] Although the ASM appears to provide slightly higher values than the ERM, the different data sources provide similar patterns for the estimates for the sectors. These updated values differ slightly (under 10 percent) from the values used in the 2012 FRM in 2013$.

[F] To estimate the proportion of domestic production affected by the change in sales, we use data from Ward's Automotive Group for total car and truck production in the U.S. compared to total car and truck sales in the U.S. Over the period 2006-2015, the proportion averages 66.3 percent. From 2012-2015, the proportion average is slightly higher, at 69.2 percent.

[G] At the time of access, the EC data was only available by 2-, 3-, or 6-digit NAICS industry code. To construct the 4- and 5-digit numbers, we separately summed total employees and total expenditure for each 6-digit subcategory.

Table 7.1 Employment per $1 Million Expenditures (2013$) in the Motor Vehicle Manufacturing Sector[a]

Source	Sector	Ratio of workers per $1 million expenditures	Ratio of workers per $1 million expenditures, adjusted for domestic vs. foreign production
BLS ERM	Motor vehicle mfg (3361)	0.39	0.26
BLS ERM	Motor vehicle parts mfg (3363)	1.71	1.13
ASM	Motor vehicle mfg (3361)	0.58	0.39
ASM	Automobile and light duty motor vehicle mfg (33611)	0.54	0.36
ASM	Automobile mfg (336111)	0.63	0.42
ASM	Motor vehicle [arts mfg (3363)	2.08	1.38
EC	Motor vehicle mfg (3361)	0.59	0.39
EC	Automobile and light duty motor vehicle mfg (33611)	0.55	0.36
EC	Automobile mfg (336111)	0.63	0.42
EC	Motor vehicle parts mfg (3363)	2.13	1.41

Note:
[a] BLS ERM refers to the U.S. Bureau of Labor Statistics' Employment Requirement Matrix, 2014 values. ASM refers to the U.S. Census Bureau's Annual Survey of Manufactures, 2014 values. EC refers to the U.S. Census Bureau's Economic Census, 2012 values.

Over time, the amount of labor needed in the motor vehicle industry has changed: automation and improved methods have led to significant productivity increases. The BLS ERM, for instance, provided estimates that, in 1997, 1.09 workers in the Motor Vehicle Manufacturing sector were needed per $1 million, but only 0.39 workers by 2014 (in 2013$).28 Because the ERM is available annually for 1997-2014, we used these data to estimate productivity improvements over time. We regressed logged ERM values on a year trend for the Motor Vehicle Manufacturing and Motor Vehicle Parts Manufacturing sectors. We used this approach because the coefficient describing the relationship between time and productivity is a direct measure of the average percent change in productivity per year. The results suggest a 6.6 percent per year productivity improvement in the Motor Vehicle Manufacturing Sector, and a 4.9 percent per year improvement in the Motor Vehicle Parts Manufacturing Sector.

We then used the regression results to project the number of workers per $1 million through 2025. We calculated separate sets of projections (adjusted to 2013$) for both the BLS ERM data as well as the EC and ASM for all sectors discussed above. The BLS ERM projections were calculated directly from the fitted regression equations since the regressions themselves used ERM data. For the ASM and EC projections, we used the ERM's ratio of the projected value in each future year to the projected value in 2014 for the ASM and 2012 for the EC (the base years in our data) to determine how many workers will be needed per $1 million of 2013$. In other words, we apply the projected productivity growth estimated using the ERM data to the ASM and EC numbers.

Finally, to simplify the presentation and give a range of estimates, we compared the projected employment among the sectors for the ERM, EC, and ASM, and we provide here only the maximum and minimum effects in each year across all sectors. We provide the range rather than a point estimate because of the inherent difficulties in estimating employment impacts; the range gives an estimate of the expected magnitude. The details of the calculations may be found in the docket. The Motor Vehicle Parts Manufacturing Sector value from the ASM provides the maximum employment estimates per $1 million; the Motor Vehicle Manufacturing Sector value from the ERM provides the minimum estimates.

Chapter 12 of this Draft TAR discusses the vehicle cost estimates developed for this rule. The final step in estimating employment impacts is to multiply costs (in $ millions) by workers per $1 million in costs, to estimate employment impacts in the regulated and parts manufacturing sectors. Table 7.2 presents the projected reference case costs and the corresponding minimum and maximum estimated employment impacts. For each year, additional ranges in parentheses are included that reflect estimates from projections using high and low fuel price scenarios.[H] Increased costs of vehicles and parts, by itself, and holding labor intensity constant, would be expected to increase employment between 2021 and 2025 by several hundred to 12,000 jobs each year. These values are lower than those estimated in the 2012 FRM, primarily because the cost estimates are lower, for reasons explained in Chapter 12.

While we estimate employment impacts, measured in job-years, beginning with program implementation, some of these employment gains may occur earlier as vehicle manufacturers and parts suppliers hire staff in anticipation of compliance with the standards. A job-year is a way to calculate the amount of work needed to complete a specific task. For example, a job-year is one year of full-time work for one person.

Table 7.2 Partial Employment Impact due to Substitution Effect of Increased Costs of Vehicles and Parts, in Job-years[a]

Year	Costs (Millions of 2013$)	Minimum Employment Due to Substitution Effect (ERM estimates, expenditures in the Motor Vehicle Mfg Sector)	Maximum Employment Due to Substitution Effect (ASM estimates, expenditures in the Parts Sector)
2021	$3,045 ($2,872 - 2,876)	300 (300 - 300)	3,000 (2,800 - 2,800)
2022	$5,877 ($5,766 - $5,769)	600 (600 - 600)	5,500 (5,400 - 5,400)
2023	$8,736 ($8,620 - $8,709)	800 (800 - 800)	7,800 (7,700 - 7,700)
2024	$11,649 ($11,483 - $11,727)	1,000 (1,000 - 1,100)	9,800 (9,700 - 9,900)
2025	$14,678 ($14,433 - $14,871)	1,200 (1,200 - 1,300)	11,800 (11,600 - 12,000)

Note:
[a] Numbers in parentheses reflect the estimates derived from scenarios with high and low fuel prices.

[H] As discussed in Chapter 12, the costs for the reference fuel price scenario do not necessarily fall between those of the high and low fuel price scenarios, because fuel prices are not the only difference in the scenarios; they differ in assumptions about the vehicle fleet as well.

7.4.3 Summary of Employment Effects in the Motor Vehicle Sector

The overall effect of the rule on motor vehicle sector employment depends on the relative magnitude of the output effect and the substitution effect. Because we do not have quantitative estimates of the output effect, and only a partial estimate of the substitution effect, we cannot reach a quantitative estimate of the overall employment effects of the standards on auto sector employment or even whether the total effect will be positive or negative.

The standards are not expected to provide incentives for manufacturers to shift employment between domestic and foreign production. This is because the standards will apply to vehicles sold in the U.S. regardless of where they are produced. Ward's automotive data suggest that the current share of domestic production for cars and trucks is very similar to the share in 2006: 66 percent in 2006, and 68 percent in 2015. If production overseas already involved increased expertise in satisfying the requirements of the standards, there may be some initial incentive for foreign production, but meeting the standards may lead to increased opportunities for domestic production to sell in other markets. To the extent that the requirements of these standards might lead to installation and use of technologies that other countries may seek now or in the future, developing this capacity for domestic production now may provide some additional ability to serve those markets.

7.4.4 Motor Vehicle Parts Manufacturing Sector

Some vehicle parts are made in-house and would be included directly in the regulated sector. Others are made by independent suppliers and are not directly regulated, but they will be affected by the rules as well. The parts manufacturing sector will be involved primarily in providing "add-on" parts, or components for replacement parts built internally. If demand for these parts increases due to the increased use of these parts, employment effects in this sector are expected to be positive. If the output effect in the regulated sectors is significantly negative enough, it is possible that demand for other parts may decrease. As noted, the agencies do not predict a magnitude or direction for the output effect.

7.5 Employment Impacts in Other Affected Sectors

7.5.1 Effects on Employment for Auto Dealers

The effects of the standards on employment for auto dealers depend principally on the effects of the standards on light duty vehicle sales: increases in sales are likely to contribute to employment at dealerships, while reductions in sales are likely to have the opposite effect. As discussed in Chapter 6, it is difficult to separate the effects of the standards on vehicle sales from effects due to macroeconomic conditions; however, the standards have not prevented sales from returning to (and exceeding) pre-recession levels. In addition, auto dealers may be affected by any changes in maintenance and service costs. Increases in those costs are likely to increase labor demand in dealerships, and reductions are likely to decrease labor demand.

Concerns have been raised about consumer acceptance of technologies used to meet the standards, though these effects do not seem significant to date (see Chapter 6). Auto dealers may play a major role in explaining the merits and disadvantages of these new technologies to vehicle buyers. This additional role may also affect employment levels at dealers.

7.5.2 Effects on Employment for Fuel Suppliers

In addition to the effects on the auto manufacturing and parts sectors, the standards result in changes in fuel use that lower GHG emissions.

Expected petroleum fuel consumption reductions can be found in Chapter 12. While this reduced consumption represents fuel savings for purchasers of fuel, it represents a loss in value of output for the petroleum refinery industry, fuel distributors, and gasoline stations. The loss of expenditures to petroleum fuel suppliers throughout the petroleum fuel supply chain, from the petroleum refiners to the gasoline stations, is likely to result in reduced employment in these sectors. Because the fuel production sector is material-intensive, the employment effect is not expected to be large.[I] Although gasoline stations will sell less fuel, the fact that many provide other goods, such as food and car washes, moderates losses in this sector. In addition, it may be difficult to distinguish these effects from other trends, such as increases in petroleum sector labor productivity that may also lower labor demand.

Auto manufacturers may choose to meet the standards through alternatively-fueled vehicles, such as those that use electricity, hydrogen, or compressed natural gas (CNG), though the agencies do not project large use of these vehicles. Such fuels may require additional infrastructure, such as electricity charging locations or hydrogen fueling stations. See Chapter 9. Providing this infrastructure will require some increased employment. In addition, the production of these fuels is likely to require some additional labor. We have insufficient information at this time to predict whether the increases in labor associated with increased infrastructure provision and generation for electricity and hydrogen production will be greater or less than the employment reductions associated with reduced demand for petroleum fuels.

7.5.3 Effects on Employment due to Impacts on Consumer Expenditures

As a result of these standards, consumers will likely pay higher up-front costs for the vehicles, but they are expected to recover those costs in a fairly short payback period (see Chapters 6 and 12). As a result, consumers are expected to have additional money to spend on other goods and services, though the timing for access to that additional money depends on the payback period and whether the consumer borrows money to buy the vehicle. These increased expenditures could support employment in those sectors where consumers spend their savings.

These increased expenditures will occur in the years in which the fuel savings exceed expenditures on the up-front costs. If, on the one hand, the economy is at full employment during that time, any change in consumer expenditures would primarily represent a shift in employment among sectors. If, on the other hand, the economy has substantial unemployment, these expenditures would contribute to employment through increased consumer demand.

7.6 Summary

The primary employment effects of these standards are expected to be found in several key sectors: auto manufacturers, auto parts manufacturing, auto dealers, fuel production and supply, and consumers. In an economy with full employment, the primary employment effect of a

[I] In the 2014 BLS ERM cited above, the Petroleum and Coal Products Manufacturing sector has a ratio of workers per $1 million of 0.215, lower than all but two of the 181 sectors with non-zero employment per $1 million.

rulemaking is likely to be to shift employment from one sector to another, rather than to increase or decrease employment. For that reason, we focus our partial quantitative analysis on employment in the regulated sector, to examine the impacts on that sector directly. We discuss the likely direction of other impacts in the regulated sector as well as in other directly related sectors, but we do not quantify those impacts, because they are more difficult to quantify with reasonable accuracy, particularly so far into the future.

For the regulated sector, the partial employment impact due to the substitution effect of increased costs of autos is expected to be positive. The total effect of the standards on motor vehicle employment depends in addition on changes in vehicle sales, which are not quantified; thus, we do not estimate the total effects of the standards in the regulated industry.

Effects in other sectors that are affected by vehicle sales are also ambiguous. Reduced petroleum fuel production implies less employment in the petroleum sectors, although there could be increases in employment related to providing infrastructure for alternative fuels if manufacturers choose to comply with the standard through increased production of vehicles that use those fuels. Finally, consumer spending is expected to affect employment through changes in expenditures in general retail sectors; net fuel savings by consumers are expected to increase demand (and therefore employment) in other sectors. Thus, while the standards are likely to have some effect on employment, this effect is likely to be small enough that it cannot be distinguished from other factors affecting employment, especially macroeconomic conditions. As has been noted, under conditions of full employment, any changes in employment levels in the regulated sector due to this program are mostly expected to be offset by changes in employment in other sectors.

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Chapter 8: Assessment of Vehicle Safety Effects

8.1 Safety Considerations in Establishing CAFE/GHG Standards

8.1.1 Why Do the Agencies Consider Safety?

The primary goals of CAFE and GHG standards are to reduce fuel consumption and GHG emissions from the on-road light-duty vehicle fleet, but in addition to these intended effects, the agencies also consider the potential of the standards to affect vehicle safety.[A] As a safety agency, NHTSA has long considered the potential for adverse safety consequences when establishing CAFE standards,[B] and under the CAA, EPA considers factors related to public health and human welfare, including safety, in regulating emissions of air pollutants from mobile sources.[C] Safety trade-offs associated with fuel economy increases have occurred in the past, particularly before NHTSA CAFE standards were attribute- based,[1] and the agencies must be mindful of the possibility of future ones. These past safety trade-offs may have occurred because manufacturers chose at the time, partly in response to CAFE standards, to build smaller and lighter vehicles, rather than adding more expensive fuel-saving technologies while maintaining vehicle size and safety, and the smaller and lighter vehicles did not fare as well in crashes as larger and heavier vehicles. Historically, as shown in FARS data analyzed by NHTSA (e.g., Kahane, 2012[2]), the safest cars generally have been heavy and large, while the cars with the highest fatal-crash rates have been light and small.

The question, then, is whether past is necessarily prologue when it comes to potential changes in vehicle size (both footprint and “overhang”) and mass in response to the more stringent future CAFE and GHG standards. Manufacturers have stated that they will reduce vehicle mass as one of the cost-effective means of increasing fuel economy and reducing CO2 emissions in order to meet the standards, and the agencies have incorporated this expectation into our modeling analysis supporting the standards. Because the agencies discern a historical relationship between vehicle mass, size, and safety, one potential means of assessing the impact of future standards on vehicle safety is to assume that these relationships will continue in the future. In formulating the MY2017-2025 final rule, the agencies were encouraged by comments to the NPRM from the Alliance of Automotive Manufacturers reflecting a commitment to safety stating that, while improving the fuel efficiency of the vehicles, the vehicle manufacturers are “mindful that such improvements must be implemented in a manner that does not compromise the rate of safety improvement that has been achieved to date.” The question of whether vehicle design can mitigate the adverse effects of mass reduction is discussed below.

[A] In this document, “vehicle safety” is defined as societal fatality rates per vehicle miles traveled (VMT), which include fatalities to occupants of all the vehicles involved in the collisions, plus any pedestrians.

[B] This practice is recognized approvingly in case law. As the United States Court of Appeals for the D.C. Circuit stated in upholding NHTSA’s exercise of judgment in setting the 1987-1989 passenger car standards, “NHTSA has always examined the safety consequences of the CAFE standards in its overall consideration of relevant factors since its earliest rulemaking under the CAFE program.” *Competitive Enterprise Institute v. NHTSA (“CEI I”)*, 901 F.2d 107, 120 at n. 11 (D.C. Cir. 1990).

[C] As noted in Section I.D above, EPA has considered the safety of vehicular pollution control technologies from the inception of its Title II regulatory programs. See also NRDC v. EPA, 655 F. 2d 318, 332 n. 31 (D.C. Cir. 1981). (EPA may consider safety in developing standards under section 202 (a) and did so appropriately in the given instance).

Due to the structure of the standards put in place by the MY2017-2025 rulemaking, manufacturers are less likely than they were in the past to reduce vehicle footprint in order to reduce mass for increased fuel economy. This factor is important because, as the agencies have noted, historic studies have shown a positive relationship between overall vehicle size and safety, although the relationship should continuously be re-tested as materials change in the future. This will be described in greater detail below.

The primary mechanism in the MY2017-2025 rulemaking for mitigating the potential negative effects on safety was the application of footprint-based standards, which create a disincentive for manufacturers to produce smaller-footprint vehicles (Section II.G.1, MY 2017-2025 Final Rule). This is because, as footprint decreases, the corresponding fuel economy/GHG emission target becomes more stringent. We also believe that the shape of the footprint curves themselves is approximately "footprint-neutral," that is, that it should neither encourage manufacturers to increase the footprint of their fleets, nor to decrease it. Upsizing footprint is also discouraged through the curve "cut-off" at larger footprints.[D] However, the footprint-based standards do not discourage downsizing the portions of a vehicle in front of the front axle and to the rear of the rear axle, or of other areas of the vehicle outside the wheels. The crush space provided by those portions of a vehicle can make important contributions to managing crash energy. Additionally, simply because footprint-based standards minimize the incentive to downsize vehicles does not mean that some manufacturers will not downsize if doing so makes it easier for them to meet the overall CAFE/GHG standard in a cost-efficient manner, as for example, if the smaller vehicles are so much lighter (or de-contented) that they exceed their targets by much greater amounts. On balance, however, we believe the target curves and the incentives they provide generally will not encourage down-sizing (or up-sizing) in terms of footprint reductions (or increases).[E]

Given that we expect manufacturers to reduce vehicle mass in response to the standards, and do not expect manufacturers to reduce vehicle footprint in response to the standards, the agencies must attempt to predict the safety effects, if any, of the final rule based on the best information currently available. This section explained why the agencies consider safety; the following section discusses how the agencies consider safety.

[D] The agencies recognize that at the other end of the curve, manufacturers who make small cars and trucks below 41 square feet (the small footprint cut-off point) have some incentive to downsize their vehicles to make it easier to meet the constant target. That cut-off may also create some incentive for manufacturers who do not currently offer models that size to do so in the future. However, at the same time, the agencies believe that there is a limit to the market for cars and trucks smaller than 41 square feet: most consumers likely have some minimum expectation about interior volume, for example, among other things. Additionally, vehicles in this segment are the lowest price point for the light-duty automotive market, with several models in the $10,000-$15,000 range. Manufacturers who find themselves incentivized by the cut-off will also find themselves adding technology to the lowest price segment vehicles, which could make it challenging to retain the price advantage. Because of these two reasons, the agencies believe that the incentive to increase the sales of vehicles smaller than 41 square feet due to the final rule, if any, is small. *See* Chapter 1 of the Joint TSD for more information on the agencies' choice of "cut-off" points for the footprint-based target curves.

[E] This statement makes no prediction of how consumer choices of vehicle size will change in the future, independent of the standards.

8.1.2 How Do the Agencies Consider Safety?

Assessing the effects of vehicle mass reduction and size on societal safety is a complex issue. One part of estimating potential safety effects involves trying to understand better the relationship between mass and vehicle design. The extent of mass reduction that manufacturers may be considering to meet more stringent fuel economy and GHG standards may raise different safety concerns from what the industry has previously faced. Heavier vehicles, especially truck-based LTVs and lighter vehicles, perform differently in collisions with each other than in collisions with another car or LTV. When two vehicles of unequal mass collide, the change in velocity (delta V) is higher in the lighter vehicle, similar to the mass ratio proportion. As a result of the higher change in velocity in lighter vehicles, the fatality risk may also increase. Removing more mass from the heavier vehicle than in the lighter vehicle by amounts that bring the mass ratio closer to 1.0 reduces the delta V in the lighter vehicle and thereby reducing fatality risk and possibly resulting in a net societal benefit.

Another complexity is that if a vehicle is made lighter, adjustments must be made to the vehicle's structure such that it will be able to manage the energy in a crash while limiting intrusion into the occupant compartment. To maintain an acceptable occupant compartment deceleration, the effective front-end stiffness has to be managed such that the crash pulse does not increase as lighter yet stiffer materials are utilized. If the energy is not well managed, the occupants may have to "ride down" a more severe crash pulse, putting more burdens on the restraint systems to protect the occupants[3]. There may be technological and physical limitations to how much the restraint system may mitigate these effects.

The agencies must attempt to estimate now, based on the best information currently available to us for analyzing these CAFE and GHG standards, how the assumed levels of mass reduction without additional changes (i.e. footprint, performance, functionality) might affect the safety of vehicles, and how lighter vehicles might affect the safety of drivers and passengers in the entire on-road fleet. The agencies seek to ensure that the standards are designed to encourage manufacturers to pursue a path toward compliance that is both cost-effective and safe.

To estimate the possible safety effects of the MY2022-2025 standards, then, the agencies have undertaken research that approaches this question from several angles. First, we are using a statistical approach to study the effect of vehicle mass reduction on safety historically, as discussed in greater detail in section 8.2 below. Statistical analysis is performed using the most recent historical crash data available (calendar year 2005-2011 data for MY2003-2010 vehicles), and is considered as the agencies' best estimate of potential mass-safety effects. The agencies recognize that negative safety effects estimated based on the historical relationships could potentially be tempered with safety technology advances in the future, and may not represent the current or future fleet. Second, we are using an engineering approach to investigate what amount of mass reduction is affordable and feasible while maintaining vehicle safety and functionality such as durability, drivability, NVH, and acceleration performance. Third, we are also studying the new challenges these lighter vehicles might bring to vehicle safety and potential countermeasures available to manage those challenges effectively. Comments received to the proposed 2012 Final Rule are summarized in the 2012 Final Rule preamble.

The agencies have looked closely at these issues, and we believe that our approach of using both statistical analyses of historical data to assess societal safety effects, and design studies to assess the ability of individual designs to comply with the FMVSS and perform well on NCAP and IIHS tests responds to these concerns.

A large body of traffic safety literature exists that examines the relationship between vehicle mass and traffic fatality rates. Most of the literature estimates aggregate State-level time series correlations (Khazzoom, 1994[4]; Noland, 2004[5]; Ahmad and Greene, 2005[6]; Evans, 2001[7]) from various angles or on a specific crash type. In general, these studies come to varying conclusions regarding the sign of the relationship between average vehicle mass and overall fatality rates, but all conclude that the magnitude of this relationship is relatively modest.

In recent years economists have studied the "arms race" nature of vehicle choice, and the effect of disparity in the mass and/or size in the vehicle fleet on fleetwide safety. In particular, they focus on the internal and external safety effect posed by larger vehicles –pickup trucks and sport utility vehicles (SUVs)--relative to passenger cars. Anderson and Auffhammer 2014,[8] White 2004,[9] Gayer 2004,[10] Anderson 2008,[11] Li 2012,[12] and Jacobsen 2013[13] all conclude that light trucks (pickups and SUVs) impose significant societal risks relative to passenger cars. Overall, light trucks pose a significant hazard to other users of the highway system but on average provide no additional protection to their own occupants. Anderson (2008) estimates the implied Pigovian tax is approximately $3850 per light truck sold, using standard value of statistical life figures. Anderson and Auffhammer (2014) recommend two policy options for internalizing the external safety cost, a weight-varying mileage tax and a gas tax, and find that they are similar for most vehicles.

Some of these papers use State-level data on fatalities and VMT, instead of data at the individual vehicle level. Some estimate fatality risk once a crash has occurred, but do not account for the effect of crash frequency on risk. Some account for vehicle type, but not for vehicle mass, footprint, and other characteristics by vehicle model, or for driver characteristics or crash circumstances. None of the listed literature includes all of these elements in its analysis or serves the purpose of estimating the change in societal fatality risk from reducing vehicle mass, while holding size (footprint) unchanged.

It should be noted that those safety articles on the "arms race" focus on the potential role of policy in changing the size mix, or the type mix, of the vehicle fleet. As discussed in the TSD for the MY 2017-25 final rulemaking, Chapter 2, in developing the footprint-based standards the agencies sought to preserve rather than change the distribution of vehicle sizes; and by continuing to set a standard for light trucks distinct from that for cars, the agencies sought to preserve consumer choice for different types of vehicles that fit their transportation needs.

The safety analysis presented in this chapter is a statistical analysis that, unlike these cited papers, takes all the factors listed above into account. To consider what technologies are available for improving fuel economy, including mass reduction, the agencies have to consider the potential effect that those technologies may have on safety. The purpose of our analysis is to find a statistical relationship between mass, footprint, and safety. Specifically, the analysis is to estimate the fatality risk effect per 100 pounds mass reduction while holding the vehicle footprint constant. The results of the analysis are applied in estimating fatality risk in the NHTSA Volpe model or EPA OMEGA model. The relationships among a vehicle's mass, size, and fatality risk are complex, and they vary in different types of crashes and by different vehicle categories. The performed analysis is built on the weighted logistic regression model at each fatality case level by using updated micro data from historic annual NHTSA fatality data and State police-reported crash data.

The safety analysis presented in this chapter says that reducing the mass of the heavier vehicles enhances societal safety, while reducing the mass of the lighter vehicles diminishes societal safety .These findings agree with the disparity research discussed above that less mass disparity is a good thing. The agencies believe that the safety analysis in this chapter is the most comprehensive analysis available at this time of the relationship between vehicle weight, footprint, and societal fatality risk, and is the most appropriate to estimate what effect reduction in vehicle mass, while holding footprint constant, of current vehicles will have on societal fatality risk per VMT.

The sections below discuss more specifically the state of the research on the mass-safety relationship, and how the agencies have integrated that research into our assessment of the safety effects of the MY2017-2025 CAFE and GHG standards.

8.2 What is the Current State of the Research on Statistical Analysis of Historical Crash Data?

8.2.1 Background

Researchers have been using statistical analysis to examine the relationship of vehicle mass and safety in historical crash data for many years, and continue to refine their techniques over time. In the MY2012-2016 final rule, the agencies conducted further study and research into the interaction of mass, size and safety to assist future rulemakings, and started to work collaboratively by developing an interagency working group between NHTSA, EPA, DOE, and CARB to evaluate all aspects of mass, size and safety. The team coordinated government supported studies and independent research, to the greatest extent possible, to help ensure the work is complementary to previous and ongoing research and to guide further research in this area.

The agencies also identified three specific areas to direct research in preparation for future CAFE/GHG rulemaking in regards to statistical analysis of historical data.

First, NHTSA would contract with an independent institution to review the statistical methods that NHTSA and DRI have used to analyze historical data related to mass, size and safety, and to provide recommendations on whether the existing methods or other methods should be used for future statistical analysis of historical data. This study would include a consideration of potential near multi-collinearity in the historical data and how best to address it in a regression analysis. The 2010 NHTSA report was also peer reviewed by two other experts in the safety field - Charles Farmer (Insurance Institute for Highway Safety) and Anders Lie (Swedish Transport Administration).[F]

Second, NHTSA and EPA, in consultation with DOE, would update the MY 1991–1999 database on which the safety analyses in the NPRM and final rule are based with newer vehicle

[F] All three of the peer reviews are available in Docket No. NHTSA-2010-0152. You can access the docket at http://www.regulations.gov/#!home by typing ‘NHTSA-2010-0152’ where it says “enter keyword or ID” and then clicking on “Search.”

data, and create a common database that could be made publicly available to help address concerns that differences in data were leading to different results in statistical analyses by different researchers.

And third, in order to assess if the design of recent model year vehicles that incorporate various mass reduction methods affect the relationships among vehicle mass, size and safety, the agencies sought to identify vehicles that are using material substitution and smart design, and to try to assess if there is sufficient crash data involving those vehicles for statistical analysis. If sufficient data exists, statistical analysis would be conducted to compare the relationship among mass, size and safety of these smart design vehicles to vehicles of similar size and mass with more traditional designs.

By the time of the MY2017-2025 final rule, significant progress had been made on these tasks since the MY2012-2016 final rule: The independent review of recent and updated statistical analyses of the relationship between vehicle mass, size, and crash fatality rates had been completed. NHTSA contracted with the University of Michigan Transportation Research Institute (UMTRI) to conduct this review, and the UMTRI team led by Paul Green evaluated over 20 papers, including studies done by NHTSA's Charles Kahane, Tom Wenzel of the U.S. Department of Energy's Lawrence Berkeley National Laboratory, Dynamic Research, Inc., and others. UMTRI's basic findings will be discussed below.

Some commenters in recent CAFE rulemakings, including some vehicle manufacturers, suggested that the designs and materials of more recent model year vehicles may have weakened the historical statistical relationships between mass, size, and safety. The agencies agreed that the statistical analysis would be improved by using an updated database that reflects more recent safety technologies, vehicle designs and materials, and reflects changes in the overall vehicle fleet, and an updated database was created and employed for assessing safety effects in the final rule. The agencies also believed, as UMTRI also found, that different statistical analyses may have produced different results because they each used slightly different datasets for their analyses.

In order to try to mitigate this issue and to support 2012 rulemaking, NHTSA created a common, updated database for statistical analysis that consisted of crash data of model years 2000-2007 vehicles in calendar years 2002-2008, as compared to the database used in prior NHTSA analyses based on model years 1991–1999 vehicles in calendar years 1995-2000. The 2012 database was the most up-to-date possible at that time, given the processing lead time for crash data and the need for enough crash cases to permit statistically meaningful analyses. NHTSA made the preliminary version of the new database, which was the basis for NHTSA's 2011 report, available to the public in May 2011, and an updated version in April 2012,[G] enabling other researchers to analyze the same data and hopefully minimizing discrepancies in the results that would have been due to inconsistencies across databases.[14]

The agencies were aware that several studies had been conducted using the 2011 version or the 2012 version of NHTSA's safety database. In addition to three NHTSA studies, which are discussed in Section 8.2.5, other studies included two by Wenzel at Lawrence Berkeley National Laboratory (LBNL) under contract with the U.S. DOE, and one by Dynamic Research, Inc.

[G] These databases are available at ftp://ftp.nhtsa.dot.gov/CAFE/.

(DRI) contracted by the International Council on Clean Transportation (ICCT). These studies took somewhat different approaches to examine the statistical relationship between fatality risk, vehicle mass and size. In addition to a detailed assessment of the NHTSA 2011 report, Wenzel considered the effect of mass and footprint reduction on casualty risk per crash, using data from thirteen states, where casualty risk included both fatalities and serious or incapacitating injuries. Both LBNL studies were peer reviewed and subsequently revised and updated. DRI used models that separate the effect of mass reduction on two components of fatality risk, crash avoidance and crashworthiness. DRI studies were also peer reviewed and revised in response to peer reviewer's questions. The LBNL and DRI studies were made available in the docket for the 2012 final rule.[H] The database was made available for download to the public from NHTSA's website.

Finally, EPA and NHTSA with DOT's Volpe Center, part of DOT's Office of the Assistant Secretary for Research and Technology, attempted to investigate the implications of "Smart Design," by identifying and describing the types of "Smart Design" and methods for using "Smart Design" to result in vehicle mass reduction, selecting analytical pairs of vehicles, and using the appropriate crash database to analyze vehicle crash data. The analysis identified several one-vehicle and two-vehicle crash datasets with the potential to shed light on the issue, but the available data for specific crash scenarios was insufficient to produce consistent results that could be used to support conclusions regarding historical performance of "Smart Designs." This study was also available in the docket for the final rule.[15]

[H] Wenzel, T. (2011a). Assessment of NHTSA's Report "Relationships Between Fatality Risk, Mass, and Footprint in Model Year 2000-2007 Passenger Cars and LTVs – Draft Final Report." (Docket No. NHTSA-2010-0152-0026). Berkeley, CA: Lawrence Berkeley National Laboratory; Wenzel, T. (2011b). An Analysis of the Relationship between Casualty Risk Per Crash and Vehicle Mass and Footprint for Model Year 2000-2007 Light-Duty Vehicles – Draft Final Report." (Docket No. NHTSA-2010-0152-0028). Berkeley, CA: Lawrence Berkeley National Laboratory; Wenzel, T. (2012a). Assessment of NHTSA's Report "Relationships Between Fatality Risk, Mass, and Footprint in Model Year 2000-2007 Passenger Cars and LTVs – Final Report." (To appear in Docket No. NHTSA-2010-0152). Berkeley, CA: Lawrence Berkeley National Laboratory; Wenzel, T. (2012b). An Analysis of the Relationship between Casualty Risk Per Crash and Vehicle Mass and Footprint for Model Year 2000-2007 Light-Duty Vehicles – Final Report." (To appear in Docket No. NHTSA-2010-0152). Berkeley, CA: Lawrence Berkeley National Laboratory; Van Auken, R.M., and Zellner, J. W. (2012a). Updated Analysis of the Effects of Passenger Vehicle Size and Weight on Safety, Phase I. Report No. DRI-TR-11-01. (Docket No. NHTSA-2010-0152-0030). Torrance, CA: Dynamic Research, Inc.; Van Auken, R.M., and Zellner, J. W. (2012b). Updated Analysis of the Effects of Passenger Vehicle Size and Weight on Safety, Phase II; Preliminary Analysis Based on 2002 to 2008 Calendar Year Data for 2000 to 2007 Model Year Light Passenger Vehicles to Induced-Exposure and Vehicle Size Variables. Report No. DRI-TR-12-01, Vols. 1-3. (Docket No. NHTSA-2010-0152-0032). Torrance, CA: Dynamic Research, Inc.; Van Auken, R.M., and Zellner, J. W. (2012c). Updated Analysis of the Effects of Passenger Vehicle Size and Weight on Safety, Phase II; Preliminary Analysis Based on 2002 to 2008 Calendar Year Data for 2000 to 2007 Model Year Light Passenger Vehicles to Induced-Exposure and Vehicle Size Variables. Report No. DRI-TR-12-01, Vols. 4-5. (Docket No. NHTSA-2010-0152-0033). Torrance, CA: Dynamic Research, Inc.; Van Auken, R.M., and Zellner, J. W. (2012d). Updated Analysis of the Effects of Passenger Vehicle Size and Weight on Safety; Sensitivity of the Estimates for 2002 to 2008 Calendar Year Data for 2000 to 2007 Model Year Light Passenger Vehicles to Induced-Exposure and Vehicle Size Variables. Report No. DRI-TR-12-03. (Docket No. NHTSA-2010-0152-0034). Torrance, CA: Dynamic Research, Inc.

Since the publication of the MY2017-2025 final rule, NHTSA has sponsored new studies and research to inform the midterm evaluation and the MY2022-2025 rulemaking. A newly updated NHTSA study, presented in Section 8.2.5, represents the latest iteration of the database and analysis applied in the 2011 and 2012 NHTSA reports. The updated database created for the study consists of crash data of MY2003-2010 vehicles in calendar years 2005-2011, and follows the identical analytical structure as the peer-reviewed method applied in the 2011 and 2012 reports. NHTSA published a separate preliminary report in 2016, applying this newly updated database.[I] The agencies recognize, however, that the updated database may not represent the future fleet, because vehicles have continued and will continue to change.

Wenzel at Lawrence Berkeley National Laboratory (LBNL) also conducted a statistical analysis using the new database. Wenzel's new findings are summarized in Section 8.2.6.

In addition, the National Academy of Sciences published a new report in this area in 2015, discussed in Section 8.2.4.[16]

Throughout the midterm evaluation process, NHTSA's goal is to publish as much of our research as possible. Thus, while some of these reports have already been published, all are summarized below. In establishing standards, the agencies will consider all available data, studies and information objectively without regard to whether they were sponsored by the agencies.

Technical assessment and review of previous studies and current findings helps the agencies come closer to resolving some of the ongoing debates in statistical analysis research of historical crash data that are detailed later in this chapter. We intend to apply these conclusions going forward in Draft TAR future rulemakings, and we believe that the public discussion of the issues will be facilitated by the research conducted.

The following sections chronologically discuss the findings from these studies and others in greater detail. Section 8.2.2 summarize historical activities leading up to the 2017-2025 final rule published in 2012, and sections 8.2.4 cover developments since 2012 conducted for the midterm evaluation and anticipation of rulemaking for model years 2022-2025, including updated analyses.

8.2.2 Historical Activities Informing the 2017-2025 Final Rule

8.2.2.1 2011 NHTSA Workshop on Vehicle Mass, Size and Safety

On February 25, 2011, NHTSA hosted a workshop on mass reduction, vehicle size, and fleet safety at the Headquarters of the U.S. Department of Transportation in Washington, DC.[J] The purpose of the workshop was to provide the agencies with a broad understanding of current research in the field and provide stakeholders and the public with an opportunity to weigh in on this issue, by bringing together experts in the field to discuss some of the overarching questions

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[I] The preliminary report can be found in Docket No. NHTSA-2010-0131.

[J] A video recording, transcript, and the presentations from the NHTSA workshop on mass reduction, vehicle size and fleet safety is available at http://www.nhtsa.gov/fuel-economy (look for "NHTSA Workshop on Vehicle Mass-Size-Safety on Feb. 25").

to be examined in NHTSA's impending CAFE rulemaking. NHTSA also created a public docket to receive comments from interested parties that were unable to attend.

The speakers included Charles Kahane of NHTSA, Tom Wenzel of Lawrence Berkeley National Laboratory, R. Michael Van Auken of Dynamic Research Inc. (DRI), Jeya Padmanaban of JP Research, Inc., Adrian Lund of the Insurance Institute for Highway Safety, Paul Green of the University of Michigan Transportation Research Institute (UMTRI), Stephen Summers of NHTSA, Gregg Peterson of Lotus Engineering, Koichi Kamiji of Honda, John German of the International Council on Clean Transportation (ICCT), Scott Schmidt of the Alliance of Automobile Manufacturers, Guy Nusholtz of Chrysler, and Frank Field of the Massachusetts Institute of Technology.

The wide participation in the workshop allowed the agencies to hear from a broad range of experts and stakeholders. The contributions were particularly relevant to the agencies' analysis of the effects of mass reduction for the MY2017-2025 final rule. The presentations were divided into two sessions that addressed the two expansive sets of issues: statistical evidence of the roles of mass and size on safety, and engineering realities regarding structural crashworthiness, occupant injury and advanced vehicle design.

Some main points from the workshop were:

- Statistical studies of crash data that attempt to identify the relative recent historical effects of vehicle mass and size on fleet safety shows complicated relationships with many confounding influences in the data.
- Analyses must also control for individual technologies with significant safety effects (e.g., Electronic Stability Control, airbags).
- The physics of a two-vehicle crash require that the lighter vehicle experience a greater change in velocity, which, all else being equal, often leads to disproportionately more injury risk.
- The separation of key parameters is a challenge to the analyses, as vehicle size has historically been highly correlated with vehicle mass.
- There was no consensus on whether smaller, lighter vehicles maneuver better, and thus avoid more crashes, than larger, heavier vehicles.
- Kahane's results from his 2010 report found that a scenario which took some mass out of heavier vehicles but little or no mass out of the lightest vehicles did not impact safety in absolute terms, and noted that if the analyses were able to consider the mass of both vehicles in a two-vehicle crash, the results may be more indicative of future crashes.

8.2.2.2 Report by Green et. al., UMTRI – "Independent Review: Statistical Analyses of Relationship between Vehicle Curb Weight, Track Width, Wheelbase and Fatality Rates," April 2011

As explained above, NHTSA contracted with the University of Michigan Transportation Research Institute (UMTRI) to conduct an independent review[K] of a set of statistical analyses of relationships between vehicle curb weight, the footprint variables (track width, wheelbase) and fatality rates from vehicle crashes. The purpose of this review was to examine analysis methods,

[K] The review is independent in the sense that it was conducted by an outside third party without any interest in the reported outcome.

data sources, and assumptions of the statistical studies, with the objective of identifying the reasons for any differences in results. Another objective was to examine the suitability of the various methods for estimating the fatality risks of future vehicles.

UMTRI reviewed a set of papers, reports, and manuscripts provided by NHTSA (listed in Appendix A of UMTRI's report, which is available in the docket to the MY2017-2025 rulemaking) that examined the statistical relationships between fatality or casualty rates and vehicle properties such as curb weight, track width, wheelbase and other variables.

Fundamentally, the UMTRI team concluded that the database created by Kahane appeared to be an impressive collection of files from appropriate sources and the best ones available for answering the research questions considered in this study; and that the disaggregate logistic regression model used by NHTSA in the 2003 report[17] seemed to be the most appropriate model, and valid for the analysis in the context that it was used: finding general associations between fatality risk and mass – and the general directions of the reported associations were correct.

8.2.2.3 2012 NHTSA, LBNL, and DRI Reports

NHTSA published a study in 2012 (Kahane, 2012) that estimated the effect of mass reduction on US societal fatality risk per VMT, using light vehicles from model years 2000 to 2007 in calendar years 2002 to 2008. NHTSA's methodology in part responded to comments Paul Green made in his 2011 review. For the first time NHTSA included the correlated variables vehicle curb weight and footprint in its baseline regression model, for two reasons: an analysis indicated that the model variance inflation factors were not high enough to preclude including the two correlated variables in the same regression model, and the fuel economy/greenhouse gas emission standards adopted for model years 2012 to 2016 were based on a vehicle's footprint, so the regression model needed to estimate the effect mass reduction would have on safety while holding footprint constant. The model used came to be known as the "baseline" model, and the study found that mass reduction in only lighter-than-average cars was associated with a statistically-significant increase in fatality risk; for the other vehicle types, mass reduction was associated with increases or decreases in fatality risk that were not statistically significant. This study is cited in more detail in Section 8.2.6, detailing the current follow-up. NHTSA published a preliminary report in 2011 that was subject to external review; the final report was published in 2012.

In its 2012 "Phase 1" report[18], LBNL replicated the 2012 NHTSA baseline results, and conducted 19 alternative regression models to test the sensitivity of the NHTSA baseline model to changes in the measure of risk, the variables included, and the data used. In its report LBNL pointed out that other vehicle attributes, driver characteristics, and crash circumstances were associated with much larger changes in risk than mass reduction.[L] LBNL also demonstrated that

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[L] As stated at p. iv, Executive Summary of LBNL 2012 Phase 1 report, "many of the control variables NHTSA includes in its logistic regressions are statistically significant, and have a much larger estimated effect on fatality risk than vehicle mass. For example, installing torso side airbags, electronic stability control, or an automated braking system in a car is estimated to reduce fatality risk by about 10%; cars driven by men are estimated to have a 40% higher fatality risk than cars driven by women; and cars driven at night, on rural roads, or on roads with a speed limit higher than 55 mph are estimated to have a fatality risk over 100 times higher than cars driven during the daytime on low-speed non-rural roads.

there was little correlation between mass and fatality risk by vehicle model, even after accounting for all other vehicle attributes, driver characteristics, and crash circumstances.

In its 2012 "Phase 2" report[19], LBNL used data from police reported crashes in the 13 states to study casualty (fatality plus severe injury) risk per VMT, and to divide risk per VMT into its two components, crash frequency (crashes per VMT) and crashworthiness/crash compatibility (risk per crash). LBNL found that mass reduction was associated with increases in crash frequency, and decreases in risk per crash. Preliminary versions LBNL's Phase 1 and Phase 2 reports were reviewed by external reviewers[20], and comments incorporated into the final versions published in 2012.

DRI published three preliminary reports in 2012. DRI's preliminary Phase I report updated its analysis of data from 1995 to 2000, and was able to replicate the results from NHTSA's 2003 report. DRI's preliminary Phase II report replicated the 2012 NHTSA baseline results, and used a simultaneous two-stage model to estimate the separate effects of mass reduction on crash frequency and fatality risk per crash. The results from DRI's two-stage model were comparable to LBNL's Phase 2 analysis: that mass reduction was associated with increases in crash frequency, and decreases in risk per crash. DRI's preliminary Summary report showed the effect of two alternative regression models: using stopped rather than non-culpable vehicles as the basis for the induced exposure database, and replacing vehicle footprint with its components wheelbase and track width. Under these two alternatives, mass reduction was associated with more beneficial changes in fatality risk. The three preliminary DRI reports were peer-reviewed, with comments incorporated into the final versions published in 2013.

The results from LBNL's Phase 2 and DRI's Phase II reports implied that the increase in fatality risk per VMT from mass reduction in lighter cars estimated by the NHTSA baseline model was due to increasing crash frequency, and not increasing fatality risk once a crash had occurred, as mass is reduced. In the final version of its 2012 report NHTSA argued that the effects of crash frequency could not be separated from risk per crash because of reporting bias in state crash data, such as lack of a crash severity measure, and possible bias due to under-reporting of less severe crashes in certain States.

8.2.3 Final Rule for Model Years 2017-2025

In August 2012, EPA and NHTSA jointly published the Joint Technical Support Document: Final Rulemaking for (Model Years) 2017-2025, Light-Duty Vehicle Greenhouse Gas Emission Standards (EPA) and Corporate Average Fuel Economy Standards (NHTSA); EPA-420-R-12-901. Since NHTSA rules are always in lengths of five years, the standards for model years 2022-2025 for Corporate Average Fuel Economy (CAFE) are considered "augural" and must be revisited for a permanent rule. Analyses described in the following sections will inform not only the midterm evaluation of the 2017-2025 rule but the final CAFE rule for MY's 2022-2025.

8.2.4 Activities and Development since 2017-2025 Final Rule

8.2.4.1 2013 Workshop on Vehicle Mass, Size and Safety

On May 13-14, 2013, NHTSA hosted a follow-on symposium to continue to explore the relevant issues and concerns with mass, size, and potential safety tradeoffs, bringing together experts in the field to discuss questions to address CAFE standards for model years 2022-2025. The first day of the two-day symposium focused on engineering, while the second day investigated various methodologies for assessing statistical evidence of the roles of vehicle mass and size on occupant safety. All presentations may be seen on NHTSA's web site at: http://www.nhtsa.gov/Laws+&+Regulations/CAFE+-+Fuel+Economy/NHTSA+Vehicle+Mass-Size-Safety+Workshop.

The speakers for the second day, focusing on the subject matter of this chapter, included Charles Kahane of NHTSA, Joe Nolan of the Insurance Institute for Highway, Guy Nusholtz of Chrysler, Mike van Auken of Dynamic Research Incorporated, and Tom Wenzel of Lawrence Berkeley National Laboratory. Summaries of the topics follow:

- Kahane gave an overview of statistical studies designed to determine the incremental change in societal risk as vehicle mass of a particular vehicle is modified while keeping its footprint (the product of wheel base and track width) is kept constant. The physics of crashes, in particular conservation of momentum and equal and opposite forces, imply that mass reduction in the heaviest vehicles and/or mass increase in the lightest vehicles can reduce societal risk in two-vehicle crashes. It is therefore reasonable that reducing disparities in mass ratio in the vehicle fleet (such as by reducing the mass of heavy vehicles by a larger percentage than that of light vehicles) should reduce societal harm. This trend was noticed in the data for model year 2000-2007 vehicles, but only statistically significant for the lightest group of vehicles. This is similar to the results found for model year 1991-1991 vehicles in a 2003 study. Kahane acknowledged numerous confounding factors such as maneuverability of different vehicle classes (although data indicated smaller cars were more likely to be involved in crashes), driver attributes and vulnerabilities, advances in restraint safety systems and vehicle structures, and, and electronic stability control.

- Wenzel replicated Kahane's results using the same data and methods, but came to slightly different conclusions. He demonstrated that the effect of mass or footprint reduction that Kahane estimated on societal risk is much smaller than the effect Kahane estimated for other vehicle attributes, driver characteristics, or crash circumstances. Wenzel plotted actual fatality risk vs. weight by vehicle make and model, and estimated predicted risk by make and model after accounting for all control variables used in NHTSA's baseline model except for mass and footprint. The remaining, or residual risk, not explained by the control variables has no correlation with vehicle weight. He presented results of the 19 alternative regression models he conducted to test the sensitivity of the results from NHTSA's baseline model. He also presented results from LBNL's Phase 2 analysis, which examined the effect of mass or footprint reduction on the two components of risk per VMT: crashes per VMT (crash frequency), and risk per crash (crashworthiness). Both his analysis of casualty risk using crash data from 13 states, and his replication of the DRI two-state simultaneous regression model, indicate that mass reduction is associated with an increase in crash frequency, but a decrease in risk per crash.

- Van Auken also replicated Kahane's results from the NHTSA baseline model, and presented results from three sensitivity regression models. Replacing footprint with its components wheelbase and track width reduces the estimated increase in risk from mass reduction in cars, and suggests that mass reduction in light trucks decreases societal risk. Using stopped rather than non-culpable vehicles to derive the induced exposure dataset also reduces the estimated increase in risk from mass reduction in lighter-than-average cars and light trucks, and estimates that mass reduction in heavier cars and trucks decreases societal risk. Including both of these changes to the NHTSA baseline model greatly reduces the estimated increase in risk from mass reduction in the lightest cars, and is associated with decreases in risk for all other vehicle types. Van Auken described in more detail his two-stage simultaneous regression model, that allows risk per vehicle mile of travel to be decomposed into crashes per VMT (crash frequency) and risk per crash (crashworthiness/crash compatibility). As with Wenzel's analysis, Van Auken found that mass reduction is associated with an increases in crash frequency, but with a decrease in risk per crash. Once again, the resulting trends were similar to those from Kahane and Wenzel. Van Auken explored the issue of inducing the exposure of vehicles via crash statistics in which relative exposure was measured by non-culpable vehicles in the crash database versus by its subset of stopped vehicles in the data, and also investigated the impact in substituting footprint for track width and wheelbase as size variables in the regression.

- Nusholtz of Chrysler presented an analysis of the sensitivity of the fleet-wide fatality risk to changes in vehicle mass and size. He noted the difficulty in finding a definitive metric for "size." He dismissed some assertions of mass having negligible (or purely negative) effect on safety as leading to absurd conclusions in the extreme. He extended the methods of Joksch (1993) and Evans (1992) to estimate risk as a function of readily measurable vehicle attributes and reported crash characteristics. He used crash physics (closing speed, estimates of inelastic stiffness and energy absorption) to estimate changes in fleet risk as a function of changes in these parameters. He observed that mass is a dominant factor but believes crush space could begin to dominate if vehicles could be made larger. He concurred that removing more mass from larger vehicles can reduce overall risk but is not convinced that such a strategy will be sufficient to meet fuel economy goals. He regards the safety implications of mass reduction to be transition issues, of greater importance so long as legacy heavier vehicles are used in significant numbers.

- Nolan analyzed historical trends in the fleet. While median vehicle mass has increased, safety technologies have enhanced the safety of current small cars to the level only achieved by larger cars in the past. In particular, electronic stability control has reduced the relative importance of some severe crash modes. While acknowledging that smaller vehicles will always be at a disadvantage, there is hope that further technological advances such as crash avoidance systems hold promise in advancing safety. Fleet safety would be enhanced if these technologies could quickly penetrate across the fleet to small cars as well as large ones.

- An attempt was made to separate the effect of mass on crash outcome as distinct from the likelihood of the crash itself. It was acknowledged that mass can affect both. Nusholtz emphasized that crash parameters (e.g., closing speed) necessarily dominate. Kahane suggested that reporting rates might be sufficiently different to affect results. Nusholtz cautioned that physics and statistics must be considered but in a way that connects them to reality rather than abstractions. Nolan hopes that crash avoidance effects could be very significant. Nusholtz noted that assessments of that effect are difficult in that determining when and why a crash didn't occur is problematic against the backdrop of confounding information.

8.2.4.2 Subsequent Analyses by LBNL

As part of its review of the 2012 DRI studies,[21] LBNL recreated DRI's two-stage simultaneous regression model, which estimated the effect of mass or footprint reduction on the two components of fatality risk per VMT: the number of crashes per VMT and the risk of fatality per crash (Wenzel 2013). LBNL first replicated DRI's methodology of taking a random "decimated" sample of the crash data from 10 states for the induced exposure records. Although LBNL was not able to exactly recreate DRI's results, its results were comparable to DRI's, and LBNL's Phase 2 analysis: mass reduction is associated with increases in crash frequency for all vehicle types, and with decreases in fatalities per crash for all vehicle types except heavier cars. LBNL then re-ran the two-stage regression model using all crash data from the 13 states NHTSA used in their baseline model, and obtained similar results.

The LBNL Phase 2 study and DRI Phase II study had two unexpected results: that mass reduction is associated with increased crash frequency, but decreased risk per crash; and the signs on some of the control variables are in the unexpected direction. For example, side airbags in light trucks and CUVs/minivans were estimated to reduce crash frequency; the crash avoidance technologies electronic stability control (ESC) and antilock braking systems (ABS) were estimated to reduce risk once a crash had occurred; and all-wheel-drive and brand new vehicles were estimated to increase risk once a crash had occurred. In addition, male drivers were estimated to have essentially no effect on crash frequency, but were associated with a statistically significant increase in fatality risk once a crash had occurred. And driving at night, on high-speed or rural roads, were associated with higher increases in risk per crash than on crash frequency. A possible explanation for these unexpected results is that important control variables were not being included in the regression models. For example, crashes involving male drivers, in vehicles equipped with AWD, or that occur at night on rural or high-speed roads, may not be more frequent but rather more severe than other crashes, and thus lead to greater fatality or casualty risk. And drivers who select vehicles with certain safety features may tend to drive more carefully, resulting in vehicle safety features designed to improve crashworthiness or compatibility, such as side airbags, being also associated with lower crash frequency.

LBNL made several attempts to create a regression model that "corrected" these unexpected results. 22 LBNL first examined the results of three vehicle braking and handling tests conducted by Consumer Reports: the maximum speed achieved during the avoidance maneuver test, acceleration time from 45 to 60 mph, and dry braking distance. When these three test results were added to the LBNL baseline regression model of the number of crashes per mile of vehicle travel in cars, none of the three handling/braking variables had the expected effect on crash frequency. In other words, an increase in maximum maneuver speed, the time to reach 60 miles per hour, or braking distance on dry pavement in cars, either separately or combined, was associated with a decrease in the likelihood of a crash, of any type or with a stationary object. Adding one or all of the three handling/braking variables had relatively little effect on the estimated relationship between mass or footprint reduction in cars and crash frequency, either in all types of crashes or only in crashes with stationary.

LBNL next tested the sensitivity of the relationship between mass or footprint reduction and crash frequency by adding five additional variables to the regression models: initial vehicle price, average household income, bad driver rating, alcohol/drug use, and seat belt use. An increase in vehicle price, household income, or belt use was associated with a decrease in crash frequency, while an increase in alcohol/drug use was associated with an increase in crash frequency, for all three vehicle types; a poor bad driver rating increases crash frequency in cars, but unexpectedly decreases crash frequency in light trucks and CUVs/minivans. Including these five variables, either individually or including all in the same regression model, did not change the general results of the baseline LBNL regression model: that mass reduction is associated with an increase in crash frequency in all three types of vehicles, while footprint reduction is associated with an increase in crash frequency in cars and light trucks, but with a decrease in crash frequency in CUVs/minivans. The variable with the biggest effect was initial vehicle purchase price, which dramatically reduced the estimated increase in crash frequency in heavier-than-average cars (and in heavier-than-average light trucks, and all CUVs/minivans). These results suggest that other, more subtle, differences in vehicles and their drivers account for the unexpected finding that lighter vehicles have higher crash frequencies than heavier vehicles, for all three types of vehicles.

In its 2012 report NHTSA suggested two possible explanations for the unexpected results in the LBNL Phase 2 analysis and the DRI and LBNL two-stage regression models: that the analyses did not account for the severity of the crash, and possible bias in the crashes reported to police in different states, with less severe crashes being under-reported for certain vehicle types. LBNL analyzed the first of Kahane's explanations for the unexpected result of mass reduction being associated with decreased risk per crash, by re-running the baseline Phase 2 regressions after excluding the least-severe crashes from the state crash databases objects.[23] Only vehicles that were described as "disabled" or as having "severe" damage were included, while vehicles which were driven away from the crash site or had functional, none, or unknown damage were excluded. Excluding non-severe crashes had little effect on the relationship between mass reduction and crash frequency, in either LBNL's Phase 2 baseline model or the two-stage simultaneous model: mass reduction was associated with an increase in crash frequency, and a decrease in risk per crash. Excluding the non-severe crashes also did not change the unexpected results for the other control variables: most of the side airbag variables, and the crash compatibility variables in light trucks, continued to be associated with an increase in crash frequency, while antilock braking systems, electronic stability control, all-wheel drive, male drivers, young drivers, and driving at night, in rural counties, and on high speed roads all continued to be associated with an increase in risk per crash.

8.2.4.3 2013 Presentations to NAS Subcommittee

Chuck Kahane, Tom Wenzel, Stephen Ridella, (and Chuck Thomas, Honda, and Chuck Nolan, IIHS) were invited to the June 2013 NAS subcommittee on light-duty fuel economy to present the results from their 2012 analyses. At the meeting committee members raised several questions about the studies; the presenters responded to these questions at the meeting, as well as in two emails in August 2013 and December 2014.

8.2.4.4 2015 National Academy of Sciences' Report

In 2015, the National Academy of Sciences published the report "Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles." The report is the result of the work of the Committee on Assessment of Technologies for Improving the Fuel Economy of Light-Duty Vehicles, Phase 2, established upon the request of NHTSA to help inform the midterm review. The committee was asked to assess the CAFE standard program and the analysis leading to the setting of the standards, as well as to provide its opinion on costs and fuel consumption improvements of a variety of technologies likely to be implemented in the light-duty fleet between now and 2030 (see further discussion in Chapter 2.2.1).

In the particular area of mass and safety, as shown below, the Committee found the agencies' estimates of mass reductions to be conservative, particularly for mid-size and small vehicles.

Table 8.1 Mass Reductions Foreseen by NHTSA/EPA and by the Committee

Mass Reductions Foreseen by NHTSA/EPA and by the Committee (percent)[24]		
Vehicle	NHTSA/EPA TSD Estimate	Committee Estimate
Small Car	0	5
Midsize Car	3.5	10
Large Car	10	15
Minivan	20	20
Light duty truck	20	20

The Committee acknowledged the possibility of negative safety impacts during the transition period, due to variances in how reductions occurred. Because of this, the Committee recommended NHTSA consider and, if necessary, take steps to mitigate this possibility.

8.2.4.5 2016 NHTSA/Volpe Study Reported in "Relationships between Fatality Risk, Mass, and Footprint in Model Year 2003-2010 Passenger Cars and LTVs: Preliminary Report," June 2016

The relationship between a vehicle's mass, size, and fatality risk is complex, and varies depending upon the type of crash. NHTSA, along with others, has been examining this relationship for over a decade. The safety chapter of NHTSA's 2012 final regulatory impact analysis (FRIA) of CAFE standards for MYs 2017-2025 passenger cars and light trucks included a statistical analysis of relationships between fatality risk, mass, and footprint in MY2000-2007 passenger cars and LTVs (light trucks and vans), based on calendar year (CY) 2002-2008 crash and vehicle-registration data (Kahane, Aug. 2012).

The principal findings of NHTSA's 2012 analysis were that mass reduction, while holding footprint constant, was estimated to result in a statistically significant increase in societal fatality risk in lighter cars, but a statistically significant decrease in societal fatality risk in heavier LTVs by decreasing the fatality risk of occupants in lighter vehicles which collide with the heavier LTVs. NHTSA concluded that, as a result, any reasonable combination of mass reductions while holding footprint constant in MYs 2017-2025 vehicles – concentrated, at least to some extent, in the heavier LTVs and limited in the lighter cars – would likely be approximately safety-neutral; it would not significantly increase fatalities and might well decrease them. LBNL replicated these results in its 2012 assessment of the NHTSA study.

NHTSA's 2012 report partially agreed and partially disagreed with analyses published during 2010 -2012 by Dynamic Research, Inc. (DRI). NHTSA, LBNL, and DRI all found a significant protective effect for footprint, and that reducing mass and footprint together (downsizing) on smaller vehicles was harmful. DRI's analyses estimated a statistically significant decrease in fatalities from mass reduction in all light-duty vehicles if wheelbase and track width were maintained, whereas NHTSA's report showed overall fatality reductions only in the heavier LTVs, and benefits only in some types of crashes for other vehicle types. Much of the NHTSA, LBNL, and DRI 2012 reports involved sensitivity tests on the databases and models, which generated a range of estimates somewhere between the initial DRI and NHTSA results.[M]

In May 2015, NHTSA, working closely with EPA and the Department of Energy (DOE), commenced a new statistical analysis of the relationships between fatality rates, mass and footprint, updating the crash and exposure databases to the latest available model years, and utilizing the same methodology as in the 2012 NHTSA report. The new databases use the most up-to-date data available, given the processing lead time for crash data and the need for enough crash cases to permit statistically meaningful analyses. NHTSA made the first version of the new databases available to the public in 2016, concurrently with the release of its 2016 preliminary report,[25] enabling other researchers to analyze the same data and hopefully minimizing discrepancies in the results due to inconsistencies across the data used.[26]

One way to estimate the effect of mass reduction on safety is the use of statistical analyses of societal fatality risk per vehicle miles traveled (VMT) for the current on-road vehicle fleet. Consistent with this, the analysis follows the identical approach employed in the 2012 NHTSA report, centering on cross-sectional logistic regressions of societal fatality risk per billion vehicle miles of travel (the dependent variable), as a function of driver- (e.g., driver age and gender), vehicle- (e.g., safety features) and crash-specific factors (e.g., times, locations). Societal fatality risk represents total fatalities to all vehicle occupants, pedestrians, cyclists and motorcyclists involved in collisions per volume of VMT.

The paramount purpose of the analysis is to develop five parameters for use in the CAFE Compliance and Effects Modeling System (usually referred to as the "Volpe model," developed for NHTSA by the Volpe National Transportation Systems Center) to estimate the safety effects, if any, of the modeled mass reductions in MY2022-2025 vehicles over their lifetime. The primary difference from the 2012 report is that the set of case vehicles and time period for observed vehicle incidents is more recent, involving model year (MY) 2003-2010 vehicles in calendar year (CY) 2005-2011, versus MY2000-2007 vehicles in CY2002-2008 in the 2012 report. The most notable vehicle-specific factors for this analysis are curb weight and vehicle size (represented as footprint in the preferred model structure).

After controlling for driver-, crash- and other vehicle-specific factors including footprint, the logistic regression estimates percentage changes in societal fatalities as curb weight varies by 100 pounds. The logistic regressions in the analysis are applied to five vehicle classes: two passenger car classes, two LTV classes, and one class combining crossover (CUV) vehicles and minivans. In both the 2012 report and this analysis, the vehicle classes for passenger cars and

[M] Van Auken, R. M., and Zellner, J. W. (2003). A Further Assessment of the Effects of Vehicle Weight and Size Parameters on Fatality Risk in Model Year 1985-98 Passenger Cars and 1986-97 Light Trucks. Report No. DRI-TR-03-01. Torrance, CA: Dynamic Research, Inc.; Van Auken, R. M., and Zellner, J. W. (2005a). An Assessment of the Effects of Vehicle Weight and Size on Fatality Risk in 1985 to 1998 Model Year Passenger Cars and 1985 to 1997 Model Year Light Trucks and Vans. Paper No. 2005-01-1354. Warrendale, PA: Society of Automotive Engineers; Van Auken, R. M., and Zellner, J. W. (2005b). Supplemental Results on the Independent Effects of Curb Weight, Wheelbase, and Track on Fatality Risk in 1985-1998 Model Year Passenger Cars and 1986-97 Model Year LTVs. Report No. DRI-TR-05-01. Torrance, CA: Dynamic Research, Inc.; Van Auken, R.M., and Zellner, J. W. (2011).2012a). Updated Analysis of the Effects of Passenger Vehicle Size and Weight on Safety, Phase I. Report No. DRI-TR-11-01. (Docket No. NHTSA-2010-0152-0030). Torrance, CA: Dynamic Research, Inc.

LTVs are defined as the subsets of vehicles above and below the median curb weight in fatal crashes for a given group of vehicles (i.e., passenger cars or LTVs). Due to the increase in the weight of the LTV fleet, the median curb weights used to define LTV classes are notably higher than in the 2012 report, as detailed in Table 8.2

Table 8.2 Passenger Car and LTV Classes in the 2012 and 2016 Analyses

Vehicle Class	2012 Report	2016 Analysis	Difference in Median
Lighter Passenger Cars	< 3,106 pounds	< 3,197 pounds	91 pounds
Heavier Passenger Cars	3,106+ pounds	3,197+ pounds	91 pounds
Lighter LTVs	< 4,594 pounds	< 4,947 pounds	353 pounds
Heavier LTVs	4,594+ pounds	4,947+ pounds	353 pounds

The curb weight threshold defining passenger car classes in the update is only 91 pounds higher, while the curb weight threshold defining LTV classes in the update is 353 pounds higher, than the corresponding threshold in the 2012 report. The expected tendency of the influence of a heavier light truck fleet is to magnify estimated beneficial effects for mass reduction in those heavier LTVs, and to reduce estimated detrimental effects for lighter LTVs relative to the previous analysis.

The relatively short interval between the 2012 report and the update enables a generally direct comparison of findings between the two studies. However, there are at least two key empirical outcomes associated with the updated safety dataset that limit its comparability with the 2012 analysis. Firstly, CY2009-2011 data replace CY2002-2004 data within the sample. New vehicle registrations were below trend for CY2009-2011 (and hence, below corresponding levels in CY2002-2004). In turn, and in conjunction with general (improving) trends in vehicle safety, the number of fatal crashes in CY2009-2011 is about 25 percent lower than the number of crashes in CY2002-2004. Hence, the results of the analysis are calibrated with respect to a smaller number of fatal crashes, resulting in larger estimated standard errors and associated confidence bounds for the point estimates in the analysis.

Secondly, as noted in the 2012 report, light-duty trucks (LTVs) began increasing in mass around the year 2000; this trend did not appear to abate for MY2008-2010 LTVs. The heavier (relative to similar models from previous model years on or near 2000) LTVs comprised a relatively small share of the sample in the 2012 report, because relatively early-model vehicles comprise a much larger share of the observations in the database than late-model vehicles. However, the sample in the update involves not only a large share of relatively heavy LTVs in common with models in the 2012 report, but also MY2008-2010 vehicles that tend to be heavier than the MY2000-2002 vehicles no longer in the sample.

The analysis incorporates data from multiple sources required to represent fatalities, baseline driving risk (i.e., induced exposure), and VMT across distributions of driver-, crash- and vehicle-specific factors. The primary sources applied within the analysis are: the Fatality Analysis Reporting System (FARS), State crash records, IHS Automotive's (formerly R.L. Polk & Co.), National Vehicle Population Profiles (NVPP) and odometer readings, and a range of sources of values for curb weight, footprint, track width, wheelbase and other vehicle attributes.

FARS provides most of the information about fatal crashes needed for this study: the type of crash and number of fatalities, the vehicle identification number (VIN) of the vehicles involved, the age and gender of the driver(s), the time and location. The 2005-2011 FARS files contain 85,890 records of crash-involved vehicles of model years 2003-2010 with decodable VINs that can be assigned a model year, curb weight, and footprint, and identified as passenger cars or LTVs (pickup trucks, CUVs, truck-based SUVs and vans, excluding incomplete vehicles but including “300-series” pickups and vans with GVWR sometimes over 10,000 pounds). The set of FARS records in this analysis represents a decrease of around 24 percent relative to the 2012 analysis (113,248 records), due to both a general downward trend in fatalities and a decrease in new vehicle registrations beginning in 2009.

No single database has comparable detailed information on the number of total vehicles, their drivers, and their use, which is necessary to estimate exposure in order to compute fatality risk per VMT. The NVPP data count the number of vehicles of a given make-model and model year registered in any calendar year. The NVPP data specify the number of vehicles registered as of July 1 of every calendar year, and provide estimates of vehicle registrations by MY, CY, vehicle group, make-model, body style/truck type and, where needed, by State. NVPP data have no information, for example, on the age or gender of the drivers, or the annual VMT, or whether the vehicles were driven by day or at night. A file of odometer readings, also supplied by IHS Automotive was used to derive estimates of annual VMT by make and model.

Police-reported crash data from 13 states were used to develop the induced-exposure crashes; the state crash data provide information on not only the vehicles involved but also driver age and gender, urban/rural and other characteristics corresponding to the FARS data. Induced-exposure crashes are a subset of two-vehicle collisions where one vehicle can be identified as “culpable” and the other as "non-culpable.” The distribution of such vehicles within a particular area is believed to be an essentially random sample of driver and vehicle combinations travelling through that area. Accurate estimates of the curb weight and footprint of vehicles, as well as other attributes such as the presence of electronic stability control (ESC), antilock brake systems (ABS), and side or curtain air bags are assembled from several publications.

The State data represent a sample of 13 States that provide the VIN (all in common with the 2012 report): Alabama, Florida, Kansas, Kentucky, Maryland, Michigan, Missouri, Nebraska, New Jersey, Pennsylvania, Washington, Wisconsin and Wyoming. The State data include 2,255,398 records of induced-exposure cases, a decrease of around eight percent relative to the 2012 database (2,457,228 records), compared to a 24 percent decrease in FARS records relative to the 2012 database. The difference in sizes of the State and FARS data between the 2012 and 2016 reports indicate the presence of a larger decrease in the fatality rate than in the crash rate between the two samples.

The 85,890 records in the database of FARS fatal crash involvements come from all 50 States and the District of Columbia. Each of the 2,255,398 records on the database of induced-exposure crash involvements is nominally a specific crash involvement in one of 13 States, a discrete unit. But when each induced exposure record is weighted by its allocation of vehicle registrations or VMT, it becomes a cohort of vehicle registrations or VMT in the United States. The weighted induced-exposure records are a national census of model year 2003 to 2010 vehicle registrations and VMT in each calendar year. Fatal-crash records are weighted by the number of fatalities in the crash, including fatalities in the crash partner vehicle and any cyclists or pedestrians. After combining the FARS and induced exposure data, the sum of the fatalities in the fatal crashes divided by the sum of the VMT in the induced exposure crashes is the national fatality risk per mile driven, which serves as the dependent variable in the regression analyses.

The curb weight of passenger cars is formulated, as in previous reports, as a two-piece linear variable in order to estimate one effect of mass reduction in the lighter cars and another effect in the heavier cars. The boundary between “lighter” and “heavier” vehicles is itemized in Table 8.2 above. Curb weight is formulated as a simple linear variable for CUVs and minivans: because CUVs and minivans account for a relatively small share of new-vehicle sales, there are less crash data available than for cars or truck-based LTVs.

Footprint (in square feet) is represented in the model as the product of track width (the average track width at the front and rear wheels) and wheelbase. The control variables in the model include: indicators of whether an incident occurred at night, in a rural county, on roads with speed limits 55 miles per hour or above, and in States with relatively high fatality rates; indicators of whether a vehicle is equipped with ESC, anti-lock brakes, all-wheel drive, curtain airbags, curtain airbags that deploy in rollovers, torso airbags, combination airbags that provide torso and head protection, and light truck compatibility certification meeting Options 1 or 2; vehicle age at the time of incident; an indicator if the vehicle is new (i.e., MY=CY); eight gender-specific driver age categories; driver gender; and indicators of calendar year.

Separate logistic regressions were estimated for the three vehicle classes: passenger cars, LTVs, and CUVs/minivans. Within each class in the analysis, separate logistic regressions were estimated across nine sets of crash types, including: first-event rollovers; collisions with fixed objects, pedestrians/bicyclists/motorcyclists, heavy vehicles, passenger cars/CUVs/minivans lighter than 3,157 pounds, passenger cars/CUVs/minivans 3,157 pounds or heavier, LTVs lighter than 4,303 pounds, and LTVs 4,303 pounds or heavier; and all other crashes (mostly crashes involving three or more vehicles). A separate regression model was run for each of the nine crash types within each of the three vehicle types, for a total of 27 regression models.

Consistent with the definition of vehicle classes, the threshold weights for crash types involving passenger cars/CUVs/minivans and LTVs were defined in both the 2012 report and this analysis as the median curb weight for the other vehicle in a fatal collision. Similar to the changes to the mass thresholds defining vehicle classes in this analysis, the mass thresholds for crash types increased in the new analysis. The mass threshold for crashes with passenger cars/CUVs/minivans increased 75 pounds (from 3,082 pounds), and the mass threshold for crashes with LTVs increased 153 pounds (from 4,150 pounds). These increases are smaller than the corresponding increases in the thresholds for vehicle classes, due to the presence of MY2002 and earlier vehicles as partner vehicles in two-vehicle crashes.

For each vehicle class, a composite estimate of the change in societal fatality risk with respect to curb weight was identified by weighting the estimated coefficients on curb weight for a given crash type by the (adjusted) number of fatalities observed in the crash type for the vehicle class. The adjustment to the number of fatalities observed in a given crash type for a given vehicle class involves a downward revision to fatalities to take into account that the results will be used to analyze effects of mass reduction in future vehicles, which will all be equipped with electronic stability control (ESC), as required by NHTSA’s regulations. That is, although some vehicles in the database did not have ESC (and hence are more likely to be in a crash than ESC-equipped vehicles), all new vehicles are equipped with ESC; the lack of an adjustment would overstate the expected volume of fatalities that changes in curb weight could influence.

Table 8.3 presents the 2012 report's estimated percent increase in U.S. societal fatality rates per ten billion VMT for each 100-pound reduction in vehicle mass, while holding footprint constant, for each of the five vehicle classes:

Table 8.3 Results of 2012 NHTSA Final Report: Fatality Increase (%) per 100-Pound Mass Reduction While Holding Footprint Constant

MY2000-2007 CY 2002-2008	Fatality Increase (%) Per 100-Pound Mass Reduction While Holding Footprint Constant	
	Point Estimate	95% Confidence Bounds
Cars < 3,106 pounds	1.56	+ .39 to +2.73
Cars ≥ 3,106 pounds	.51	- .59 to +1.60
CUVs and minivans	- .37	-1.55 to + .81
Truck-based LTVs < 4,594 pounds	.52	- .45 to +1.48
Truck-based LTVs ≥ 4,594 pounds	- .34	-.97 to + .30

Table 8.4 presents the 2016 preliminary report's estimated percent increase in U.S. societal fatality risk per ten billion VMT for each 100-pound reduction in vehicle mass, while holding footprint constant, for each of the five classes of vehicles:

Table 8.4 Results of 2016 NHTSA Preliminary Report: Fatality Increase (%) per 100-Pound Mass Reduction While Holding Footprint Constant

MY2003-2010 CY 2005-2011	Fatality Increase (%) Per 100-Pound Mass Reduction While Holding Footprint Constant	
	Point Estimate	95% Confidence Bounds
Cars < 3,197 pounds	1.49	- .30 to +3.27
Cars ≥ 3,197 pounds	.50	- .59 to +1.60
CUVs and minivans	- .99	-2.17 to + .19
Truck-based LTVs < 4,947 pounds	-.10	- 1.08 to +.88
Truck-based LTVs ≥ 4,947 pounds	- .72	- 1.45 to + .02

The results indicate that societal fatalities per VMT would increase if the mass of passenger cars (the two lightest vehicle classes in the analysis by median weight) were reduced. Mass reduction in passenger cars below 3,197 pounds is estimated to increase societal fatality risk when holding footprint constant; a 100-pound reduction in curb weight is estimated to increase net fatalities by 1.49 percent. Mass reduction in passenger cars 3,197 pounds and above is estimated to increase societal fatality risk when holding footprint constant; a 100-pound reduction in curb weight is estimated to increase net fatalities by 0.50 percent.

Conversely, the results indicate that societal fatalities per VMT would decrease if the mass of LTVs, CUVs and minivans were reduced. Mass reduction in LTVs 4,947 pounds and above is estimated to decrease societal fatality risk when holding footprint constant; a 100-pound reduction in curb weight is estimated to reduce net fatalities by 0.72 percent. Likewise, mass reduction in CUVs and minivans (the second-heaviest vehicle class in the analysis by median weight) is estimated to decrease societal fatality risk when holding footprint constant; a 100-pound reduction in curb weight is estimated to reduce net fatalities by 0.99 percent. Mass reduction in LTVs below 4,947 pounds is estimated to decrease societal fatality risk only slightly when holding footprint constant; a 100-pound reduction in curb weight is estimated to decrease net fatalities by 0.10 percent.

None of the estimated effects is statistically significant at the 95-percent confidence level (i.e., the confidence bounds include both positive and negative values; the estimate for heavier LTVs is very close, however (statistically significant at the 94-percent confidence level). Three of the five estimated effects of mass reduction on societal fatalities are statistically significant at the 90-percent confidence level, for lighter passenger cars, heavier LTVs, and CUVs and minivans, indicating a strong likelihood that at least some of the estimated effects are significantly different from zero.

The principal difference between the results for heavier vehicles, especially truck-based LTVs, and lighter vehicles, especially passenger cars, is that mass reduction has a different effect in collisions with another light-duty vehicle in cars than in light trucks. When two vehicles of unequal mass collide, the change in velocity ("delta V") is higher in the lighter vehicle, in the same proportion as the mass ratio. As a result, all else being equal, the fatality risk in the lighter vehicle is also higher.

Removing some mass from the heavy vehicle reduces delta V in the lighter vehicle, where fatality risk is high, resulting in a large benefit, offset by a small penalty because delta V increases in the heavy vehicle, where fatality risk is low – adding up to a net societal benefit. Removing some mass from the lighter vehicle results in a large penalty offset by a small benefit – adding up to net harm. These considerations drive the overall result: mass reduction in lighter cars is associated with an increase in societal fatalities, mass reduction in the heavier LTVs is associated with a decrease in societal fatalities, and mass reduction in the intermediate classes has little effect.

It is useful to compare the results from the 2012 and 2016 reports (as detailed in Table 8.3and Table 8.4). In general, the point estimates from the updated analysis are consistent with the findings in the 2012 report. The ranges of the updated confidence bounds are similar size to the corresponding values in the 2012 report for heavier passenger cars (a range of 2.19 percent in both cases), lighter LTVs (1.96 percent in the updated analysis versus 1.93 percent in the 2012 report) and minivans (2.36 percent in both cases). This result may be unexpected, in light of the decreased sample size for fatal incidents in the update relative to the 2012 report (i.e., a smaller sample size tends to yield larger confidence bounds). The range of the confidence bound for lighter passenger cars is notably larger in the update (3.57 percent versus 2.34 percent), while the range of the confidence bound for heavier LTVs is only somewhat larger in the update (1.47 percent versus 1.27 percent).

The 2012 report presented one point estimate that was statistically significant at the 95-percent confidence level: the estimate for lighter passenger cars. The updated analysis yielded no point estimates that are significant at the 95-percent confidence level (the estimate for heavier LTVs was just short of this threshold). However, the updated analysis did yield three estimates that would be statistically significant at the 90-percent confidence level, compared to one estimate in the 2012 report: the estimates for lighter passenger cars, heavier LTVs, and CUVs and minivans. Hence, although the updated analysis indicates a greater level of uncertainty about the value of any given point estimate relative to the 2012 report (i.e., no estimated coefficients are significant at the 95-percent confidence level, versus one significant coefficient in the 2012 report), the updated analysis also indicates a greater level of certainty that at least some of the point estimates are of a particular sign (i.e., three estimated coefficients would be significant at the 90-percent confidence level, versus one in the 2012 report).

Two of the five updated point estimates are very close to the corresponding values in the 2012 report (the estimates for passenger car classes). This is consistent with the relatively small change in the definition of the two passenger car classes in the update (i.e., the updated threshold curb weight value is around 100 pounds heavier than in the 2012 report). Furthermore, the directionality of the changes in the point estimates for passenger cars are consistent with the change in the threshold curb weight value (i.e., mass reduction for a heavier group of vehicles should be more beneficial or less detrimental to society than for a lighter group of vehicles).

The updated point estimates for LTVs are distinct from the corresponding values in the 2012 report. The directionality of the changes in the point estimates for LTVs is consistent with the relatively large change in the threshold curb weight (around 350 pounds heavier in the update). While the 2012 report indicated that mass reduction of lighter LTVs would lead to an increase in net fatalities, the updated analysis indicates that, conditional on the observed increase in curb weight for LTVs in general, mass reduction of lighter LTVs would lead to a decrease in net fatalities. Likewise, the 2012 report indicated that mass reduction of heavier LTVs would lead to a decrease in net fatalities; the updated analysis indicates that, conditional on the observed increase in curb weight for LTVs in general, this relationship has become stronger.

The updated point estimates for CUVs and minivans are the most distinct from the corresponding values in the 2012 report, but still of the same sign. The directionality of the change in the point estimate for CUVs and minivans is consistent with a general increase in vehicle mass. However, there are factors limiting the inference one can draw from estimates in this vehicle class. Chiefly, the range of curb weights for minivans is relatively small, which may amplify the estimated impact of curb weight on fatality risk.

The estimates in Table 8.3 and Table 8.4 of the model are formulated for each 100-pound reduction in mass; in other words, if risk increases by 1 percent for 100 pounds reduction in mass, it would increase by 2 percent for a 200-pound reduction, and 3 percent for a 300-pound reduction. Confidence bounds around the point estimates will grow wider by the same proportions.

The regression results are best suited to predict the effect of a small change in mass, leaving all other factors, including footprint, the same. With each additional change from the current environment, the model may become somewhat less accurate and it is difficult to assess the sensitivity to additional mass reduction greater than 100 pounds. The agencies recognize that the light-duty vehicle fleet in the MYs 2022-2025 timeframe will be different from the MYs 2003-2010 fleet analyzed for this study. Nevertheless, one consideration provides some basis for confidence in applying the regression results to estimate the effects of mass reductions larger than 100 pounds or over longer time periods. This was NHTSA's fifth evaluation of the effects of mass reduction and/or downsizing, comprising databases ranging from MYs 1985 to 2010. The results of the five studies are not identical, but they have been consistent up to a point. During this time period, many makes and models have increased substantially in mass, sometimes as much as 30-40 percent.[N] If the statistical analysis has, over the past years, been

[N] For example, one of the most popular models of small 4-door sedans increased in curb weight from 1,939 pounds in MY 1985 to 2,766 pounds in MY 2007, a 43 percent increase. A high-sales mid-size sedan grew from 2,385 to 3,354 pounds (41%); a best-selling pickup truck from 3,390 to 4,742 pounds (40%) in the basic model with 2-door cab and rear-wheel drive; and a popular minivan from 2,940 to 3,862 pounds (31%).

able to accommodate mass increases of this magnitude, perhaps it will also succeed in modeling the effects of mass reductions on the order of 10-20 percent, if they occur in the future.

NHTSA's 2012 report acknowledged another source of uncertainty, namely that the baseline statistical model can be varied by choosing different control variables or redefining the vehicle classes or crash types, for example. Alternative models produce different point estimates. The principal comments on the preliminary version of the 2012 report were suggestions or demonstrations of other ways to analyze NHTSA's database, especially by Farmer and Green in their peer reviews, Van Auken (DRI) in his most recent analyses, and Wenzel in his assessment of NHTSA's report. The analyses and findings of Wenzel's and Van Auken's reports are summarized below. These reports, among other analyses, define and run specific alternative regression models to analyze NHTSA's 2012 databases.[O]

From these suggestions and demonstrations, NHTSA garnered 11 more or less plausible alternative techniques that could be construed as sensitivity tests of the baseline model; these alternative model structures were evaluated in the 2011, 2012 and 2016 reports.[P] The models use NHTSA's databases and regression-analysis approach, but differ from the baseline model in one or more terms or assumptions. All of them try to control for fundamentally the same driver, vehicle, and crash factors, but differ in how they define these factors or how much detail or emphasis they provide for some of them. NHTSA applied the 11 techniques to the latest databases to generate alternative estimates of the societal effect of 100-pound mass reductions in the five classes of vehicles. The range of estimates produced by the sensitivity tests gives an idea of the uncertainty inherent in the formulation of the models, subject to the caveat that these 11 tests are, of course, not an exhaustive list of conceivable alternatives.

Each model in the sensitivity analysis estimates fatality rates as a function of curb weight, vehicle size, driver-specific attributes and incident-specific attributes. The baseline model represents vehicle size in terms of footprint (i.e., the product of wheelbase and track width, measured in square feet), and is calibrated with respect to FARS data (the fatal outcomes in the logistic regressions) and induced exposure data incorporating non-culpable incidents across a sample of 13 states; the FARS data are a census of fatal incidents, while the induced exposure data are weighted to represent all VMT for each make-model-model year combination in each calendar year in the sample.

One alternative model represents induced exposure through the subset of non-culpable cases in the sample involving stopped vehicles (referred to here as the stopped vehicle model). This alternative was proposed under the hypothesis that restricting the analysis to stopped vehicles would minimize any bias due to uncertainty regarding which driver was at fault in the two-vehicle crash, and improve the degree to which the induced exposure data represent baseline accident risk. Furthermore, DRI assumed that the set of non-culpable incidents may induce bias because relatively skilled drivers may be more likely to avoid crashes altogether, and hence relatively skilled drivers would be under-represented. If this bias is present, the resulting estimates would over-represent the behavior of relatively unskilled drivers.

[O] Wenzel (2012a), Van Auken and Zellner (2012b, 2012c, 2012d).

[P] See Kahane (2012), pp. 14-16 and 109-128 for a further discussion of the alternative models and the rationales behind them.

The other alternative model represents vehicle size in terms of track width and wheelbase separately (referred to here as the split footprint model). DRI proposed this alternative under the hypothesis that vehicle size could be accounted for independently of curb weight more effectively by representing distinct effects of track width (e.g., rollover resistance) and wheelbase (e.g., crush space in frontal impacts). This alternative can be applied using either the baseline induced exposure data (as represented in the analytical results below), or combined with the application of stopped vehicle data.

The sensitivity analyses examined the stopped vehicle and split footprint alternatives to re-evaluate the limitations of the alternatives that were raised in the 2012 report, to confirm whether the limitations still apply. The primary limitations of the stopped vehicle model raised in the 2012 report that apply to the data in the 2016 report are:

- Restricting the analysis to stopped vehicles results in a serious loss of sample size;
- The stopped vehicle cases represent the distribution of driver age disproportionately;
- The stopped vehicle cases represent the share of incidents on roads with speed limits 55 miles per hour or above disproportionately; and
- Comments from previous (1999 and 2003) peer review support the use of the baseline model over the stopped vehicle model.

Each of the above limitations applies to the analysis in the 2016 report. Restricting the analysis to stopped vehicles results in a loss of approximately three-fourths of observations in the sample; estimates calibrated with respect to a restricted sample size are subject to greater uncertainty (i.e., larger confidence bounds) than those calibrated with respect to a larger set of data. The stopped vehicle database includes 670,230 observations, which is a large dataset by general standards. However, driver-, crash- and vehicle-specific factors explain such a large share of variability in fatality rates that it is preferable to preserve sample size in an effort to estimate effects specific to curb weight and vehicle size, all else being equal.

Consistent with the 2012 report, the stopped vehicle data in the 2016 report represent drivers with ages associated with lower risk (i.e., drivers between 30 and 60 years of age) at a higher rate than the non-culpable data, and conversely represent drivers with ages associated with higher risk (chiefly, drivers below the age of 30) at a lower rate than the non-culpable data. Similarly, as in the 2012 report, the stopped vehicle data include a smaller share of incidents: on roads with speed limits of 55 miles per hour or above; on rural roads; at night; and involving male drivers.

However, the non-culpable data are constrained by the relative accuracy of police identification of at-fault drivers. If the non-culpable cases actually include a sufficient share of culpable cases, the data would not meaningfully represent baseline risk. Hence, the findings of analysis calibrated with respect to the non-culpable data are strictly conditional on the validity of the assignment of culpability. Peer review indicated two conflicting views: (1) that stopped vehicle data under-represent risky drivers because risky drivers do not stay stopped long enough to be involved in collisions; and (2) that non-culpable vehicle data over-represent drivers because safe drivers avoid incidents more frequently. It is not clear whether the non-culpable vehicle sample or the stopped vehicle sample better represents the overall distribution of drivers and vehicles on the nation’s roadways, and therefore which sample is more appropriate to use to create the induced exposure records.

Peer review comments on the preliminary version of the 2012 report suggested that a suitable representation of induced exposure would involve distributions of VMT by vehicle-, crash- and driver-specific factors that represent the population of drivers and vehicles on the road at any given time.

The limitations of the split footprint model raised in the 2012 report that apply to the data in the 2016 report are:

- Track width and wheelbase are generally highly correlated with one another and with curb weight for the range of vehicles in the analysis, raising the threat of multicollinearity;
- The CAFE model is footprint-based, and hence working directly with footprint is preferable to decomposing it; and
- While the estimated relationship between track width and fatality risk in certain types of crashes is consistent with crash physics, the relationship between wheelbase and fatality risk is not.

The threat of multicollinearity can be evaluated in a direct manner by comparing correlations among model inputs. Multicollinearity is a significant concern even in the baseline model, through strong correlations between curb weight and footprint; correlations within vehicle classes range from around 0.73 to 0.89, (with the exceptions of correlations of around 0.24 for large pickups and 0.49 for minivans when examined separately from other LTVs and CUVs, respectively).

Critically, for all vehicle classes in the analysis, curb weight is correlated either nearly as high or higher with track width as with footprint and track width and wheelbase are also highly correlated with one another (ranging from around 0.64 to 0.80, with the exceptions of smaller correlations for large pickups and minivans). Viewed from another angle, wheelbase is almost perfectly correlated with footprint (with correlations ranging from around 0.95 to 0.97).

Considered in concert, the split footprint model essentially incorporates the full correlation issues from the baseline model (curb weight highly correlated with another independent variable) and adds a further correlation issue (the variable that is highly correlated with curb weight is also highly correlated with a separate independent variable). Ultimately, it is difficult to support the preference of a model with two correlated independent variables representing vehicle size when a single variable (footprint) tracks the two variables closely. The ability of the model to tease out separate, representative effects for three highly correlated variables is questionable; what may appear to be a distinct effect once two dimensions of vehicle size are accounted for may in fact be an artifact of unfortunate statistical properties.

In the 2016 NHTSA baseline model, a one-inch reduction in track width is associated with increases in rollover fatality risks, as expected: a 30 percent increase in rollover fatality risk in cars, and an 8 percent increase in rollover fatality risk in light trucks and CUVs/minivans. However, a one-inch reduction in wheelbase is not consistently associated with large increases in fatality risks in crashes with objects or other light-duty vehicles. This may be because wheelbase is not as good a proxy for frontal crush space, as say frontal overhang[Q] in frontal impacts; and because a large fraction of fatalities in two-vehicle crashes are not frontal impacts that would be

[Q] Frontal overhang is the distance from the front of the front bumper to the front wheel axle.

influenced by wheelbase or frontal overhang (i.e. they are the result of side impacts). So the regression coefficients for track width are consistent with crash theory, while the coefficients for wheelbase are not, possibly because they are masked by other types of crashes in which frontal crush space is not expected to protect occupants.

Table 8.5 shows the baseline and alternative results, ordered from the lowest to the highest estimated increase in societal risk for cars weighing less than 3,197 pounds:

Table 8.5 Societal Fatality Increase (%) Per 100-Pound Mass Reduction While Holding Footprint* Constant

		Cars < 3,197	Cars ≥ 3,197	CUVs & Minivans	LTVs† < 4,947	LTVs† ≥ 4,947
Baseline estimate		**1.49**	**.50**	**- .99**	**-.10**	**- .72**
95% confidence bounds (sampling error)	Lower:	- .30	- .59	-2.17	-1.08	-1.45
	Upper:	3.27	1.60	.19	.88	.02
11 Alternative Models						
1. W/O CY control variables		.53	.10	-1.13	- .10	- .53
2. Track width/wheelbase w. stopped vehicle data		.88	- .43	- .66	- .85	-2.14
3. By track width & wheelbase		.92	.48	-1.15	- .66	- .97
4. Incl. muscle/police/AWD cars/big vans		1.44	.63	- .99	- .05	- .94
5. W/O non-significant control variables		1.47	.54	- .84	- .13	- .70
6. CUVs/minivans weighted by 2010 sales		1.49	.50	- .27	- .10	- .72
7. With stopped-vehicle data		1.58	- .43	- .61	- .07	-1.80
8. Limited to drivers with BAC=0		2.22	1.38	- .92	.31	- .91
9. Control for vehicle manufacturer		2.39	1.37	.00	.32	- .09
10. Control for vehicle manufacturer/nameplate		2.65	2.96	- .43	.30	.00
11. Limited to good drivers‡		2.82	1.86	- .97	.37	- .62

Notes:

*While holding track width and wheelbase constant in alternative model nos. 1 and 3.

†Excluding CUVs and minivans.

‡Blood alcohol content=0, no drugs, valid license, at most 1 crash and 1 violation during the past 3 years.

For example, in cars weighing less than 3,197 pounds, there are an equal number of models with estimated effects of 100-pound mass reduction above and below the baseline value, a 1.49 percent increase in societal fatalities. The estimates range from a relatively small increase of 0.53 percent in the first alternative model up to a 2.82 percent increase in the last model, nearly double the baseline effect. Each of the 11 alternative point estimates for cars < 3,197 pounds is within the range of the 95 percent sampling-error confidence bounds for the baseline estimate: -0.30 to 3.27 percent.

The sensitivity tests illustrate both the fragility and the robustness of the baseline estimate. On the one hand, the variation among the alternative estimates is quite large relative to the baseline estimate: in the preceding example of cars < 3,197 pounds, from approximately one-third of the baseline value to almost double the baseline. In fact, the difference in estimates is a reflection of the small statistical effect that mass reduction has on societal risk, relative to other factors. Thus, sensitivity tests which vary vehicle, driver, and crash factors can appreciably change the estimate of the effect of mass reduction on societal risk in relative terms.

On the other hand, the variations are not all that large in absolute terms. The ranges of the alternative estimates, at least these alternatives, are about as wide as the sampling-error confidence bounds for the baseline estimates. As a general rule, in the alternative models, as in the baseline models, mass reduction tends to be relatively more harmful in the lighter vehicles, and more beneficial in the heavier vehicles. Thus, in all models, the estimated effect of mass reduction is a societal fatality increase for cars < 3,197 pounds, and in all models except one, a societal fatality reduction for LTVs ≥ 4,947 pounds. None of these models suggest mass reduction in small cars would be beneficial. All suggest mass reduction in heavy LTVs would be beneficial or, at least, close to neutral. In general, any judicious combination of mass reductions that maintain footprint and are proportionately higher in the heavier vehicles is unlikely to have a societal effect large enough to be detected by statistical analyses of crash data. NHTSA conducted a sensitivity analysis to estimate the fatality impact of the alternative models using the coefficients for these 11 test cases. The results for these sensitivity runs can be found in Table 4-2 of NHTSA's 2016 preliminary report. The discussion of the 2016 preliminary report concludes with a review of the limitations of the analysis, and corresponding implications for the interpretation and application of the results. The presence of non-significant results in this analysis is not due to a paucity of data (except, perhaps, the paucity of very small or very light cars and LTVs during MY2003-2010) or other weaknesses in the data, but because the societal effect of mass reduction while maintaining footprint, if any, is small. By contrast, statistical analyses of the effect of mass reduction allowing historically commensurate reductions of footprint (downsizing) show larger, statistically significant increases in fatality risk in passenger cars (see Alternative regression model 6 in Table 8.6 from the 2016 LBNL Phase2 study presented in the following sub-sections).

The composite effects are limited in significance, with estimated effects for three of five vehicle classes significant at the 90-percent confidence level. However, this does not indicate that the non-significant estimated composite effects should be ignored. We include and apply non-significant estimates because the regulatory analysis must provide the best estimate of the expected effect of mass reduction. Our best estimate is the estimated composite effect (i.e., an estimate of zero would be a worse fit to the data); the confidence bounds serve to indicate the range of uncertainty. One reason that the regulatory analysis must have such estimates is that it, too, is ultimately an intermediate computational tool in estimating the overall health and societal impact of CAFE and GHG regulation.

The estimates of this report are based on statistical analyses of historical data, which puts some limitations on their value for predicting the effects of future mass reductions. Analyses of historical data necessarily lag behind the latest developments in vehicles and in driving patterns because it takes years for sufficient crash data to accumulate. It is important to note that while the MY2003-2010 database represents more modern vehicles with technologies more representative of vehicles on the road today than previous reports, it still does not represent the newer vehicles that will be on the road in the 2022-2025 timeframe. The vehicles manufactured in the 2003-2010 timeframe were not subject to a footprint-based fuel-economy standard; vehicles actually became heavier on the average, not lighter during MY2003-2010 and when they became heavier it was commonly to provide additional features. NHTSA and EPA expect that the attribute-based standard will affect the design of vehicles such that manufacturers may reduce mass while maintaining footprint more than has occurred prior to model year 2010.

Therefore, it is possible that the analysis for 2003-2010 vehicles may not be fully representative of those vehicles that interact with the existing fleet in 2022 and beyond.

Statistical analyses can control for many factors such as a driver's age and gender, but there are other factors they do not control for, such as driver characteristics that cannot be quantified with available demographic variables or unobserved factors relating to how a particular vehicle was being driven at the time the crash occurred (e.g., travel speed, attention). Furthermore, the analyses of this report are "cross-sectional": they compare the fatality rates for vehicles weighing 100 pounds less than other models in the same vehicle class, rather than directly comparing the fatality rates for a specific make and model before and after a mass reduction had been implemented for the purpose of improving fuel economy. After substantial materials substitution has become more widespread, it may become feasible to improve the ability to directly compare the effects of mass reductions at the vehicle-model level. However, such models would still be limited in their ability to represent other design changes that influence fatalities beyond mass reduction.

8.2.4.6 Report by Tom Wenzel, LBNL, "An Assessment of NHTSA's Report 'Relationships between Fatality Risk, Mass, and Footprint in Model Year 2003-2010 Passenger Cars and LTVs,'" 2016

DOE contracted with Tom Wenzel of Lawrence Berkeley National Laboratory to conduct an assessment of NHTSA's updated 2016 study of the effect of mass and footprint reductions on U.S. fatality risk per vehicle miles traveled (LBNL 2016 "Phase 1" preliminary report), and to provide an analysis of the effect of mass and footprint reduction on casualty risk per police-reported crash, using independent data from thirteen states (LBNL 2016 "Phase 2" preliminary report). Both reports will be reviewed by NHTSA, EPA, and DOE staff, as well as by a panel of reviewers.[R] The final versions of the reports will reflect responses to comments made in the formal review process, as well as changes made to the VMT weights developed by NHTSA for the final rule, and inclusion of 2012 data for 13 states that were not available for the analyses in the preliminary versions included in the NPRM docket.

The 2016 LBNL Phase 1 report[27] replicates Volpe's 2016 analysis for NHTSA, using the same data and methods, and in many cases using the same SAS programs, in order to confirm NHTSA's results. The LBNL report confirms NHTSA's 2016 finding that, holding footprint constant, each 100-lbs of mass reduction is associated with a 1.49 percent increase in fatality risk per vehicle miles travelled (VMT) for cars weighing less than 3,197 pounds, a 0.50 percent increase for cars weighing more than 3,197 pounds, a 0.10 percent decrease in risk for light trucks weighing less than 4,947 pounds, a 0.71 percent decrease in risk for light trucks weighing more than 4,947 pounds, and a 0.99 percent decrease in risk for CUVs/minivans.[S] Holding mass constant, each square foot reduction in vehicle footprint is associated with a 0.28 percent

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[R] EPA sponsored the peer review of the LBNL 2011 Preliminary Phase 1 and 2 Reports.

[S] Only the changes in fatality risk for lighter cars, heavier trucks, and CUVs/minivans are statistically significant at the 95% significance level using the standard errors output by SAS. The relationship between mass reduction and fatality risk for these three vehicle types also is statistically significant at the 90% level of significance based on NHTSA's estimate of uncertainty using a jack knife method; none of the estimates are statistically significant at the 95% level of significance based on NHTSA's jack knife uncertainty method.

increase in risk in cars, a 0.38 percent increase in light trucks, and a 1.18 percent increase in CUVs/minivans.[T] Wenzel tested the sensitivity of these estimates to changes in the measure of risk and the control variables and data used in the regression models. Wenzel also concluded that there is a wide range in fatality risk by vehicle model for models that have comparable mass or footprint, even after accounting for differences in drivers' age and gender, safety features installed, and crash times and locations. This section summarizes the results of the 2016 Wenzel assessment of the 2016 NHTSA preliminary analysis.

The 2016 LBNL Phase 1 report notes that many of the control variables NHTSA includes in its logistic regressions are statistically significant, and have a much larger estimated effect on fatality risk than vehicle mass. For example, installing torso side airbags, electronic stability control, or an antilock braking system in a car is estimated to reduce fatality risk by at least 7 percent; cars driven by men are estimated to have a 40 percent higher fatality risk than cars driven by women; and cars driven at night, on rural roads, or on roads with a speed limit higher than 55 mph are estimated to have a fatality risk over 100 times higher than cars driven during the daytime on low-speed non-rural roads. While the estimated effect of mass reduction may result in a statistically-significant increase in risk in certain cases, the increase is small and is overwhelmed by other known vehicle, driver, and crash factors.

As was true in 2012, NHTSA in 2015 notes these findings are additional evidence that estimating the effect of mass reduction is a complex statistical problem, given the presence of other factors that could have large effects. The preceding examples are limited to technologies emerging in the 2005-2011 timeframe but that will be in all model year 2017-2025 vehicles (side airbags, electronic stability control) or factors that are simply unchangeable circumstances in the crash environment outside the control of CAFE or other vehicle regulations (for example, that about half of the drivers are males and that much driving is at night or on rural roads).

LBNL tested the sensitivity of the NHTSA estimates of the relationship between vehicle weight and risk using 33 different regression analyses that changed the measure of risk, the control variables used, or the data used in the regression models. LBNL analyzed alternative models 1 through 19 in its 2012 assessment of the NHTSA 2012 report; the results from these models using data updated through 2011 are shown in Table 8.6. Table 8.6 also shows the results of the 14 new alternative regression models LBNL conducted as part of its 2016 assessment. Models 20 through 23 explore two changes to how light trucks are classified: excluding light trucks with a GVWR rating over 10k pounds, and treating small (1/2-ton capacity) pickups and SUVs as a separate class distinct from large (3/4- and 1-ton capacity) pickups. As noted in the Table 8.6 footnotes, the median weight was recalculated for each alternative truck category. Models 24 through 27 test the sensitivity to which cars are included; Models 28 through 30 add a two-piece variable for CUV/minivan curb weight, based on the median CUV/minivan curb weight, as was done for cars and light trucks in the NHTSA baseline model; and two-piece variables for footprint for all vehicle types, based on the median footprint by vehicle type. Finally, Models 31 to 33 replace NHTSA's VMT weights with weights developed from annual odometer readings in Texas.

[T] Based on the standard errors output by SAS, only the increases in risk from footprint reduction in light trucks and CUVs/minivans are statistically significant at the 95% confidence level.

Table 8.6 Societal Fatality Increase (%) Per 100-Pound Mass Reduction While Holding Footprint* Constant from Wenzel Study

Regression model	Cars <3,197 lbs	Cars ≥3,197 lbs	Light trucks[1] <4,947 lbs	Light trucks[1] ≥4,947 lbs	CUV/ minivan
Baseline model	1.49%	0.50%	-0.10%	-0.71%	-0.99%
1.Weighted by current distribution of fatalities	1.37%	0.46%	-0.13%	-0.56%	-1.30%
2.Single regression model across all crash types	1.36%	0.46%	-0.13%	-0.56%	-1.31%
3.Fatal crashes per VMT	1.67%	0.58%	-0.02%	-0.72%	-1.28%
4.Fatalities per induced exposure crash	1.14%	-0.85%	-1.66%	-1.06%	-0.16%
5.Fatalities per registered vehicle-year	1.45%	2.90%	-0.56%	-1.24%	-0.42%
6.Allow footprint to vary with mass[2]	1.71%	0.68%	0.26%	-0.55%	-0.25%
7.Account for 14 vehicle manufacturers	2.39%	1.37%	0.32%	-0.09%	0.00%
8.Account for 14 manufacturers + 5 luxury brands	2.65%	2.96%	0.30%	0.00%	-0.43%
9.Account for initial vehicle purchase price	1.42%	0.70%	-0.39%	-0.99%	-1.65%
10.Exclude CY variables	0.53%	0.10%	-0.10%	-0.52%	-1.13%
11.Exclude crashes with alcohol/drugs	2.08%	1.09%	0.21%	-0.83%	-1.01%
12.Exclude crashes with alcohol/drugs, and bad drivers	2.72%	1.57%	0.42%	-0.55%	-1.00%
13.Account for median household income	1.42%	-0.11%	-0.08%	-0.62%	-1.43%
14.Include sports, police, and AWD cars, and full vans	1.44%	0.62%	-0.05%	-0.94%	-0.99%
15.Use stopped instead of non-culpable vehicles	1.58%	-0.42%	-0.09%	-1.80%	-0.61%
16.Replace footprint with track width & wheelbase	0.93%	0.48%	-0.66%	-0.97%	-1.15%
17.Above two models combined (15 & 16)	0.88%	-0.43%	-0.85%	-2.13%	-0.66%
18.Reweight CUV/minivans by 2010 sales	1.49%	0.50%	-0.10%	-0.71%	-0.27%
19.Exclude non-significant control variables	1.47%	0.54%	-0.13%	-0.70%	-0.84%
20.Exclude LTs over 10k GVWR[3]	1.49%	0.50%	0.06%	-0.80%	-0.99%
21.Small pickups and SUVs only[3]	1.49%	0.50%	-0.01%	-0.24%	-0.99%
22.Large pickups only[3]	1.49%	0.50%	-4.27%	0.52%	-0.99%
23.Large pickups only, exclude those > 10k GVWR[3] (20 & 22)	1.49%	0.50%	-6.49%	1.31%	-0.99%
24. Include AWD, but not muscle or police, cars	1.29%	0.77%	-0.10%	-0.71%	-0.99%
25. Include muscle and police, but not AWD, cars	1.66%	0.40%	-0.10%	-0.71%	-0.99%
26. Exclude 3 high-risk car models	1.38%	0.29%	-0.10%	-0.71%	-0.99%
27. Include AWD cars, exclude 3 high-risk car models (24 & 26)	1.15%	0.53%	-0.10%	-0.71%	-0.99%
28. 2-piece variable for CUV weight[4]	1.49%	0.50%	-0.10%	-0.71%	-0.31% -1.21%
29. 2-piece variable for PC and LT footprint[5]	1.31%	0.72%	-0.75%	-0.89%	-1.07%
30. 2-piece variable for weight and for footprint[4,5] (28 & 29)	1.31%	0.72%	-0.75%	-0.89%	-0.20% -1.21%
31. Remove kinks in NHTSA VMT schedules	1.47%	0.49%	-0.10%	-0.72%	-0.99%
32. Use Texas rather than Polk odometer ratios	1.21%	0.15%	-0.25%	-0.87%	-0.99%
33. Both adjustments to NHTSA VMT (31 and 32)	1.19%	0.13%	-0.26%	-0.87%	-1.00%

Notes:

Red font indicates estimate is statistically significant at 95% confidence interval.

Gray shading indicates estimate is not changed from baseline regression model in alternative regression model.

[1] Light trucks includes pickups and truck-based SUVs, and excludes car-based CUVs and minivans.

[2] In model 6 footprint is allowed to vary with mass.

[3] The median mass used for Models 20-23 is: 4,870 pounds for Model 20; 4,704 pounds for Model 21; 6,108 pounds for Model 22; and 6,062 pounds for Model 23.

[4] The median mass for CUVs/minivans used for Models 28 and 30 is 3,939 pounds.

[5] The median footprints used for Models 29 and 30 are 44.3 square feet for cars, 56.9 square feet for light trucks, and 49.0 square feet for CUVs/minivans.

Table 8.6 indicates that, for cars < 3,197 pounds, all alternative models estimate that mass reduction is associated with an increase in societal fatality risk, ranging from a 0.53 percent increase (Model 10) to a 2.72 percent increase (Model 12). 19 of the 33 alternative models estimate a smaller increase in risk, and 8 estimate a larger increase in risk, than the NHTSA baseline model (the remaining 6 alternative models, shaded in grey in Table 8.6, do not make changes to the regression model for cars). For cars ≥ 3,197 pounds, all but four of the alternative models estimate that mass reduction is associated with an increase in societal fatality risk, ranging from a 0.85 percent decrease (Model 4) to a 2.96 percent increase (Model 8). 13 of the 33 alternative models estimate a smaller increase, or a decrease, in risk, and 14 estimate a larger increase in risk, than the NHTSA baseline model (six alternative models do not make changes to the regression model for cars).

For light trucks < 4,947 pounds, Table 8.6 indicates that only six of the 31 applicable alternative models[U] estimate that mass reduction is associated with an increase in fatality risk: ranging from a 1.66 percent decrease in risk (Model 4) to a 0.42 percent increase in risk (Model 12). 12 of the 31 applicable alternative models estimate a larger decrease in risk, 11 estimate a smaller decrease, or an increase, in risk, and two estimate the same change in risk, compared to the NHTSA baseline model (six alternative models do not make changes to the regression model for light trucks). In the two models restricted to analyses of large pickups, mass reductions in large pickups < 6,108 pounds (Model 22) and < 6,062 pounds (Model 23) are associated with decreases in fatality risk an order of magnitude larger than in the baseline NHTSA model (4.3 percent and 6.5 percent decreases in risk, respectively). The classification of relatively light (i.e., below the median) trucks in Models 22 and 23 is distinct to the classification of relatively light trucks in the other models; NHTSA advises caution in the interpretation and comparison of estimates in Models 22 and 23 with other models.

For light trucks ≥ 4,947 pounds, none of the 31 applicable alternative models[V] estimate that mass reduction is associated with an increase in fatality risk, and range from a 2.13 percent decrease in risk (Model 17) to no change in risk (Model 8). 15 of the 31 applicable alternative models estimate a larger decrease in risk, 9 estimate a smaller decrease in risk, and one no change in risk, compared to the NHTSA baseline model (six alternative models do not make changes to the regression model for light trucks). In the two models restricted to analyses of large pickups, mass reductions in large pickups ≥ 6,108 pounds (Model 22) and ≥ 6,062 pounds (Model 23) are associated with increases in fatality risk (of 0.52 percent and 1.31 percent, respectively), compared to the decrease in the baseline model. The classification of relatively heavy (i.e., above the median) trucks in Models 22 and 23 is distinct to the classification of

[U] Not including Models 22 and 23, which apply to large pickups only, and use much higher median weights (6,108 and 6,062 pounds, respectively) to define lighter and heavier large pickups than in the baseline model.

[V] Not including Models 22 and 23, which apply to large pickups only, and use much higher median weights (6,108 and 6,062 pounds, respectively) to define lighter and heavier large pickups than in the baseline model.

relatively heavy trucks in the other models; as before, NHTSA advises caution in the interpretation and comparison of estimates in Models 22 and 23 with other models.

For CUVs/minivans, all but one of the 31 applicable alternative models[W] estimate that mass reduction is associated with a decrease in fatality risk, and range from a 1.65 percent decrease in risk (Model 9) to no change in risk (Model 7). 11 of the 31 applicable alternative models estimate a larger decrease in risk, and nine estimate a smaller decrease in risk, and two estimate no change in risk, than the NHTSA baseline model (9 alternative models do not make changes to the regression model for CUVs/minivans). In the two models that estimate the effect of mass reduction on risk separately for lighter- and heavier-than-average CUVs/minivans, mass reduction in lighter (< 3,939 pounds) CUVs/minivans is associated with smaller decreases in fatality risk (0.31 percent and 0.20 percent decreases in Models 28 and 30, respectively) than mass reduction in heavier (≥ 3,939 pounds) CUVs/minivans (1.21 percent decrease in both models).

LBNL noted that if the relationship between mass reduction and societal fatality risk is strong, one would expect to observe a relatively low sensitivity of estimated effects from NHTSA's baseline model when substituting alternative induced exposure data, excluding certain cases, and including supplementary independent variables. However this is not the case; the baseline results can be sensitive, especially for cars, to changes in the variables and data used. For instance, accounting for vehicle manufacturer (Model 8), or removing crashes involving alcohol, drugs, or bad drivers (Model 12), substantially increases the detrimental effect of mass reduction in cars on risk. On the other hand, the DRI measures (using stopped instead of non-culpable vehicles and replacing footprint with wheelbase and track width, Model 17), including AWD cars but excluding three high-risk sporty compact cars (Model 27), and using VMT weights based on Texas odometer data (Model 33) substantially decreases the detrimental effect of mass reduction in cars on risk.

The differences among the point estimates of the alternative regression models in Table 8.6 are within the uncertainty bounds NHTSA estimated using a jack knife method. However, because the Volpe model uses the point estimates, and not the uncertainty bounds, using the estimates from one of the alternative models could result in large changes in the estimated change in fatalities from mass reduction. For example, if NHTSA used the estimated relationship between mass reduction for lighter cars and societal fatality risk from Model 17 (0.88 percent reduction) rather than the estimate from the baseline model (1.49 percent), the Volpe model would enable manufacturers to make much larger reductions in mass without compromising safety.

Using two or more variables that are strongly correlated in the same regression model (referred to as multicollinearity) can lead to inaccurate results. However, the correlation between vehicle mass and footprint may not be strong enough to cause serious concern. The Pearson correlation coefficient r between vehicle mass and footprint ranges from 0.95 for four-door sedans and SUVs, to 0.19 for minivans.[X] The variance inflation factor (VIF) is a more formal measure of multicollinearity of variables included in a regression model. Allison[28] "begins to get

[W] Not including Models 28 and 30, which estimate the effect of mass reduction on risk separately for lighter (< 3,939 pounds) and heavier (≥ 3,939 pounds) CUVs/minivans.

[X] Removing one minivan model, the Kia Sedona, improves the correlation for minivans to 0.50

concerned" with VIF values greater than 2.5, while Menard[29] suggests that a VIF greater than 5 is a "cause for concern," while a VIF greater than 10 "almost certainly indicates a serious collinearity problem;" however, O'Brien[30] suggests that "values of VIF of 10, 20, 40 or even higher do not, by themselves, discount the results of regression analyses." When both weight and footprint are included in the regression models, the highest VIF associated with any variable exceeds 5 for four-door cars, small pickups, SUVs, and CUVs, exceeds 2.5 for two-door cars and minivans, and is 1.5 for large pickups. NHTSA included several analyses to address possible effects of the near-multicollinearity between mass and footprint.

First, NHTSA ran a sensitivity case where footprint is not held constant, but rather allowed to vary as mass varies (i.e., NHTSA ran a regression model which includes mass but not footprint); this is Model 6 in Table 8.6.[Y] If the multicollinearity was so great that including both variables in the same model gave misleading results, removing footprint from the model would give much different results than keeping it in the model. NHTSA's sensitivity test estimates that when footprint is allowed to vary with mass, the effect of mass reduction on risk increases for all vehicles types: from a 1.49 percent increase to a 1.71 percent increase for lighter cars, and from a 0.50 percent increase to a 0.68 percent increase for heavier cars; from a 0.10 percent decrease to a 0.26 percent increase for lighter light trucks, and from a 0.71 percent decrease to a 0.55 percent decrease for heavier light trucks; and from a 0.99 percent decrease to a 0.25 percent decrease for CUVs and minivans.

Second, NHTSA conducted a stratification analysis of the effect of mass reduction on risk by dividing vehicles into deciles based on their footprint, and running a separate regression model for each vehicle and crash type, for each footprint decile (3 vehicle types times 9 crash types times 10 deciles equals 270 regressions).[Z] This analysis estimates the effect of mass reduction on risk separately for vehicles with similar footprint. The analysis indicates that reducing vehicle mass does not consistently increase risk across all footprint deciles for any combination of vehicle type and crash type. Risk increases with decreasing mass in a majority of footprint deciles for 12 of the 27 crash and vehicle combinations, but few of these increases are statistically significant. On the other hand, risk decreases with decreasing mass in a majority of footprint deciles for 5 of the 27 crash and vehicle combinations; in some cases these risk reductions are large and statistically significant.[AA] If reducing vehicle mass while maintaining footprint inherently leads to an increase in risk, the coefficients on mass reduction should be more consistently positive, and with a larger R2, across the 27 vehicle/crash combinations, than shown in the analysis. These findings are consistent with the conclusion of the basic regression analyses; namely, that the effect of mass reduction while holding footprint constant, if any, is small.

LBNL noted that one limitation of using logistic regression to estimate the effect of mass reduction on risk is that a standard statistic to measure the extent to which the variables in the model explain the range in risk, equivalent to the R2 statistic in a linear regression model, does not exist. (SAS does generate a pseudo-R2 value for logistic regression models; in almost all of the NHTSA regression models this value is less than 0.10). For this reason LBNL conducted an

[Y] Kahane (2012), pp. 93-94.
[Z] Ibid., pp. 73-78.
[AA] And in 10 of the 27 crash and vehicle combinations, risk increased in 5 deciles and decreased in 5 deciles with decreasing vehicle mass.

analysis of risk versus mass by vehicle model, for 246 models with at least 10 billion VMT, or at least 100 fatalities (90 car models, 113 light truck models, and 43 CUV/minivan models); these 246 models represent nearly 90 percent of all fatalities, vehicle registration-years, and VMT. Figure 8.1 shows the relationship between vehicle mass and actual, or unadjusted, societal risk per VMT, by vehicle type and model; the curb weight for each model is averaged over model years 2003 to 2010. For most vehicle types, risk decreases as mass increases; however, risk does not appear to change as small pickup mass increases, and risk actually increases with increasing mass of large pickups. And the correlation between mass and risk is quite low, ranging from an R2 of 0.25 for large pickups to essentially zero for SUVs. LBNL then estimated adjusted risk, after accounting for all of the variables in the baseline regression model except for vehicle weight and footprint. First LBNL calculated the predicted risk for each induced exposure case, based on its vehicle attributes, driver characteristics, and crash circumstances. Then standardized risks for each vehicle model were estimated for a 50-year old male driving a 4-year old vehicle in the day, in a non-rural county, in a low-risk state, on a high-speed road. The standardized risk was then multiplied by the ratio of actual risk to predicted risk (a measure of the residual risk not controlled for by the NHTSA baseline model) to estimate adjusted risk per VMT for each vehicle model, which controls all vehicle, driver and crash variables other than weight or footprint.

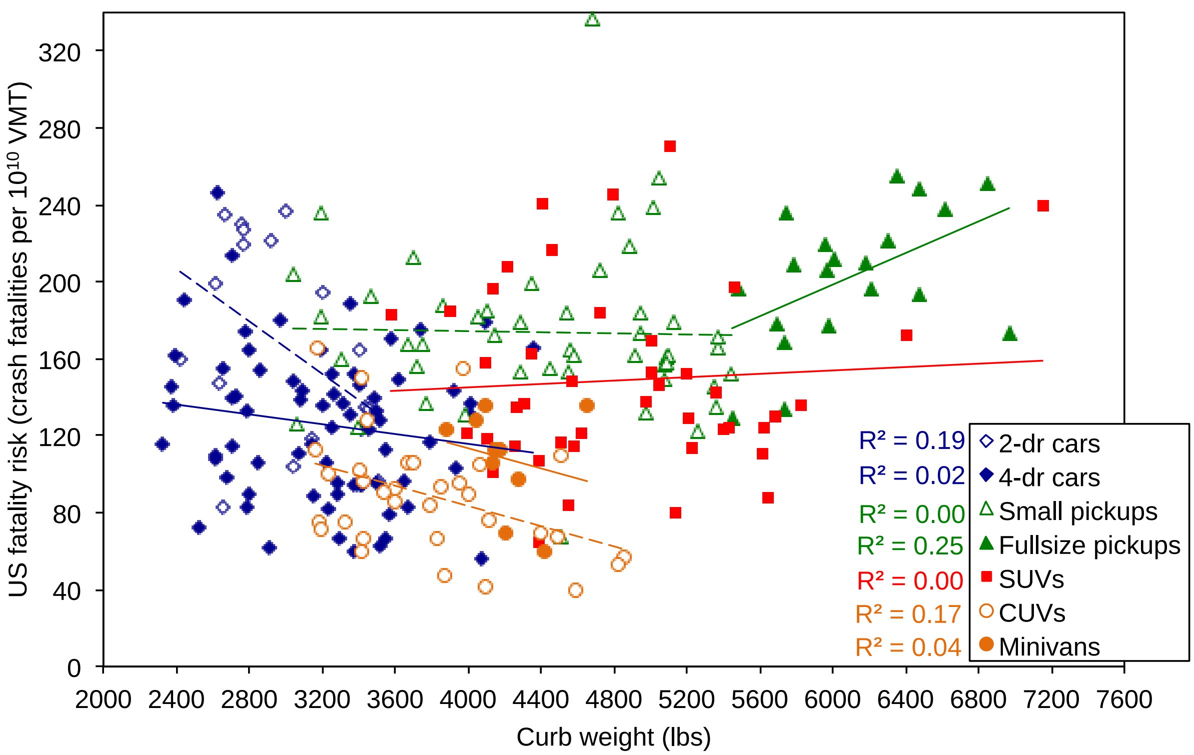


Figure 8.1 Actual (Unadjusted) U.S. Societal Fatality Risk per VMT vs. Curb Weight, By Vehicle Type and Model

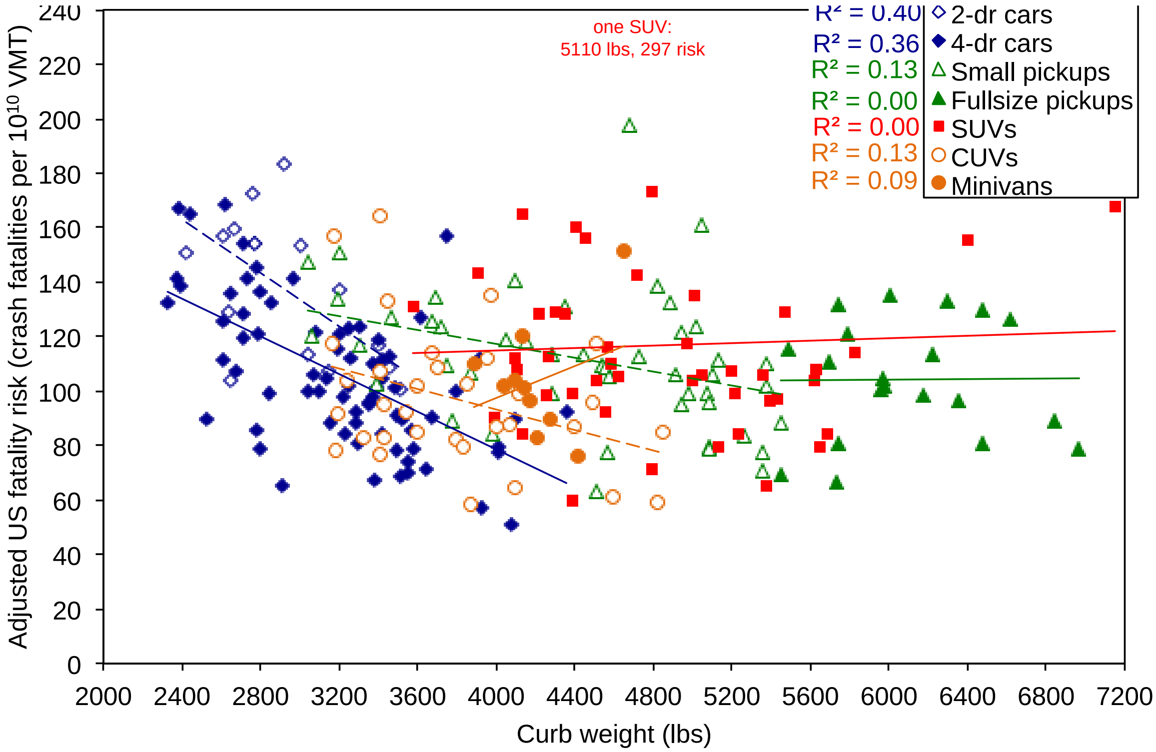


Figure 8.2 Adjusted U.S. Societal Fatality Risk per VMT vs. Curb Weight, by Vehicle Type and Model, After Accounting for All Driver, Crash, and Vehicle Variables except Mass and Footprint

As shown in Figure 8.2, after accounting for all the control variables except vehicle mass and footprint, adjusted risk does decrease as mass increases, at least for all vehicle types except SUVs and large pickups. However, risk and mass are not strongly correlated, with the R2 ranging from 0.40 for two-door cars and 0.36 for four-door cars, to essentially zero for SUVs and large pickups. This means that, on average, risk decreases as mass increases, but the variation in risk among individual vehicle models is stronger than the trend in risk from light to heavy vehicles.

Figure 8.2 indicates that some vehicles on the road today have the same, or lower, fatality risk than models that weigh substantially more, and are substantially larger in terms of footprint. After accounting for differences in driver age and gender, safety features installed, and crash times and locations, there are numerous examples of different models with similar weight and footprint yet widely varying fatality risk. The variation of fatality risk among individual models may reflect differences in vehicle design, differences in the drivers who choose such vehicles (beyond what can be explained by demographic variables such as age and gender), and statistical variation of fatality rates based on limited data for individual models.

The figure shows that when the data are aggregated at the make-model level, the combination of differences in vehicle design, vehicle selection, and statistical variations has more influence than mass on fatality rates. The figure perhaps also suggests that, to the extent these variations in fatality rates are due to differences in vehicle design rather than vehicle selection or statistical variations, there is potential for lowering fatality rates through improved vehicle design. This is consistent with NHTSA's 2012 opinion that some of the changes in its regression results between the 2003 study and the 2012 study are due to the redesign or removal of certain smaller and lighter models of poor design.

In its 2012 report NHTSA estimated the effect of four scenarios of mass reduction in the recent vehicle fleet on the overall number of fatalities, using the relationships between mass reduction and societal fatality risk estimated in the NHTSA baseline model. LBNL recreated this methodology using the updated 2016 NHTSA baseline model, for the four scenarios NHTSA analyzed in 2012 plus two additional scenarios:

- Scenario 1: 100-lb reduction in all vehicles;
- Scenario 2: proportionate 2.5 percent mass reduction in all vehicles;
- Scenario 3: mass reduction of 5.0 percent in heavier light trucks, 2.5 percent in all other vehicle types except cars, whose mass is kept constant;
- Scenario 4: a safety-neutral scenario (2012: 0.5 percent mass reduction in lighter cars, 2.1 percent in heavier cars, 3.1 percent in CUVs/minivans, 2.6 percent in lighter light trucks, and 4.6 percent in heavier light trucks; 2016: 2.0 percent mass reduction in cars, 2.5 percent in lighter light trucks and CUVs/minivans; and 3.0 percent in heavier light trucks);
- Scenario 5: reduce mass of light trucks to the median mass of cars; and
- Scenario 6: mass reduction estimated in 2015 NRC committee report (reduce mass in small cars by 5 percent, midsize cars 10 percent, large cars 15 percent, and all light trucks, including CUVs/minivans, 20 percent; LBNL translated the mass reductions for cars into 5 percent for lighter-than-average cars and 12.5 percent for heavier-than-average cars).

Table 8.7 shows that the relationship between mass reduction and risk estimated in 2012 resulted in an annual 224 increase in fatalities under the mass reduction scenario called for in the 2015 NRC report (Scenario 6). However, using the updated relationships from the 2016 NHTSA baseline, this fleet mass reduction scenario is estimated to result in 220 lives saved, and over 1,300 lives saved using the relationships estimated after including the two DRI measures (stopped vehicle induced exposure and split-footprint model).

Table 8.7 Estimated Annual Change in Fatalities from Six Different Fleetwide Mass Reduction Scenarios, Using Coefficients Estimated By 2012 and 2016 NHTSA Baseline Models and 2016 DRI Measures

Coefficients used	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
2012 NHTSA baseline	157	108	-8	0	-150	224
2016 NHTSA baseline	55	22	-53	0	-404	-220
2016 DRI measures	-114	-152	-282	-174	-1,901	-1,306

8.2.4.7 Fleet Simulation Model

NHTSA has traditionally used real world crash data as the basis for projecting the future safety implications for regulatory changes. However, since lightweight vehicle designs are introducing fundamental changes to the structure of the vehicle, there is some concern that the historical safety trends may not apply. To address this concern, NHTSA developed an approach to utilize the lightweight vehicle designs to evaluate safety in a subset of real world representative crashes. The methodology focused on frontal crashes due to the availability of existing vehicle and occupant restraint models. Representative crashes were simulated between baseline and lightweight vehicles against a range of vehicles and roadside objects using two different size belted driver occupants (adult male and small female) only. No passenger(s) or unbelted driver occupants were considered in this fleet simulation. The occupant injury risk from each of the simulations were calculated and summed to obtain combined occupant injury risk. The combined occupant injury risk was weighted according to the frequency of real world occurrences to develop overall societal risk for baseline and light-weighted vehicles. Note here, the generic restraint system developed and used in the baseline occupant simulations were also used in the light-weighted vehicle occupant simulations as the purpose of this fleet simulation is to understand changes in societal injury risks due to mass reduction for different class of vehicles in frontal crashes. No modifications to the restraint systems were done for light-weighted vehicle occupant simulations. Any modifications to the restraint systems to improve occupant injury risks or societal injury risks in the light-weighted vehicle, would have conflated the results without identifying the effects of mass reduction only. The following sections provide an overview of the fleet simulation study -

NHTSA contracted with George Washington University to develop a fleet simulation model[31] to study the impact and relationship of light-weighted vehicle design with injuries and fatalities. In this study, there were eight vehicles as follows:

- 2001 model year Ford Taurus finite element model baseline and two simple design variants included a 25 percent lighter vehicle while maintaining the same vehicle front end stiffness and 25 percent overall stiffer vehicle while maintaining the same overall vehicle mass[32].
- 2011 model year Honda Accord finite element baseline vehicle and its 20 percent light-weight vehicle designed by Electricore. (This mass reduction study was sponsored by NHTSA[33]).
- 2009/2010 model year Toyota Venza finite element baseline vehicle and two design variants included a 20 percent light-weight vehicle model (2010 Venza) (Low option mass reduction vehicle funded by EPA and International Council on Clean Transportation (ICCT)) and a 35 percent light-weight vehicle (2009 Venza) (High option mass reduction vehicle funded by California Air Resources Board[34]).

The light weight vehicles were designed to have similar vehicle crash pulses to the baseline vehicles. Over 440 vehicle crash simulations were conducted for the range of crash speeds and crash configurations to generate the crash pulse and intrusion data points shown in Figure 8.3. The crash pulse data and intrusion data points will be used as inputs in the occupant simulation models.

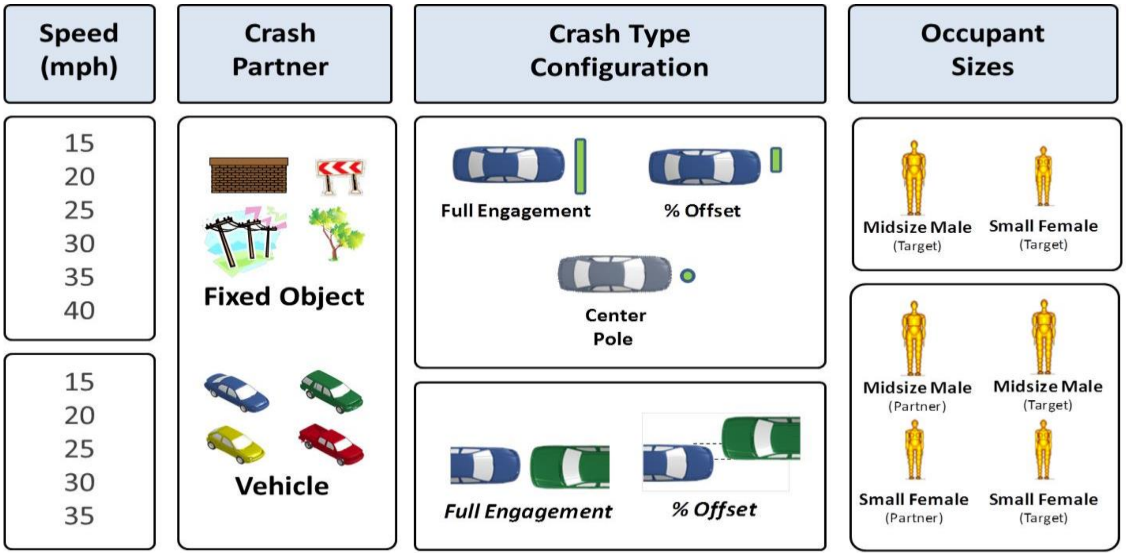
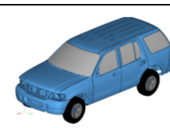


Figure 8.3 Vehicle Crash Simulations

For the vehicle to vehicle impact simulations, four finite element models were chosen to represent the fleet as shown in Table 8.8. The partner vehicle models were selected to represent a range of vehicle types and weights. It was assumed that the vehicle models would reflect the crash response for all vehicles of the same type, e.g. mid-size car. Only the safety or injury risk for the driver in both the target vehicle and in partner vehicle was evaluated in this study.

Table 8.8 Base Vehicle Models Used in the Fleet Simulation Study

Vehicle Model (NCAC) http://www.ncac.gwu.edu/vml/models.html		FE Weight No. Parts/Elements	
Taurus (MY2000 – 2007)			1505 kg 802/ 973,351
Yaris (MY2005 – 2013)			1100 kg 917/ 1,514,068
Explorer (MY2002 – 2005)			2025 kg 923/ 714,205
Silverado (MY2007 –2013)			2270 kg 719/ 963,482

As noted earlier, the vehicle simulations generated vehicle deformations and acceleration responses that were utilized to drive occupant restraint simulations and predict the risk of injury to the head, neck, chest, and lower extremities. In all, over 1,520 occupant restraint simulations were conducted to evaluate the risk of injury for mid-size male and small female drivers.

The computed societal injury risk (SIR) for a target vehicle $\boldsymbol{v}$ in frontal crashes is an aggregate of individual serious crash injury risks weighted by real-world frequency of occurrence ($\boldsymbol{v}$) of a frontal crash incident. A crash incident corresponds to a crash with different partners (Npartner) at a given impact speed (Pspeed), for a given driver occupant size (Loccsize), in the target or partner vehicle (T/P), in a given crash configuration (Mconfig), and in a single- or two-vehicle crash (Kevent). CIR (v) represents the combined injury risk (by body region) in a single crash incident. (v) designates the weighting factor, i.e., percent of occurrence, derived from National Automotive Sampling System Crashworthiness Data System (NASS CDS) for the crash incident. A driver age group of 16 to 50 years old was chosen to provide a population with a similar, i.e., more consistent, injury tolerance. Figure 8.4 shows how overall change in the societal risk is computed.

$$SIR_{frontal}(v) = \sum_{k=1}^{Kevent} \sum_{l=1}^{Loccsize} \sum_{m=1}^{Mconfig} \sum_{n=0}^{Npartner} \sum_{o=1}^{T/P} \sum_{p=1}^{Pspeed} w_{klmnop}(v) * CIR_{klmnop}(v)$$

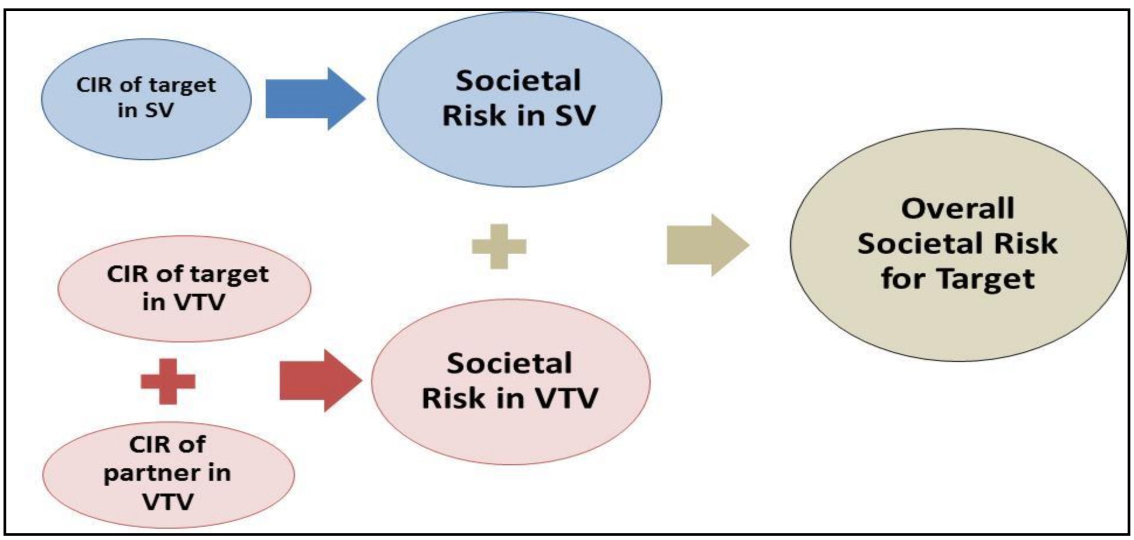


Figure 8.4 Diagram of Computation for Overall Change in Societal Risk

The fleet simulation was performed using the best available engineering models, with base vehicle restraint and airbag settings, to estimate societal risks of future lightweight vehicles. The range of the predicted risks for the baseline vehicles is from 1.25 percent to 1.56 percent, with an average of 1.39 percent, for the NASS frontal crashes that were simulated. The change in driver injury risk between the baseline and light-weighted vehicles will provide insight into the estimate of modification needed in the restraint and airbag systems of lightweight vehicles. If the difference extends beyond the expected baseline vehicle restraint and airbag capability, then adjustments to the structural designs would be needed. The results from the fleet simulation study show the trend of increased societal injury risk for light-weighted vehicle designs, as compared to their baselines, occurs for both single vehicle and two-vehicle crashes. Results are listed in Table 8.9.

In general, the societal injury risk, in the frontal crash simulation, associated with the small size driver is elevated when compared to that of the mid-size driver. However, both occupant sizes had reasonable injury risk in the simulated impact configurations that are representative of the regulatory and consumer information testing. NHTSA examined three methods for combing injuries to different body regions. One observation was that the baseline mid-size CUV model was more sensitive to leg injuries.

Table 8.9 Overall Societal Risk Calculation Results for Model Runs, with Base Vehicle Restraint and Airbag Settings Being the same for All Vehicles, in Frontal Crash Only

Target Vehicle	Passenger Car Baseline	Passenger Car LW	CUV Baseline	CUV Low Option	CUV High Option
Weight (lbs)	3681	2964	3980	3313	2537
reduction		716		668	1444
% mass reduction		19%		17%	36%
Societal Risk I	1.56%	1.73%	1.36%	1.46%	1.57%
Delta Increase		0.17%		0.10%	0.21%
Societal Risk II	1.43%	1.57%	1.14%	1.20%	1.30%
Delta Increase		0.14%		0.06%	0.16%
Societal Risk IIP	1.44%	1.59%			
Delta Increase		0.15%			
Societal Risk I - Target + Partner Combined AIS3+ risk of Head, Neck, Chest & Femur					
Societal Risk II - Target + Partner Combined AIS3+ risk of Head, Neck, and Chest					
Societal Risk IIP - Target + Partner Combined AIS3+ risk of Head, Neck, and Chest with A-Pillar Intrusion Penalty					

This study only looked at lightweight designs for a midsize sedan and a mid-size CUV and did not examine the safety implications for heavier vehicles. The study was also limited to only frontal crash configurations and considered just mid-size CUVs whereas the statistical regression model considered all CUVs and all crash modes.

The change in safety risk from the MY2010 fleet simulation study was directionally consistent with the results for passenger cars from NHTSA 2012 regression analysis study[BB], which covered data for MY2000-MY2007. The NHTSA 2012 regression analysis study was updated in 2016 to reflect newer MY 2003 to MY 2010. Comparing the fleet simulation overall societal risk to the to the 2016 update of the NHTSA 2012 regression analysis, the risk assessment from the fleet simulation is similarly directionally consistent with the passenger car risk assessment from NHTSA 2016 regression analysis. As noted above, the fleet simulations were performed only in frontal crash mode and did not consider other crash modes including

[BB] The 2012 Kahane study considered only fatalities, whereas, the fleet simulation study considered severe (AIS 3+) injuries and fatalities (DOT HS 811 665).

rollover crashes. (The risk assessment for CUV in the regression model combined CUVs and minivans in all crash modes and included belted and unbelted occupants)

This fleet simulation study does not provide information that can be used to modify the coefficients derived by NHTSA 2016 regression analysis study due to the restricted types of crashes[CC] and vehicle designs. The fleet simulation modeling study does not affect the agencies' assessment of the amount of mass reduction that may be implemented with a neutral effect on safety. As explained earlier, the fleet simulation study assumed restraint equipment to be as in the baseline model, in which the restraints/airbags are not redesigned to be optimal with light-weighting.

8.2.5 Based on this Information, What do the Agencies Consider to be the Current State of Statistical Research on Vehicle Mass and Safety?

The agencies believe that statistical analysis of historical crash data continues to be an informative and important tool in assessing the potential safety impacts of the proposed standards. The newest studies described in this chapter affirm that the effect of mass reduction while maintaining footprint is a complicated topic, and there are still open questions of whether future vehicle designs will reduce the historical correlation between weight and size. It is important to note that while the updated database (with MY2003-MY2010) represents more current vehicles with technologies more representative of vehicles on the road today, that database cannot fully represent what vehicles will be on the road in the MYs 2017-2025 timeframe. As was also true with the 2000-2007 model year data, the vehicles manufactured in model years 2003-2010 were not subject to footprint-based fuel economy standards. As explained earlier, the agencies expect that the attribute-based standards will likely facilitate the design of vehicles such that manufacturers may reduce mass while maintaining footprint. Therefore, it is possible that the analysis for MYs 2003-2010 vehicles may not be fully representative of the vehicles that will be on the road in 2017 and beyond.

We recognize that statistical analysis of historical crash data may not be the only way to think about the future relationship between vehicle mass and safety. However, we recognize that other assessment methods are also subject to uncertainties, which makes statistical analysis of historical data an important starting point if employed mindfully and recognized for how it can be useful and what its limitations may be.

Before the 2017-2025 final rule, NHTSA had funded an independent review of statistical studies and held a mass-safety workshop in 2011 in order to help the agencies sort through the ongoing debates over how statistical analysis of the historical relationship between mass and safety should be interpreted. After the final rule, NHTSA held a follow-up workshop in May 2013. Previously, the agencies had assumed that differences in results were due in part to inconsistent databases. By continuing to create updated common databases and making them publicly available, we are hopeful that this aspect of the problem has been resolved.

At the 2013 workshop, it was reported by UMTRI that the 2011 independent review of 18 statistical reports suggested that differences in data were probably less significant than the agencies may have thought. UMTRI stated that statistical analyses of historical crash data should be examined more closely for potential multicollinearity issues that exist in some of the

[CC] The fleet simulation considered only frontal crashes.

current analyses. The agencies will continue to monitor issues with multicollinearity in our analyses, and hope that outside researchers will do the same.

Finally, based on the findings of the independent review, the agencies continue to be confident that NHTSA's regression (Kahane)) analytical technique is one of the best for the purpose of analyzing potential safety effects of future CAFE and GHG standards. UMTRI concluded that the approach is valid, and NHTSA continued and refined that approach for the 2011 and 2012 analyses; the 2016 NHTSA/Volpe preliminary report continues NHTSA 2012 approach but with newer data, and finds directionally similar (although fewer statistically significant) relationships between vehicle mass, size, and footprint. Based on these findings, the agencies continue to believe that in the future, fatalities due to mass reduction will be best reduced if mass reduction is concentrated in the heaviest vehicles. Analyses should be continually updated to determine how the effect of mass reduction on safety changes over time.

Both agencies continue to agree that there are several identifiable safety trends already in place or expected to occur in the foreseeable future that may influence the historical relationship between mass and safety. For example, there are several important new safety standards that have already been issued and have been phasing in after MY2010 and some potential safety standards, as shown in Table 8.10. In addition, there are several safety requirements on the horizon, such as automated braking, that could further influence the overall historical relationship between mass and safety.

Table 8.10 Additional Safety Requirements Post 2010 (FMVSS, IIHS)[35,36]

Final Rules	Specifics	Compliance Dates
FMVSS No. 126	(49 CFR § 571.126) requires electronic stability control in all new vehicles	2012
FMVSS No. 214	Side Impact Protection, (49 CFR § 571.214) new vehicles being equipped with head-curtain air bags by MY2014.	Sept 2009-2012
FMVSS No. 216	(49 CFR Parts 571 and 585) Vehicle roof structure must withstand 3.0 times vehicle weight - up from 1.5 times, applicable up to 10k lbs from 6klb vehicles	Sept 2012-2015
FMVSS No. 226	(49 CFR Parts 571, 585) reduce partial and complete ejection of vehicle occupants through side windows in crashes, particularly rollovers, applies to vehicles </=10k lbs	Sept 2013-2017
FMVSS No. 111	(49 CFR Part 571) Vehicles 10klbs to 26k lbs required to have rear object detection system	(NPRM) May 2016-2018
IIHS small overlap	Assuring passenger compartment structure strength if crash bypasses front rail/frame structure	2012/2014 for Top Safety

Additionally, based on historical trends, we anticipate continued improvements in driver (and passenger) behavior, such as higher safety belt use rates. All of these may tend to reduce the absolute number of fatalities. Moreover, as crash avoidance technology improves, future statistical analysis of historical data may be complicated by a lower number of crashes. In summary, the agencies have relied on the coefficients in the updated NHTSA/Volpe 2016 study, based on 2003-2010 vehicle crash data, for estimating the potential safety effects of the 2022-

2025 CAFE and GHG standards for the midterm evaluation of our assumptions that mass reduction could be used to meet the standards in a cost-effective way without adversely affecting safety. Section 8.4.1 below discusses the methodology used by the agencies in more detail.

While the results of the 2016 safety effects analysis are less statistically significant than the results in the MYs 2017-2025 final rule, the agencies still believe that any statistically significant results warrants careful consideration of the assumptions about appropriate levels of mass reduction, and have acted accordingly in conducting this draft technical analysis.

8.3 How do the Agencies Think Technological Solutions Might Affect the Safety Estimates Indicated by the Statistical Analysis?

As mass reduction continues to be an important technology option for manufacturers in meeting future CAFE and GHG standards, manufacturers may invest more and more resources in developing increasingly lightweight vehicle designs that meet their needs for manufacturability and the public's need for vehicles that are also safe, useful, affordable, and enjoyable to drive. There are many different ways to reduce mass, and a considerable amount of information is available today on lightweight vehicle designs currently in production and that may be able to be put into production in the MYs 2022-2025 timeframe. Discussion of lightweight material designs from NHTSA's workshop is presented below.

Besides "lightweighting" technologies themselves, though, there are a number of considerations when attempting to evaluate how future technological developments might affect the safety estimates indicated by the historical statistical analysis. As discussed in the first part of this section, for example, careful changes in design and/or materials used might mitigate some of the potential increased risk from mass reduction for vehicle self-protection, through improved distribution of crash pulse energy, etc. At the same time, these lightweighting techniques can sometimes lead to other problems, such as increased crash forces on vehicle occupants that have to be mitigated, or greater aggressiveness against other vehicles in crashes. Manufacturers may develop new and better restraints – air bags, seat belts, etc. – to protect occupants in lighter vehicles in crashes, but NHTSA's current safety standards for restraint systems are designed based on the current fleet, not the yet-unknown future fleet. The agency will need to monitor trends in the crash data to see whether changes to the safety standards (or new safety standards) become advisable. Manufacturers are also increasingly investigating a variety of crash avoidance technologies – forward collision warning, auto braking, lane departure warning, lane departure prevention, adaptive headlights, blind spot detection, and vehicle-to-vehicle (V2V) communications – that, as they become more prevalent in the fleet, are expected to reduce the number of overall crashes, and thus crash fatalities. Until these technologies are present in the fleet in greater numbers, however, it will be difficult to assess whether they can mitigate the observed relationship between vehicle mass and safety in the historical data.

8.3.1 Workshops on Technological Opportunities and Constraints to Improving Safety under Mass Reduction

8.3.1.1 2011 Workshop on Vehicle Mass, Size and Safety

As stated above in Section 8.2.3, on February 25, 2011, NHTSA hosted a workshop on mass reduction, vehicle size, and fleet safety at the headquarters of the U.S. Department of Transportation in Washington, DC. The purpose of the workshop was to provide the agencies with a broad understanding of current research in the field and provide stakeholders and the public with an opportunity to weigh in on this issue. The agencies also created a public docket to receive comments from interested parties that were unable to attend. The presentations were divided into two sessions that addressed the two expansive sets of issues. The first session explored statistical evidence of the roles of mass and size on safety, and is summarized in Section 8.2.3. The second session explored the engineering realities of structural crashworthiness, occupant injury and advanced vehicle design, and is summarized here. The speakers in the second session included Stephen Summers of NHTSA, Gregg Peterson of Lotus Engineering, Koichi Kamiji of Honda, John German of the International Council on Clean Transportation (ICCT), Scott Schmidt of the Alliance of Automobile Manufacturers, Guy Nusholtz of Chrysler, and Frank Field of the Massachusetts Institute of Technology.

The second session explored what degree of mass reduction and occupant protection are feasible from technical, economic, and manufacturing perspectives. Field emphasized that technical feasibility alone does not constitute feasibility in the context of vehicle mass reduction. Sufficient material production capacity and viable manufacturing processes are essential to economic feasibility. Both Kamiji and German noted that both good materials and good designs will be necessary to reduce fatalities. For example, German cited the examples of hexagonally structured aluminum columns, such as used in the Honda Insight that can improve crash absorption at lower mass, and of high-strength steel components that can both reduce weight and improve safety. Kamiji made the point that widespread mass reduction will reduce the kinetic energy of all crashes which should produce some beneficial effect.

Summers described NHTSA's plans for a model to estimate fleet wide safety effects based on an array of vehicle-to-vehicle computational crash simulations of current and anticipated vehicle designs. In particular, three computational models of lightweight vehicles are under development. They are based on current vehicles that have been modified or redesigned to substantially reduce mass. The most ambitious was the "high development" derivative of a Toyota Venza developed by Lotus Engineering and discussed by Mr. Peterson. The Lotus light-weighted Venza structure contains about 75 percent aluminum, 12 percent magnesium, 8 percent steel, and 5 percent advanced composites. Peterson expressed confidence that the design had the potential to meet federal safety standards. Nusholtz emphasized that computational crash simulations involving more advanced materials were less reliable than those involving traditional metals such as aluminum and steel.

Nusholtz presented a revised data-based fleet safety model in which important vehicle parameters were modeled based on trends from current NCAP crash tests. For example, crash pulses and potential intrusion for a particular size vehicle were based on existing distributions. Average occupant deceleration was used to estimate injury risk. Through a range of simulations of modified vehicle fleets, he was able to estimate the net effects of various design strategies for lighter weight vehicles, such as various scaling approaches for vehicle stiffness or intrusion. The approaches were selected based on engineering requirements for modified vehicles. Transition from the current fleet was considered. He concluded that protocols resulting in safer transitions (e.g., removing more mass from heavier vehicles with appropriate stiffness scaling according to a 3/2 power law) were not generally consistent with those that provide the greatest reduction in GHG production: i.e., that the most effective mass reduction in terms of reducing GHG emissions was not necessarily the safest.

German discussed several important points on the future of mass reduction. Similar to Kahane's discussion of the difficulties of isolating the impact of mass reduction, German stated that other important variables, such as vehicle design and compatibility factors, must be held constant in order for size or weight impacts to be quantified in statistical analyses. He presented results that the safety impacts of size and weight are small and difficult to quantify when compared to driver, driving influences, and vehicle design influences. He noted that several scenarios, such as rollovers, greatly favored the occupants of smaller and lighter cars once a crash occurred. He pointed out that if size and design are maintained, lower weight should translate into a lower total crash force. He thought that advanced material designs have the potential to "decouple" the historical correlation between vehicle size and weight, and felt that effective design and driver attributes may start to dominate size and weight issues in future vehicle models.

Other presenters noted industry's perspective of the effect of incentivizing mass reduction. Field highlighted the complexity of institutional changes that may be necessitated by mass reduction, including redesign of material and component supply chains and manufacturing infrastructure. Schmidt described an industry perspective on the complicated decisions that must be made in the face of regulatory change, such as evaluating goals, gains, and timing.

Field and Schmidt noted that the introduction of technical innovations is generally an innate development process involving both tactical and strategic considerations that balance desired vehicle attributes with economic and technical risk. In the absence of challenging regulatory requirements, a substantial technology change is often implemented in stages, starting with lower volume pilot production before a commitment is made to the infrastructure and supply chain modifications which are necessary for inclusion on a high-volume production model. Joining, damage characterization, durability, repair, and significant uncertainty in final component costs are also concerns. Thus, for example, the widespread implementation of high-volume composite or magnesium structures might be problematic in the short or medium term when compared to relatively transparent aluminum or high strength steel implementations. Regulatory changes will affect how these tradeoffs are made and these risks are managed.

Koichi Kamiji presented data showing in increased use of high strength steel in their Honda product line to reduced vehicle mass and increase vehicle safety. He stated that mass reduction is clearly a benefit in 42 percent of all fatal crashes because absolute energy is reduced. He followed up with slides showing the application of certain optimized designs can improve safety even when controlling for weight and size. A philosophical theme developed that explored the ethics of consciously allowing the total societal harm associated with mass reduction to approach the anticipated benefits of enhanced safety technologies. Although some participants agreed that there may eventually be specific fatalities that would not have occurred without downsizing, many also agreed that safety strategies will have to be adapted to the reality created by consumer choices, and that “We will be ok if we let data on what works – not wishful thinking – guide our strategies.”

8.3.1.2 2013 Workshop on Vehicle Mass, Size and Safety

As stated above in Section 8.2.4, on May 13-14, 2013, NHTSA hosted a follow-on symposium to continue to explore the relevant issues and concerns with mass, size, and safety tradeoffs. The first day of the two-day symposium addressed “engineering realities,” specifically the feasible amount of mass reduction and the implications for structural crashworthiness, occupant injury, and advanced vehicle design.

The first-day speakers included Greg Kolwich of FEV, Inc. (Forschungsgesellschaft fur Energietechnik und Verbrennungsmotoren (FEV)), Gregg Peterson of Lotus Engineering, Jackie Rehkopf of Plasan Carbon Composites, Doug Richman of Kaiser, Stephen Ridella of NHTSA, Scott Schmidt of the Alliance of Automobile Manufacturers, Harry Singh of EDAG Engineering GmbH. (Engineering and Design Aktiengesellschaft (EDAG)), Chuck Thomas of Honda, and Blake Zuidema of Arcelor Mittal.

Peterson discussed continued analysis of the “high development” and “low development” options for mass reduction of a Toyota Venza as published in 2012. Lotus Engineering's further review of the 2010 "high development" study, through CAE and crash analyses, revealed that some design changes would be required for the aluminum intensive design. The amount of mass reduction from the body-in-white was likely to decrease but it was felt that much of this could be offset with mass reduction elsewhere in the vehicle. Joining durability and cycle time were important considerations, as was the need to evaluate capital expenditures to implement various material and structural options.

Kolwich described an effort to provide detail design, structural simulation, and cost analysis to the low development Venza model in an attempt to provide a reasonable mix of manufacturability, cost, and increased fuel economy. Optimization of material, geometry, and gauge (thickness) were considered. FEV believes a cost-neutral 18 percent mass reduction is possible but noted that the modeling includes no verification of the redesigned vehicle’s dynamic characteristics.

Singh described a similar effort to redesign the 2011 Honda Accord. The economic constraint was a limit of a 10 percent increase in estimated manufacturing costs. They investigated combinations of steel, aluminum, magnesium, plastic, and composites applications and alternative joining and manufacturing technologies. They employed topology optimization of the structural elements while maintain interior volume and other functionality. They required the revised structure to maintaining an equivalent rating in existing regulatory and consumer testing programs (e.g., roof crush, side impact, etc.).

A review of the EDAG design by Honda and presented by Thomas acknowledged that may of the concepts have tremendous potential and are under consideration, but the estimated 332 kg (22 percent) in mass reduction might be overly optimistic. He identified some possible deficiencies against internal testing and performance standards, such as drivability and noise, vibration, and harshness (NVH) that might require remediation of up to 50 kg. He also noted the economic reality that manufacturers must leverage platforms across several vehicle models to maintain a competitive array of vehicles. This platform commonality is inherently non-optimal.

After that adjustment and the associated reinstatement of engine horsepower and other structural enhancements, the feasible mass reduction might be as little as 175 kg.

Schmidt discussed two top concerns of automakers for mass reduction approaches. First, substantial mass reduction will require comprehensive platform redesign. This has practical economic concerns in terms of infrastructure investment and the maintenance of stable economically viable global supply chains for advanced materials. Second, fleet-wide safety considerations of mass reduction need to be estimated carefully, especially in light of the possible effect on baseline mass of any new global safety regulation. He reiterated the theme that these concerns must be addressed in the context of maintaining current levels of performance and comfort.

Zuidema presented the perspectives of the steel industry. Through optimizing grade, gauge, and geometry, it is believed that advanced high strength steel applications can provide significant mass reduction of many components while minimizing required infrastructure changes. There are numerous new grades being developed that have combinations of ultimate strength and ultimate elongation that can be used to address the specific requirements of particular components. These often result in a minimum cost solution for any strength critical application and many stiffness-controlled structures. He also noted that life cycle CO2 emissions (i.e., accounting for the emissions is material production) and recyclability considerations make steels even more attractive.

Richman represented the Aluminum Association and talked about the ability of aluminum to meet the needs of automotive mass reduction. He noted the differences in stiffness-controlled load cases (e.g., vibration and handling) and strength-controlled load cases (e.g., crash). He cited a German university study (see his slide 14) that implies steel could generate an 11 percent mass reduction for the vehicle considered while aluminum could generate a 40 percent reduction. Practical considerations, such as maintaining a crush zone of approximately 650 mm and economics as applied by the industry broadly will determine the ultimate multi-material mix in any vehicle design.

Rehkopf discussed carbon fiber composites applications in current and future vehicles. Composites can be designed to produce complex geometries with fiber orientations optimized to give strength and stiffness only where required. The consolidation of numerous parts into one can reduce both manufacturing time and mass. Analytical capabilities, material costs, and production improvements (e.g., faster curing resins for reduced cycle time) are continually bringing down manufactured part costs. Currently, carbon fiber vehicle components are most cost competitive when the production rate is under 50,000 per year.

Ridella presented planned NHTSA research on the introduction of lightweight vehicles into the vehicle fleet. NHTSA has developed crash models of several vehicles from recent model years. The recent mass reduction studies (Venza by FEV, Accord by EDAG, modified Taurus model). A matrix of computer crash simulations will be performed across a fleet of various existing crash models and the new lightweight models. The frontal crash simulations will be run at multiple speeds (15 to 40 mph for fixed object crashes, 15 to 35 mph for vehicle-to-vehicle crashes), multiple geometries (pole impact, full engagement, offset engagement), and with multiple occupants (midsize male, small female). Crash pulses extracted from the vehicle models will be inputs for injury models. Preliminary findings of societal injury risk (defined as combined likelihood of AIS3 or higher injury by various criteria to target and partner vehicle occupants) did rise by 5 to 21 percent in the lighter vehicles. The final report was expected out several months later.

A panel discussion from the first day panelists focused on the realities of mass reduction as a moving target both in terms of technology development and in terms of the existing baseline for each incumbent vehicle design. In any regular redesign cycle, technologies are often frozen two years before model year release and then remain substantially unchanged for five to seven years. Thus, as technology advances before the next design cycle, there is likely to be a fair amount of low hanging fruit. Thomas estimated that 10 percent mass reduction may be a realistic estimate of the mass reduction broadly feasible by 2025. Peterson concurred, noting that the Lotus studies were not subject to all the constraints that arise in the full process required to design a vehicle for high volume manufacturing. Kolwich felt it may be possible to extract only 4 percent from the body but as much as 14 percent from the rest of the vehicle. The influence of non-structural mass (e.g., interior, HVAC) has implications.

The point was made that footprint-based regulations may have fewer unintended consequences than mass-based regulation. Ridella cautioned that tradeoffs by all the stakeholders must be considered carefully, especially in their impact on overall safety. The practical consideration of reliable repair of advanced material components was raised.

8.3.2 Technical Engineering Projects

The agencies conducted several technical/engineering projects described below to estimate the potential for advanced materials and improved designs to reduce mass in the MY 2017-2025 timeframe, while continuing to meet safety regulations and maintain functionality and affordability of vehicles. Another NHTSA-sponsored study will estimate the effects of these design changes on overall fleet safety. The detailed discussions about these studies can be found in the 2012 FRM Joint TSD Section 3.3.5.5. After reviewing comments from Honda regarding the first of these studies discussed below, NHTSA sponsored a subsequent study to modify the results of the first study.

8.3.2.1 Honda Accord Study

NHTSA awarded a contract in December 2010 to Electricore, with EDAG and George Washington University (GWU) as subcontractors, to study potential for mass reduction of a mid-size car – specifically, a Honda Accord -- while maintaining the functionality of the baseline vehicle (the LWV study). The project team was charged to maximize the amount of mass reduction with the technologies that are considered feasible for 200,000 units per year production volume during the time frame of this rulemaking while maintaining the retail price in parity (within ±10 percent variation) with the baseline vehicle. When selecting materials, technologies and manufacturing processes, the Electricore/EDAG/GWU team utilized, to the extent possible, only those materials, technologies and design which are currently used or planned to be introduced in the near term (MY2012-2015) on low-volume production vehicles. This approach, commonly used in the automotive industry, is employed by the team to make sure that the technologies used in the study will be feasible for mass production for the time frame of this rulemaking. The Electricore/EDAG/GWU team took a "clean sheet of paper" approach and adopted collaborative design, engineering and CAE process with built-in feedback loops to incorporate results and outcomes from each of the design steps into the overall vehicle design and analysis. The team tore down and benchmarked 2011 Honda Accord and then undertook a series of baseline design selections, new material selections, new technology selections and overall vehicle design optimization. Vehicle performance, safety simulation and cost analyses were run in parallel to the design and engineering effort to help ensure that the design decisions are made in-line with the established project constrains.

Multiple materials were used for this study. The body structure was redesigned using a significant amount of high strength steel. The closures and suspension were designed using a significant amount of aluminum. Magnesium was used for the instrument panel cross-car beam. A limited amount of composite material was used for the seat structure.

Safety performance of the light-weighted design was compared to the safety rating of the baseline MY2011 Honda Accord for seven consumer information and federal safety crash tests using LS-DYNA.[DD] These seven tests are the NCAP frontal test, NCAP lateral MDB test, NCAP lateral pole test, IIHS roof crush, IIHS lateral MDB, IIHS front offset test, and FMVSS No. 301 rear impact tests. These crash simulation analyses did not include use of a dummy model. Therefore only the crash pulse and intrusion were compared with the baseline vehicle test results. The vehicle achieved equivalent safety performance in all seven self-protection tests comparing to MY2011 Honda Accord with no damage to the fuel tank. Vehicle handling is evaluated using MSC/ADAMS[EE] modeling on five maneuvers, fish-hook test, double lane change maneuver, pothole test, and 0.7G constant radius turn test and 0.8G forward braking test. The results from the fish-hook test show that the light-weighted vehicle can achieve a five-star rating for rollover, same as baseline vehicle. The double lane change maneuver tests show that the chosen suspension geometry and vehicle parameter of the light-weighted design are within acceptable range for safe high speed maneuvers.

Overall the complete light weight vehicle achieved a total weight savings of 22 percent (332kg) relative to the baseline vehicle (1480 kg). The study has been peer reviewed by three technical experts from the industry, academia and a DOE national lab. The project team addressed the peer review comments in the report and also composed a response to peer review comment document. The final report, CAE model and cost model are published in docket NHTSA-2010-0131 and can also be found on NHTSA's website.[FF] The peer review comments with responses to peer review comments can also be found at the same docket and website.

8.3.2.2 Second Honda Accord Study

After the LWV design was complete, IIHS added the Small Overlap (SOL) crash test to its program. The test replicates what happens when the front corner of a vehicle strikes another vehicle or an object like a tree or a utility pole. In the test, 25 percent of a vehicle's front end on the driver side strikes a 5-foot-tall rigid barrier at 40 mph. Small overlap crashes accounted for nearly 25 percent of the frontal crashes involving serious or fatal injury to front seat occupants. In many vehicles the impact at a 25 percent overlap misses the primary structures designed to manage crash energy in a frontal impact. That increases the risk of severe damage to or collapse of the occupant compartment structure. Also, vehicles tend to rotate and slide sideways during

[DD] LS-DYNA is a software developed by Livermore Software Technologies Corporation used widely by industry and researchers to perform highly non-linear transient finite element analysis.

[EE] MSC/ADAMS: Macneal-Schwendler Corporation/Automatic Dynamic Analysis of Mechanical Systems.

[FF] Final report, CAE model and cost model for NHTSA's light weighting study can be found at NHTSA's website: http://www.nhtsa.gov/fuel-economy.

this type of collision, and that can move the driver's head outboard, away from the protection of the front airbag.

Additionally, Honda provided comments to the agency on the findings located here (http://www.nhtsa.gov/staticfiles/rulemaking/pdf/MSS/4-Thomas-Honda_Report.pdf). In 2013, NHTSA awarded a subsequent contract to Electricore to modify the initial LWV design to: 1) Update the original LWV design to address Honda’s comments (LWV1.1); and 2) Update the LWV design model to correlate to the IIHS Small Overlap (SOL) crash test results (LWV1.2).

The Electricore team created a detailed finite element model of the MY2011 Baseline Honda Accord. The team then re-designed the original LWV version 1.0 to version 1.1 to address the comments from Honda, including improving the vehicle’s torsional stiffness and the performance on IIHS offset barrier, side crash and rear impact.

In addressing Honda’s comments, the weight of the body structure of the LWV 1.1 is increased by 11.5 kg and the cost is reduced by $13.08 from the original LWV 1.0 design. In addition, some of Honda’s recommendations for NVH and drivability were also accepted. The total weight and cost of the LWV 1.1 increased by 21.75 kg and $18.13, respectively.

The LWV1.1 was then upgraded to address the IIHS SOL test (LWV1.2). To address the IIHS SOL test (LWV 1.2) the weight of the vehicle is increased by 6.90 kg and the cost by $26.88. The new LWV 1.2 design was modeled and assessed for the performance of crashworthiness in seven crash safety tests such as frontal NCAP test, lateral NCAP moving deformable test, lateral NCAP pole test, IIHS roof crush test, IIHS lateral moving deformable test, IIHS moderate frontal offset test and IIHS small overlap front test. The new design achieved a “good,” rating in all crash tests which are comparable to the safety rating of the MY2013 Accord. When the new design was applied to each of the light vehicle sub-classes, which span sub-compact cars to large SUV/light trucks, the project mass saving potential decreased from a range of 17.7 percent to 19.3 percent (18.2 percent on average) for LWV 1.0 to a range of 15.8 percent to 17.5 percent (16.3 percent on average) for LWV 1.2.

In summary, the study demonstrated that the mass of a current production vehicle could be reduced and yet achieves a “good” rating in all crash tests, including the new IIHS Small Overlap (SOL) crash test.

8.3.2.3 NHTSA Silverado Study and Light-Duty Fleet Analysis

In September 2013, NHTSA awarded a contract to automotive design and engineering company EDAG, Inc., to conduct vehicle weight reduction and cost study of a full size pick-up truck, specifically, the 2014 Chevrolet Silverado. The goal was to determine the maximum feasible weight reduction while maintaining the same vehicle functionalities, such as performance, safety, and crash rating, as the baseline vehicle. The light weighted version of the full size pick-up truck (LWT) uses technologies, materials, and manufacturing processes projected to be available in model year 2025-2030 and capable of high volume production.

The EDAG team performed a comprehensive teardown/benchmarking of the baseline vehicle for engineering analysis that included manufacturing technology assessment, material utilization and complete vehicle geometry scanning. The geometry and material test data from the baseline vehicle tear down was used to build detailed finite element analysis (FEA) simulation models suitable crash worthiness using Livermore Software (LS-DYNA) simulation program. Before the vehicle teardown, torsional stiffness tests, bending stiffness tests, and normal modes of vibration tests were performed on the baseline vehicle so that these results can be compared with the light-weighted design. The FEA LS-DYNA models based on the tear-down information and necessary material properties, such as the stress-strain curve, were based on test results and information from other available databases or Computer Aided Engineering (CAE) models. An FEA LS-DYNA model was created and correlated to the baseline vehicle crash results which include FMVSS, New Car Assessment Program NCAP and Insurance Institute for Highway Safety (IIHS) tests. All of the modeled tests were comparable to the actual crash tests performed on the 2014 Silverado. For load cases that did not have real vehicle test data of which to correlate to, the results are compared with similar reference vehicles, such as, the 2015 Ford F-150.

The project team then used computer modeling and optimization techniques to design the light-weighted pickup truck and optimized the vehicle structure. The recommended materials, manufacturing processes, and assembly methods are at present used, some to a lesser degree than others. These technologies can be fully developed within the normal product design cycle using the current design and development methods. The researchers then developed a comprehensive direct manufacturing incremental cost estimate for the LWT concept vehicle, including both detailed direct manufacturing and indirect cost estimates for tooling and equipment investment.

From the various technologies that were reviewed for future mass saving potential, four different vehicle build scenarios were developed. Ranging from a vehicle mass saving of about 11 percent to 23 percent, the light weighting vehicle build options are as follows:

1) For an all Advanced High Strength Steel (AHSS) intensive LWT design, including cab, pickup box, closures, chassis frame, seat frames and instrument panel beam structures.
2) Design with AHSS chassis frame structure and aluminum cab, pickup box, closures, and multi-material seats.
3) An aluminum intensive solution, using aluminum for body structure, closures, chassis frames and magnesium for seats.
4) An advanced carbon fiber and multi-material Solution, using carbon fiber reinforced composite body structure, CFRP/magnesium/aluminum closures, aluminum chassis frames and magnesium/composite seat structures.

From the options above, the design with AHSS chassis frame structure and aluminum cab, pickup box and multi-material seats and closures (Option 2), was selected as most likely to be implemented for production years 2025 to 2030. The selected technology options were included in the detail design and comprehensive Computer-Aided Engineering (CAE) performance assessment of the complete LWT design. The recommended design for LWT achieved a vehicle mass saving of over 17 percent (428 kg) relative to the baseline weight (2,432 kg). To maintain the same vehicle performance as the baseline vehicle, the size of the engine is proportionally reduced from the baseline 5.3L (355 HP) to 5.0L (335HP) for the LWT. Without the mass reduction allowance for the powertrain, the mass saving for the LWT 'glider' is about 21 percent (379 kg).

The report details engineering analyses and documentation showing how the functionalities for the light-weighted vehicle are maintained or improved. These functionalities include safety, fuel economy, vehicle utility/performance (e.g. towing, acceleration, etc.), Noise Vibration and

Harshness (NVH), vehicle dynamics (e.g. vehicle weight distribution, rollover stability, etc.), manufacturability, aesthetics, ergonomics, durability and serviceability. Appropriate CAE tools as used by OEMs for this vehicle class were used when comparing baseline vehicle functionalities to the light-weighted design, such as for safety, NVH, powertrain performance, towing, durability, etc. Mass reduction technologies assessed for the lightweight truck (LWT) were applied to other light-duty passenger vehicles and light-duty trucks to estimate the mass savings while maintaining vehicle size, performance and functionality. This assessment was conducted for the following light-duty vehicle classes:

- Subcompact passenger cars
- Compact passenger cars
- Midsize passenger cars
- Large passenger cars
- Minivans
- Small CUV/SUV/light-duty trucks
- Midsize CUV/SUV/light-duty trucks
- Large CUV/SUV/light-duty trucks

The chosen mass reduction technologies are feasible within the time frame of model years 2017-2025 and would be available across the passenger car and light-truck vehicle fleet. In addition to the introduction of weight saving technologies, consideration was also given to the capability of suppliers to deliver these mass saving measures in sufficient volumes to support this initiative.

All of the weight reduction technologies developed for the LWT program using the 2014 Chevrolet Silverado 1500 as the baseline vehicle can readily be introduced to all of the selected vehicles within each of the vehicle subclasses, subcompact to large SUV/light truck, to achieve weight savings from 15 percent to 18 percent over next two design cycles for model years 2020 and 2025. Further, there is a significant weight improvement when downsizing the powertrain; this shows the importance of matching the powertrain to the vehicle weight when undergoing a weight reduction program as this impacts other sub-systems within the vehicle.

As demonstrated through detailed design and computer simulation of LWT, these estimated weight reductions can be achieved. It is important to use the latest weight saving optimization tools such body structure CAE optimization for material gage-grade-geometry selection. Taking full advantage of mass compounding and resizing all sub-systems is also critical to achieve the most mass efficient design. The pick-up truck lightweighting study and fleet analysis is currently undergoing peer-review and not publicly available, but is expected to be available in 2016.

8.3.2.4 EPA Midsize CUV "Low Development" Study

EPA, along with ICCT, funded a contract with FEV, with subcontractors EDAG (CAE modeling) and Munro & Associates, Inc. (component technology research) to study the feasibility, safety and cost of 20 percent mass reduction on a 2017-2020 production ready mid-size CUV (crossover utility vehicle) specifically, a Toyota Venza while trying to achieve the same or lower cost. The EPA report is entitled “Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle.”[37] This study is a Phase 2 study of the low development design in the 2010 Lotus Engineering study "An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Vehicle Program"[38], herein described as "Phase 1."

The original 2009/2010 Phase 1 effort by Lotus Engineering was funded by Energy Foundation and ICCT to generate a technical paper which would identify potential mass reduction opportunities for a selected vehicle representing the crossover utility segment, a 2009 Toyota Venza. Lotus examined mass reduction for two scenarios – a low development (20 percent mass savings and 2017 production with technology readiness of 2014) and high development (40 percent mass savings and 2020 production with technology readiness of 2017). Lotus disassembled a 2009 Toyota Venza and created a bill of materials (BOM) with all components. Lotus then investigated emerging/current technologies and opportunities for mass reduction. The report included the BOM for full vehicle, systems, sub-systems and components as well as recommendations for next steps. The potential mass reduction for the low development design includes material changes to portions of the body in white (underfloor and body, roof, body side, etc.), seats, console, trim, brakes, etc. The Phase 1 project achieved 19 percent (without the powertrain), 246 kg, at 99 percent of original cost at full phase-in after peer review comments taken into consideration.[GG],[HH] This was calculated to be -$0.45/kg utilizing information from Lotus.

The peer reviewed Lotus Phase 1 study created a good foundation for the next step of analyses of CAE modeling for safety evaluations and in-depth costing (these steps were not within the scope of the Phase 1 study) as noted by the peer reviewer recommendations.[39]

Similar to Lotus Phase 1 study, the EPA Phase 2 study "low development" begins with vehicle tear down and BOM development. FEV and its subcontractors tore down a MY2010 Toyota Venza in order to create a BOM as well as understand the production methods for each component. Approximately 140 coupons from the BIW were analyzed in order to understand the full material composition of the baseline vehicle. A baseline CAE model was created based on the findings of the vehicle teardown and analysis. The model's results for static bending, static torsion, and modal frequency simulations (for evaluating NVH) were obtained and compared to actual results from a Toyota Venza vehicle. After confirming that the results were within acceptable limits, this model was then modified to create light-weighted vehicle models. EDAG reviewed the Lotus Phase 1 low development BIW ideas and found redesign was needed to achieve the full set of acceptable NVH characteristics. EDAG utilized a commercially available computerized optimization tool called HEEDS MDO to build the optimization model. The model consisted of 484 design variables, 7 load cases (2 NVH + 5 crash), and 1 cost evaluation. The outcome of EDAG's lightweight design optimization included the optimized vehicle assembly and incorporated the following while maintaining the original BIW design: optimized gauge and material grades for body structure parts, laser welded assembly at shock towers, rocker, roof rail, and rear structure subassemblies, aluminum material for front bumper, hood, and tailgate parts, TRBs on B-pillar, A-pillar, roof rail, and seat cross member parts, design change on front rail side members. EDAG achieved 13 percent mass reduction in the BIW including closure. If aluminum doors were included then an additional decrease of 28kg could be achieved for a total of 18 percent mass reduction from the body structure. All other systems

[GG] The original powertrain was changed to a hybrid configuration.

[HH] Cost estimates were given in percentages – no actual cost analysis was presented for it was outside the scope of the study, though costs were estimated by the agency based on the report.

within the vehicle were examined for mass reduction, including the powertrain (engine, transmission, fuel tank, exhaust, etc.). FEV and Munro incorporated the Lotus Phase 1 low development concepts into their own idea matrix. Each component and sub-system chosen for mass reduction was scaled to the dimensions of the baseline vehicle, trying to maximize the amount of mass reduction with cost effective technologies and techniques that are considered feasible and manufactureable in high volumes in MY2017. FEV included a full discussion of the chosen mass reduction options for each component and subsystem.

Safety performance of the baseline and light-weighted designs (Lotus Phase 1 low development and the final EPA Phase 2 design) were evaluated by EDAG through their constructed detailed CAD/CAE vehicle models. Five federal safety crash tests were performed, including FMVSS flat frontal crash, side impact, rear impact and roof crush (using IIHS resistance requirements) as well as Euro NCAP/IIHS offset frontal crash. Criteria including the crash pulse, intrusion and visual crash information were evaluated to compare the results of the light weighted models to the results of the baseline model. The light weighted vehicle achieved equivalent safety performance in all tests to the baseline model with no damage to the fuel tank. In addition, CAE was used to evaluate the BIW vibration modes in torsion, lateral bending, rear end match boxing, and rear end vertical bending, and also to evaluate the BIW stiffness in bending and torsion.

The Phase 2 study 2010 Toyota Venza lightweight vehicle achieved, with powertrain, a total weight savings of 18 percent (312 kg) relative to the baseline vehicle (1710 kg) at -$0.43/kg, and the cost figure is near zero at 20 percent. The study report and models have been peer reviewed by four technical experts from a material association, academia, DOE, and a National Laboratory. The peer review comments for this study were generally complimentary, and concurred with the ideas and methodology of the study. A few of the comments required further investigation, which were completed for the final report. The project team addressed the peer review comments in the report and also composed a response to peer review comment document. Changes to the BIW CAE models resulted in minimal differences. The final report is published in EPA's docket EPA-HQ-OAR-2010-0799 and the CAE LS DYNA model files and overview cost model files are found on EPA's website http://www.epa.gov/otaq/climate/publications.htm#vehicletechnologies. The peer review comments with responses to peer review comments can also be found at the same docket and website.

8.3.2.5 CARB Phase 2 Midsize CUV "High Development" Study

The California Air Resources Board (CARB) funded a study with Lotus Engineering to further develop the high development design from Lotus' 2010 Toyota Venza work ("Phase 1"). The CARB-sponsored Lotus "Phase 2" study provides the updated design, crash simulation results, detailed costing, and analysis of the manufacturing feasibility of the BIW and closures. Based on the safety validation work, Lotus strengthened the design with a more aluminum-intensive BIW (with less magnesium). In addition to the increased use of advanced materials, the new design by Lotus included a number of instances in which multiple parts were integrated, resulting in a reduction in the number of manufactured parts in the lightweight BIW. The Phase 2 study reports that the number of parts in the BIW was reduced from 419 to 169. The BIW was analyzed for torsional stiffness and crash test safety with Computer-Aided Engineering (CAE). The new design's torsional stiffness was 32.9 kNm/deg, which is higher than the baseline vehicle and comparable to more performance-oriented models. The research supported the conclusion that the lightweight vehicle design could pass standard FMVSS 208 frontal impact, FMVSS No. 210 seatbelt anchorages, FMVSS child restraint anchorage, FMVSS No. 214 side impact and side pole, FMVSS 216 roof crush (with 3xcurb weight), FMVSS 301 rear impact, IIHS low speed front, and IIHS low speed rear. Crash tests simulated in CAE showed results that were listed as acceptable for all crash tests analyzed. No comparisons or conclusions were made if the vehicle performed better or worse than the baseline Venza. For FMVSS 208 frontal impact, Lotus based its CAE crash test analyses on vehicle crash acceleration data rather than occupant injury as is done in the actual vehicle crash. The report from the study stated that accelerations were within acceptable levels compared to current production vehicle acceleration results and it should be possible to tune the occupant restraint system to handle the specific acceleration pulses of the Phase 2 high development vehicle. FMVSS No. 210 seatbelt anchorages are concerned with seatbelt retention and certain dimensional constraints for the relationship between the seatbelts and the seats. Overall both the front and rear seatbelt anchorages met the requirements specified in the standard. FMVSS No. 214 side impact show the energy is effectively managed. Since dummy injury criteria was not used in the CAE modeling, a maximum intrusion tolerance level of 300mm was instituted which is the typical distance between the door panel and most outboard seating positions. For example, the Phase 2 design was measured at 115mm for the crabbed barrier test. The side pole test resulted in 120mm intrusion for the 5th percentile female and intrusion was measured at 190mm for the 50th percentile male. The report stated FMVSS 216 roof crush simulation shows the Phase 2 high development vehicle will meet roof crush performance requirements under the specified load case of 3 times the vehicle weight. For the FMVSS rear impact, results show plastic strain in the fuel tank/system components to be less than 3.5 percent, which is less than the 10 percent strain allowed in the test. The pressure change in the fuel tank is less than 2 percent so risk of tank splitting is minimal. The IIHS low speed front and rear show no body structural issues, however styling adjustments should be made to improve the rear bumper low speed performance.

The Lotus design achieved a 37 percent (141 kg) mass reduction in the body structure, a 38 percent (484kg) mass reduction in the vehicle excluding the powertrain, and a 32 percent (537 kg) mass reduction in the entire vehicle including the powertrain. The report was peer reviewed by a cross section of experts and the comments were addressed by Lotus in the peer review documents. The comments requiring modification were incorporated into the final document. The documents can be found on EPA's website http://www.epa.gov/otaq/climate/publications.htm#vehicletechnologies.

8.3.2.6 EPA Light Duty Truck Study

The U.S. EPA contracted with FEV North America to perform this study utilizing the methodology developed in the Midsize CUV light -weighting effort (2012) and the study was completed in 2015. The results of this work went through a detailed and independent peer reviewed as well as through the SAE paper publication process. Feedback was received by OEM's and others independent of the official peer review process.

For this study a 2011 Silverado 1500 was purchased and torn down. The components were placed into 19 different systems. The components were evaluated for mass reduction potential given research into alternative materials and designs. The alternatives were evaluated for the best cost and mass reduction and then compared to each other. CAE analyses for NVH and safety was completed for the baseline and the light-weighted aluminum intensive vehicle. A high strength steel structure with aluminum closures was the first choice of a solution for this project; however, this was not fully completed for the decision was made by the project team to change course and pursue the aluminum structure solution due to the expected introduction of the aluminum intensive F150 into the marketplace. Durability analyses on both the baseline and light-weighted vehicle designs were performed through data gathered by instrumenting a Silverado 1500 light duty pickup truck and operating it over various road conditions. Included in the durability analyses are durability evaluations on the light weighted vehicle frame, door and other components in CAE space. The crash and durability CAE analyses allowed for gauge and grade determinations for specific vehicle components. Load path redesign of the light duty truck structure (cabin and box structure and vehicle frame) was not a part of this project.

Most mass reduction was achieved in the cabin and box structure and the closures, which were converted from steel to aluminum. The suspension system is the second highest system for mass reduction and includes composite fiber leaf springs. A 50kg and $150 allowance was considered to mitigate NVH. Secondary mass savings achieved were based on the amount of total primary mass reduction achieved. In this study the engine was able to be downsized 7 percent due to the mass reduction in the vehicle design and still maintain the current towing and hauling capacities. The other systems that were reduced in size, while considering truck performance characteristics, included the transmission, bumpers, suspension, brake, frame and mounting systems, exhaust, and fuel systems.

8.4 How have the Agencies Estimated Safety Effects for the Draft TAR?

8.4.1 What was the Agencies' Methodology for Estimating Safety Effects?

As explained above, the agencies consider the latest 2016 preliminary statistical analysis of historical crash data by NHTSA/Volpe to represent the current best estimates of the potential relationship between mass reduction and fatality increases in the future fleet. This section discusses how the agencies used the NHTSA/Volpe's 2016 preliminary analysis to calculate specific estimates of safety effects in the Draft TAR, based on the analysis of how much mass reduction manufacturers might use to meet the CAFE and GHG standards.

The CAFE/GHG standards do not mandate mass reduction, nor require that mass reduction occur in any specific manner. However, mass reduction is one of the technology applications available to the manufacturers and a degree of mass reduction is used by both agencies' models to determine the capabilities of manufacturers and to predict both cost and fuel consumption/emissions impacts of more stringent CAFE/GHG standards. To estimate the amount of mass reduction to apply in the rulemaking analysis, the agencies considered fleet safety effects for mass reduction. As shown in Table 8.3 and Table 8.4, both the Kahane 2012 final report and the NHTSA/Volpe 2016 preliminary report show that applying mass reduction to CUVs, minivans, and light duty trucks will generally decrease societal fatalities, while applying mass reduction to passenger cars will increase fatalities. The CAFE model uses coefficients from the 2016 preliminary report along with the mass reduction level applied to each vehicle model to project societal fatality effects in each model year. NHTSA used the CAFE model and conducted iterative modeling runs varying the maximum amount of mass reduction applied to each subclass in order to identify a combination that achieved a high level of overall fleet mass reduction while not adversely affecting overall fleet safety. These maximum levels of mass reduction for each subclass were then used in the CAFE model for the Draft TAR analysis. The agencies believe that mass reduction of up to 20 percent is feasible on light trucks, CUVs and minivans. Thus, the amount of mass reduction selected is based on our assumptions about how much is technologically feasible without compromising safety. While we are confident that manufacturers will build safe vehicles and meet (or surpass) all applicable federal safety standards, we cannot predict with certainty that they will choose to reduce mass in exactly the ways that the agencies have analyzed in response to the standards. In the event that manufacturers ultimately choose to reduce mass and/or footprint in ways not analyzed or anticipated by the agencies, the safety effects of the rulemaking may likely differ from the agencies' estimates.

In the 2012 final rule analysis, NHTSA utilized the 2012 Kahane study relationships between weight and safety, expressed as percent changes in fatalities per 100-pound mass reduction while holding footprint constant. However, several identifiable safety trends already were occurring, or expected to occur at the time of 2012 FRM, which were not accounted for in the study. For example, the two important new safety standards that were discussed above for electronic stability control and side curtain airbags, have already been issued and began phasing in after MY2008. Also in 2012, the shifts in market shares in 2012 from pickups and SUVs to cars and CUVs were growing due to high gasoline prices, but if the gasoline prices fell, then the demand for SUVs, CUVs or LDT could rise and consequent growth in vehicle miles travelled if the economy does not stagnate. And improvements in driver (and passenger) behavior, such as higher safety belt use rates, may continue. All of these will tend to reduce the absolute number of fatalities in the future. The agencies estimated the overall change in fatalities by calendar year after adjusting for ESC, Side Impact Protection, and other Federal safety standards and behavioral changes projected through this time period.

To estimate the amount of mass reduction to apply in the analysis, the agencies considered fleet safety effects for mass reduction. As previously discussed the agencies believe that mass reduction of up to 20 percent is feasible on light trucks, CUVs and minivans, [II] but that less mass reduction should be implemented on other vehicle types to avoid increases in societal fatalities. To find a safety-neutral compliance path for use in the agencies' Draft TAR analysis, NHTSA uses the fatality coefficients derived in the NHTSA/Volpe 2016 preliminary report with mass reduction levels presented in Table 8-11. Maximum mass reduction level are 7.5 and 10 percent for small and medium cars, respectively. Light trucks, CUVs, and minivans achieve mass reduction levels up to 20 percent.

Table 8.11 Mass Reduction Levels to Achieve Safety Neutral Results in the Draft TAR Analysis

Mass Reduction Level	Passenger Car			Light Truck			CUV/Minivan	
	SmallCar	MedCar	SmallSUV	SmallSUV	MedSUV	Pickup	SmallSUV	MedSUV
MR1	5%	5%	5%	5%	5%	5%	5%	5%
MR2	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%

[II] When applying mass reduction, NHTSA capped the maximum amount of mass reduction to 20 percent for any individual vehicle class. The 20 percent cap is the maximum amount of mass reduction the agencies believe to be feasible in MYs 2017-2025 time frame.

MR3	-	10%	10%	10%	10%	10%	10%	10%
MR4	-	-	15%	15%	15%	15%	15%	15%
MR5	-	-	20%	20%	20%	20%	20%	20%

Notes:
*MR1-MR5: different levels of mass reduction used in CAFE model

For the CAFE model, these percentages apply to a vehicle's total weight, including the powertrain. Table 8.12 shows the amount of mass reduction in pounds for these percentage mass reduction levels for average vehicle weight in each subclass.

Table 8.12 Examples of Mass Reduction (in Pounds) for Different Vehicle Subclasses Using the Percentage Information as Defined for the CAFE Draft TAR Analysis

Mass Reduction (lbs)	Passenger Car			Light Truck			CUV/Minivan	
	Small Car	Med Car	Small SUV	Small SUV	Med SUV	Pickup	Small SUV	Med SUV
Average Vehicle Weight (sales-weighted)	2,908	3,576	3,490	3,693	4,633	5,053	3,621	4,348
MR1: 5%	145	179	175	185	232	253	181	217
MR2: 7.5%	218	268	262	277	347	379	272	326
MR3: 10%	-	358	349	369	463	505	362	435
MR4: 15%	-	-	524	554	695	758	543	652
MR5: 20%	-	-	698	739	927	1,011	724	870

These maximum amounts of mass reduction discussed above were applied in the technology input files for the CAFE model. NHTSA divides vehicles into classes for purposes of applying technology in the CAFE model in a way that differs from the Kahane study which divides vehicles into classes for purposes of determining safety coefficients. These differences require that the "safety class" coefficients be applied to the appropriate vehicles in the CAFE "technology subclasses." For the reader's reference, for purposes of this Draft TAR, the safety classes and the technology subclasses relate[JJ] as shown in 3.

[JJ] This is not to say that all vehicles within a technology subclass will necessarily fall within a single safety class – as the chart shows, some technology subclasses are divided among safety classes.

Table 8.13 Mapping between Safety Classes and Technology Classes in the CAFE Analysis

Safety Class	Technology Class
PC (Passenger Car)	Small Car
	Medium Car
	Small SUV
LT (Light Truck)	Small SUV
	Medium SUV
	Pickup
CM (CUV and Minivan)	Small SUV
	Medium SUV

Note:*CM = CUV and MiniVan

Table 8.144 shows CAFE model results for societal safety for each model year based on the application of the above mass reduction limits.[KK] These are the estimated increases or decreases in fatalities over the lifetime of the model year fleet. A positive number means that fatalities are projected to increase, a negative number (indicated by parentheses) means that fatalities are projected to decrease. The results are significantly affected by the mass reduction limitations used in the CAFE model, which allow more mass reduction in light trucks, CUVs, and minivans than in other vehicles. As the negative coefficients only appear for light trucks, CUVs, and minivans, a statistically significant improvement in safety can only occur if more weight is taken out of these vehicles than out of passenger cars. Combining passenger car and light truck safety estimates for the Draft TAR analysis results in a decrease in fatalities over the lifetime of the nine model years of MY2017-2025 of 24 fewer fatalities with the 2015 baseline. Broken up into passenger car and light truck categories, there is an increase of 464 fatalities in passenger cars and a decrease of 488 fatalities in light trucks with the 2015 baseline.

Table 8.14 NHTSA Calculated Mass-Safety-Related Fatality Impacts of the Draft TAR Analysis over the Lifetime of the Vehicles Produced in each Model Year Using 2015 Baseline

Regulatory Class	MY 2017	MY 2018	MY 2019	MY 2020	MY 2021	MY 2022	MY 2023	MY 2024	MY 2025	Total
Passenger Cars	1	9	11	21	58	70	84	98	114	465
Light Trucks	0	1	(46)	(48)	(44)	(52)	(108)	(104)	(125)	(525)
Total	1	12	(35)	(28)	13	17	(24)	(6)	(11)	(61)

Using the same coefficients from the 2016 NHTSA/Volpe study, EPA used the OMEGA core model to estimate the impact of weight reduction on net fatalities per mile driven by the fleet. This is done using the weight reductions applied by OMEGA and applying to those weight reductions the safety metrics shown in Table 8.15. The "Change per 100 lbs" column, presented earlier in Chapter 8 (Table 8.4) shows the change in the number of fatalities as a percentage for

[KK] NHTSA has changed the definitions of a passenger car and light truck for fuel economy purposes between the time of the Kahane 2003 analysis and the NPRM (as well as the final rule). About 1.4 million 2 wheel drive SUVs have been redefined as passenger cars instead of light trucks. The Kahane 2011 and 2012 analyses and the 2016 NHTSA/Volpe study continue to use the definitions used in the Kahane 2003 analysis.

each 100 pounds of weight removed from vehicles described by the "Safety Class Description" column. The "FMVSS Adjustment" factor is also applied to calculate the impact on fatalities per billion miles of vehicle travel. All of the inputs presented in Table 8.15 are consistent with inputs used in the CAFE modeling supporting NHTSA's analysis.[40]

Table 8.15 Metrics Used in the OMEGA Safety Analysis

Safety Class Description	Change per 100 lbs	Base per billion miles	FMVSS Adjustment
PC below 3197	1.49%	13.59	0.904
PC above 3197	0.51%	11.15	0.904
LT below 4947	-0.10%	14.35	0.904
LT above 4947	-0.72%	16.06	0.904
CUE Minivan	-0.99%	9.00	0.904

Using these metrics, EPA calculated the impact of mass reduction on net vehicle-related fatalities, as shown in Table 8.16, which shows the results of EPA's safety analysis over the lifetimes of MY2021 to 2025 vehicles (EPA explains in Chapter 12 why MY2021 vehicles are included even though this Draft TAR is considering the MY2022 to 2025 standards). A positive number would mean that fatalities are projected to increase; a negative number means that fatalities are projected to decrease. As shown, the EPA analysis projects considerable fatality decreases in the reference and control cases. Those decreases should be seen as being relative to the current fleet moving forward in time without mass reductions in response to new standards (i.e., relative to the projected MY2021 through 2025 baseline fleet). The reference case standards reduce fatalities relative to the projected baseline fleet (a fleet that continues to meet the 2014 standards in place for the year upon which our baseline fleet is generated) due to mass reduction done to move the fleet from the 2014 standards to the 2021 standards (the reference case standards). In the reference case, those 2021 standards continue indefinitely for subsequent model year vehicles. The control case (i.e., the 2022 through 2025 standards) then result in further mass reduction beyond the reference case level. This further mass reduction further reduces fatalities relative to both the baseline and reference cases. On net, the EPA analysis shows small net fatality decreases over the lifetimes of MY2021 through 2025 vehicles.

Table 8.16 EPA's Net Fatality Impacts over the Lifetimes of MY2021-2025 Vehicles

Case	Fatality Impacts Reference Case	Fatality Impacts Control Case	Net Fatality Impacts
AEO 2015 reference fuel price case using ICMs	-800	-874	-74
AEO 2015 high fuel price case using ICMs	-448	-484	-36
AEO 2015 low fuel price case using ICMs	-994	-1063	-69
AEO 2015 reference fuel price case using RPEs	-923	-929	-6

8.4.2 Why Might the Real-World Safety Effects be Less Than or Greater Than What the Agencies Have Calculated?

As discussed above, the ways in which future technological advances could potentially mitigate the safety effects estimated for this Draft TAR include the following: lightweight vehicles could be designed to be both stronger in materials without becoming more intrusive in crash force; restraint systems could be improved to deal with higher crash pulses in lighter vehicles; crash avoidance technologies could reduce the number of overall crashes; roofs could be strengthened to improve safety in rollovers. As also stated above, however, while we are confident that manufacturers will strive to build safe vehicles, it will be difficult for both the agencies and the industry to know with certainty ahead of time how crash trends will change in the future fleet as light-weighted vehicles become more prevalent. Going forward, we will continue to monitor the crash data as well as changes in vehicle mass and conduct analyses to understand the interaction of vehicle mass and size on safety.

Additionally, we note that the total amount of mass reduction used in the agencies' analysis was chosen based on our assumptions about how much is technologically feasible without compromising safety. Again, while we are confident that manufacturers are motivated to build safe vehicles, we cannot predict with certainty that they will choose to reduce mass in exactly the ways or amounts that the agencies have analyzed in response to the standards. In the event that manufacturers ultimately choose to reduce mass and/or footprint in ways not analyzed by the agencies, the safety effects may likely differ from the agencies' estimates.

The agencies note that the standard is flat for vehicles smaller than 41 square feet and that downsizing in this category could help achieve overall compliance, if the vehicles are desirable to consumers. The agencies note that 4.4 percent of MY2015 passenger cars were below 41 square feet, and due to the overall lower level of utility of these vehicles, and the engineering challenges involved in ensuring that these vehicles meet all applicable federal motor vehicle safety standards (FMVSS), we do not expect a significant increase in the use of mass reduction in this segment of the market.

The agencies acknowledge that the final rule did not prohibit manufacturers from redesigning vehicles to change wheelbase and/or track width (footprint). However, as NHTSA explained in promulgating the MY2008-2011 light truck CAFE standards and the MY2011 passenger car and light truck CAFE standards, and as the agencies jointly explained in promulgating the MYs 2012-2016 CAFE and GHG standards, we believe that such engineering changes are significant enough to be unattractive as a measure to undertake solely to reduce compliance burdens.

Similarly, the agencies acknowledge that a manufacturer could, without actually reengineering specific vehicles to increase footprint, shift production toward those that perform well with respect to their footprint-based targets. However, NHTSA and EPA have previously explained, because such production shifts could run counter to market demands, they could also be competitively unattractive.

8.4.3 What Are the Agencies' Plans Going Forward?

The agencies continue to closely monitor the visible effects of CAFE/GHG standards on vehicle safety as these standards are implemented, and will conduct a full analysis of safety impacts as part of further steps in EPA's midterm evaluation and NHTSA's future rulemaking to establish final MYs 2022-2025 standards.

NHTSA will closely monitor the safety data, the trends in vehicle weight and size, the trends in vehicle mass reduction, as well as the trend for the active and passive vehicle safety during the period between the release of this Draft TAR and the future rulemaking to establish final CAFE standards for MYs 2022-2025. Consistent with confidentiality and other requirements, NHTSA intends to make these data publicly available when they are compiled. NHTSA will also make appropriate updates to the statistical study of historical data on the effects on mass and size societal safety on an ongoing basis. At the same time, working closely with EPA and DOE, NHTSA will continue to assess its analytical methods for assessing the effects of vehicle mass and size on societal safety and make appropriate updates, including a final version of the 2016 NHTSA/Volpe preliminary report.

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Chapter 9: Assessment of Alternative Fuel Infrastructure

9.1 Overview

As part of the midterm evaluation, one of the relevant factors to be examined included "actual and projected availability of public and private charging infrastructure for electric vehicles, and fueling infrastructure for alternative fueled vehicles."[1] In September 2010, EPA, NHTSA, and CARB issued a joint interim technical assessment report (TAR, or 2010 TAR) on light-duty vehicle GHG emission standards and Corporate Average Fuel Economy (CAFE) standards for model years 2017-2025, which supported the final rulemaking issued in 2012. The 2010 TAR included a discussion of infrastructure for plug-in electric vehicles (PEVs) and hydrogen fueled fuel cell electric vehicles (FCEVs). These analyses recognized PEVs and FCEVs, among others, as technologies that could potentially be used to meet future CAFE and GHG standards. In the 2012 final rule, EPA and NHTSA projected that only a few percent of PEVs, and no FCEVs, would be needed to meet the MY2025 standards; the agencies' show similar projections with this Draft TAR analysis as discussed in Chapters 12 and 13. Since then, electric drive vehicles have entered the market with significant growth in the number of models offered and have proven to reduce or eliminate GHG emissions and improve fuel economy compared to conventional technologies. In addition, electric drive vehicles have the potential to derive some or all of their fuel from sustainable pathways with up to 100 percent renewable fuel sources. With zero tailpipe emissions, and with nearly half of Americans living in the regions where PEVs produce lower GHG emissions than even the most fuel-efficient gasoline hybrids on the market today (greater than 50 mpg)[2], electric drive vehicles hold the promise to dramatically transform the future vehicle fleet into one with a lower carbon footprint and petroleum consumption.

Though the agencies are projecting in this Draft TAR that only a very small fraction of the fleet will need to be PEVs to meet the MY2025 standards, alternative fuel vehicles such as battery electric vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) (collectively called PEVs), and FCEVs are an essential part of any future vehicle fleet intended to meet long term climate and air quality goals. In additional, other alternative fuels such as ethanol (E85) and compressed natural gas (CNG) have the potential to contribute to GHG emission reductions. This chapter is intended to provide an overview of the status, costs, and trends in PEV charging infrastructure and hydrogen infrastructure today, as well as examine the challenges being addressed to scale up the infrastructure as advanced vehicle sales grow in response to market demand and for compliance with the federal standards.

Electric vehicle charging infrastructure is different from other alternative fuel infrastructure. PEVs rely on access to the existing electric grid and distribution network. At a minimum, most PEVs can charge at low power using the charging equipment supplied with the vehicle; all they need is access to a standard household electrical outlet with a dedicated circuit. Since the 2012 FRM, the U.S. Department of Energy (U.S. DOE) has supported efforts to study how and where PEV drivers charge their vehicles. This research reveals that, currently, the majority of charging is taking place at home.[3] Further, public and workplace charging network infrastructure has greatly expanded, offering higher power charging in a greater number of locations. This rapid expansion of PEV infrastructure is continuing to alter the paradigm of charging behavior and PEV use patterns. This dynamic paradigm coupled with a rapidly expanding PEV infrastructure landscape and evolving battery/vehicle technology will impact how additional PEV infrastructure is planned and developed; it may actually lessen the need for, or change the power requirements of, future public infrastructure. As discussed more fully in section 9.2, PEV charging infrastructure expansion may transform how PEVs are viewed and ultimately change their usage patterns. However, charging infrastructure growth will adjust as vehicle needs change.

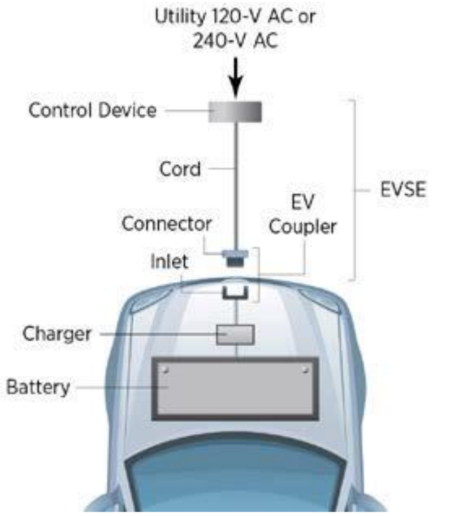
With regard to hydrogen FCEVs, a robust network of hydrogen stations, comparable to conventional gasoline stations, is required to facilitate wide-spread commercialization. Although California may be the first state to plan, fund, and develop a hydrogen station network, other regions, such as the Northeast states, have commenced hydrogen infrastructure planning and development.

This chapter will examine the status of hydrogen fueling infrastructure in the United States with a focus on progress in California and the Northeast states. Section 9.3 will draw from California's work in planning, funding, and development of a statewide hydrogen station network and apply the lessons learned from these efforts toward a national hydrogen infrastructure. With current public and private investments in California, the hydrogen network is currently sufficient for FCEVs to launch in California and establish an example for how other regions can further develop their markets around the country. While the agencies do not expect FCEVs to be needed to meet the 2025 national program standards, the agencies recognize the importance of these vehicles in meeting longer term climate goals.

This chapter also discusses the status and trends in fueling infrastructure for compressed natural gas (CNG) vehicles and E85 (Flex-Fuel) vehicles.

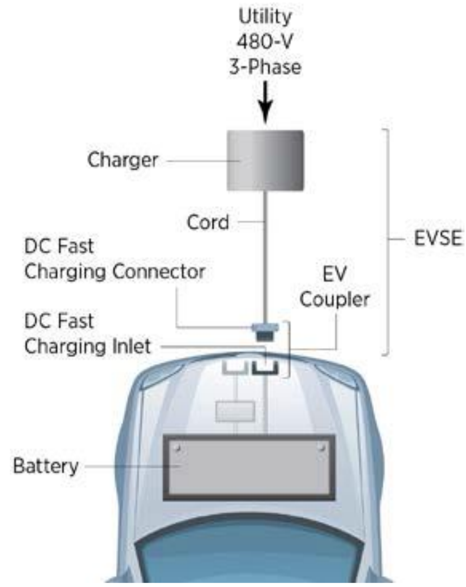
9.2 Electric Vehicle Infrastructure

PEVs store electrical energy in on-board batteries that supply power to electric motors for vehicle propulsion. Today's PEVs have on-board chargers, which are systems that monitor, regulate, and convert AC power from an external source to DC power for on-board storage. The electricity supplied to these on-board chargers can be managed by off-board Electric Vehicle Supply Equipment (EVSE) devices which include connectors with well-insulated power cables, energy management systems, and telemetry systems. EVSEs are often called "chargers" even though they do no actual charging. (Figures 9.1a and 9.1b) details the components of an EVSE and related vehicle and utility equipment associated with various types of charging described later in the document.



AC Level 1 & Level 2 Charging Schematic

Figure 9.1a



DC Fast Charging Schematic

Figure 9.1b

Figure 9.1 Charging Schematics for Electric Vehicles[4]

9.2.1 Classification of Electric Vehicle Supply Equipment (EVSE)

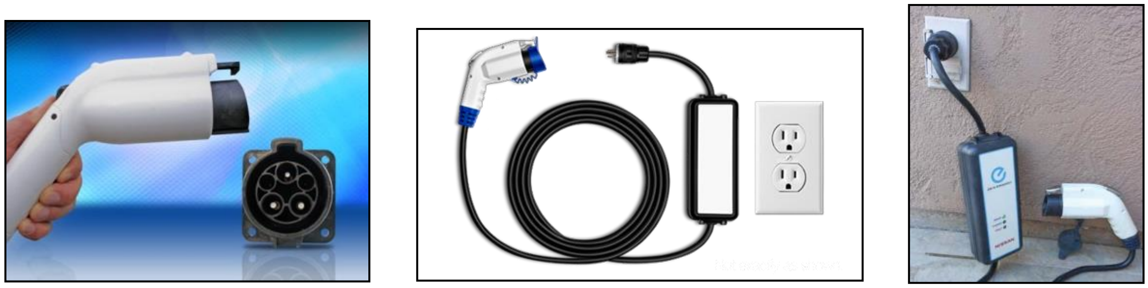
EVSE devices are typically classified as Level 1, Level 2, or DC Fast Charge. Each of these types of EVSE is described in further detail below.

9.2.1.1 Level 1 EVSE

The lowest power, and most common, EVSE is often referred to as Level 1 or a "Level 1 charger" or "Level 1 cord set." A Level 1 cord set provides AC power at 120 volts, and 12 amps from a standard 3-prong (NEMA 5-15) household electrical plug/receptacle. Most household garages have a standard 3-prong electrical receptacle on a 15 amp circuit so no additional electrical work or expense is required. Although there is no additional expense in this scenario, the power transfer under Level 1 charging is ultimately limited by the available circuit amperage.

Most, if not all, OEMs provide a Level 1 cord set at no additional charge with each sale or lease of a PEV. Since the cost of the Level 1 cord set is factored into the price of the vehicle, there is no additional out-of-pocket expense to the consumer opting to use this option to charge their vehicle.

The hardware at the end of the cord set that physically attaches to the vehicle is called a connector and is designed to a common architecture standard specified by SAE J1772. This ensures operational and dimensional interoperability between vehicle OEMs and electrical equipment suppliers. The J1772 connector utilizes 5 pins to deliver up to 240V at 80 amps of AC power to the vehicle. The J1772 connector is used in both Level 1 and Level 2 charging. In a Level 1 cord-set, one end terminates in a J1772 connector while the other end terminates in a standard household 3-prong electrical plug (see Figure 9.2 below).



From PR Log **From Plug-In America** **From PEV Collaborative**

Figure 9.2 J1772 Connector and Cord Sets for Level 1 EVSEs

As mentioned, Level 1 EVSEs provide a low level of power, typically 120V AC at 12 amps, to the vehicle. At maximum power, a Level 1 EVSE will fully charge a 2015MY Nissan Leaf in 17 hours or a 2015MY Chevrolet Volt in approximately 8 hours. The most common application of Level 1 charging is residential over-night or in the workplace where a driver may park for 8 to 9 hours a day. Due to the relatively slow charge rate of only 2-5 miles of range per hour charging, Level 1 EVSEs may be most appropriate for PHEVs with smaller battery packs or for BEVs at locations with long dwell times. As battery size and vehicle range continues to grow with new PEV product offerings, the practicality of Level 1 may decrease.

9.2.1.2 Level 2 EVSE

For higher power charging, a Level 2 EVSE provides AC power up to 240V at up to 80 amps. Level 2 EVSEs also use the aforementioned SAE J1772 connector. A Level 2 EVSE can be either hard-wired to a dedicated building circuit or plugged into a 240V wall receptacle similar to that used for an electric dryer, range, or recreational vehicle (RV) electrical receptacle. A Level 2 EVSE is not standard with the purchase of most PEVs. In addition, many household garages do not have the required wiring to support a Level 2 EVSE. Therefore, additional costs are associated with installing Level 2 charging; these cost are discussed in section 9.2.3.

The advantage of a Level 2 EVSE over a Level 1 EVSE is the higher power output. This allows most PEVs to charge in a fraction of the time required using Level 1 EVSEs. For example, a Level 2 EVSE can charge a 2015MY Nissan Leaf equipped with a 6.6kW on-board charger in approximately 4 hours. Since a Level 2 EVSE can deliver more power to a PEV's on-board charger, they are most appropriate for PEVs with larger batteries, or in locations where the vehicle may have a shorter dwell time, such as parking lots, shopping centers, churches, libraries, civic buildings, college campuses, etc. Figure 9.3 below depicts several commercial and residential Level 2 EVSEs.

From Clipper Creek **From AeroViroment** **From Charge Point**

Figure 9.3 Commercial and Residential Level 2 EVSEs

9.2.1.3 Direct Current (DC) Fast Charge

Direct Current (DC) Fast Charge is a fast, high power charging system that uses high voltage, 3-phase Alternating Current (AC) grid electricity and converts it to DC power for direct storage in vehicle batteries. Unlike Level 1 and Level 2 charging, the conversion of AC power to DC power occurs off-board in the charging equipment. This additional conversion equipment combined with the very high input power (3-phase at 480V or higher) makes DC Fast Charge systems significantly higher in cost to install, operate, and maintain. As a result, nearly all DC Fast Chargers are located in public, workplace, or commercial settings.

Table 9.1 details the various charging levels, the supply power requirements, and the additional ranges per unit of time and power.

Table 9.1 Vehicle Range Added at Various Charging Levels[5]

Charging Level	Vehicle Range Added per Charging Time and Power	Supply Power
AC Level 1	4 mi/hour @ 1.4kW 6 mi/hour @ 1.9kW	120VAC/20A *(12-16A continuous)*
AC Level 2	10 mi/hour @ 3.4kW 20 mi/hour @ 6.6kW 60 mi/hour @ 19.2 kW	208/240VAC/20-100A *(16-80A continuous)*
DC Fast Charging	24 mi/20minutes @24kW 50 mi/20minutes @50kW 90 mi/20minutes @90kW	208/480VAC 3-phase *(input current proportional to output power; ~20-400A AC)*

DC fast chargers can have different types of connectors (to connect to the vehicle itself); currently there is no universal standard. Generally, DC fast charge connectors fall into one of three types: SAE Combo Connector, CHAdeMO,[A] or Tesla Superchargers and examples of each are provided in Figure 9.4 below.

Tesla Connector **SAE Combo** **CHAdeMO**

Figure 9.4 DC Fast Charge Connectors

Figure 9.5 below details the SAE J1772 connector, the SAE Combo connector (DC Fast charge) and the charging times associated with each. For example, using a Level 2 EVSE, a BEV with a 25 kWh battery pack and a 6.6 kW on-board charger, can charge from a 20 percent state of charge (SOC) to a 100 percent SOC in approximately 3.5 hours. Using DC fast charge, this same vehicle can complete the same charge in approximated 1.2 hours. Given the shorter charge times associated with DC fast charging, this type of infrastructure is well suited for interregional corridors or along interstate routes.

	**AC level 1** (SAE J1772™) PEV includes on-board charger 120V, 1.4 kW @ 12 amp 120V, 1.9 kW @ 16 amp Est. charge time: PHEV: 7hrs (SOC* - 0% to full) BEV: 17hrs (SOC – 20% to full)		**DC Level 1** (SAE J1772™) EVSE includes an off-board charger 200-500 V DC, up to 40 kW (80 A) Est. charge time (20 kW off-board charger): PHEV: 22 min. (SOC* - 0% to 80%) BEV: 1.2 hrs. (SOC – 20% to 100%)
	AC level 2 (SAE J1772™) PEV includes on-board charger (see below for different types) 240 V, up to 19.2 kW (80 A) Est. charge time for 3.3 kW on-board charger PEV: 3 hrs (SOC* - 0% to full) BEV: 7 hrs (SOC – 20% to full) Est. charge time for 7 kW on-board charger PEV: 1.5 hrs (SOC* - 0% to full) BEV: 3.5 hrs (SOC – 20% to full) Est. charge time for 20 kW on-board charger PEV: 22 min. (SOC* - 0% to full) BEV: 1.2 hrs (SOC – 20% to full)		**DC Level 2** (SAE J1772™) EVSE includes an off-board charger 200-500 V DC, up to 100 kW (200 A) Est. charge time (45 kW off-board charger): PHEV: 10 min. (SOC - 0% to 80%) BEV: 20 min. (SOC – 20% to 80%)

Voltages are nominal configuration voltages, not coupler ratings
Rated Power is at nominal configuration operating voltage and coupler rated current
Ideal charge times assume 90% efficient chargers, 150W to 12V loads and no balancing of Traction Battery Pack

Notes:
1) BEV (25 kWh usable pack size) charging always starts at 20% SOC, faster than a 1C rate (total capacity charged in one hour) will also stop at 80% SOC instead of 100%
2) PHEV can start from 0% SOC since the hybrid mode is available. *ver. 100312*

Figure 9.5 SAE Charging Configurations and Ratings Terminology

[A] CHAdeMO is an abbreviation of the phrase "CHArge de MOve," which is equivalent to the translation of Japanese phrase "move using charge" or "move by charge."

9.2.2 Where People Charge

In the most general terms, charging of a PEV occurs in one of two places: at home or away from home. Away from home charging can be further subdivided into workplace charging or non-work (public) charging. Both home and the workplace are well suited for Level 1 charging since an individual usually spends several contiguous hours at both locations. Some public installations, like airport parking, can be accommodated with Level 1 EVSEs. Movie theaters, shopping centers, hospitals, churches, or other publicly accessible locations are better suited for Level 2 EVSEs since an individual usually has a shorter dwell time at these public charging locations. DC fast charging sites could be well placed along routes serving inter-regional or inter-state travel such as roadside rest areas. DC fast charge locations are much less common than Level 1 or Level 2 charging sites. As detailed in section 9.2.1.3, DC fast chargers deliver high, direct current power to a PEV and are most appropriate where vehicles have a short dwell time and need a large amount of power.

Many studies have been, and continue to be, conducted on the charging patterns and behaviors of PEV drivers. The results from these various studies can be summarized using a construct called the "charging pyramid." Argonne National Laboratory developed one such "charging pyramid" (Figure 9.6) which graphically depicts the interconnected relationships between charger type, location, costs, and frequency of charge events. The majority of charging events occur at home, at lower costs, and over longer periods of time. However, as power transfer rates increase, charging time decreases, but costs increase leading to fewer charging events at that level. As the charging pyramid depicts, the majority of charge events occur at low cost Level 1, followed by more expensive Level 2. The fewest charging events occur at relatively high cost DC fast chargers.

Source: Argonne National Laboratory

Figure 9.6 Charging Pyramid

One study regarding charging behavior was conducted with the EV Project by the Idaho National Laboratory (INL). In 2009, the U.S. DOE funded the EV Project which was an infrastructure deployment and analysis project where one of the goals was to evaluate the effectiveness of PEV infrastructure. The ultimate goal of the EV Project was to utilize lessons learned from the early deployment of infrastructure and vehicles and enable the efficient deployment of subsequent PEVs and infrastructure across the United States.

The EV Project included an analysis of the charging patterns of over 4,000 Nissan Leaf drivers studied from October 2012 through December 2013. Study participants were given a Level 2 EVSE for home charging, and their vehicles were outfitted with tracking devices. Although the participants were early adopters and had access to Level 2 charging, the key finding of this study can be interpreted for the larger PEV population. Figure 9.7 shows the key findings:

- Leaf drivers relied on home charging for the bulk of their charging. Of all charging events, 84 percent were performed at drivers' home locations. Over 80 percent of those home charges were performed overnight, and about 20 percent of home charges were performed between trips during the day.

- The remaining 16 percent of charging events were performed away from home. The vast majority of these were daytime Level 1 or Level 2 charges.

- Overall, usage of DCFC (DC fast charging) by drivers of vehicles in this study, all having access to a Level 2 charging unit at home and some having workplace charging access, was low. DC fast charging (all away from home) represented only about 1 percent of all charging events and charging energy consumed. Ignoring charges by vehicles that never charged away from home, DC fast chargers were used for 6 percent of all away-from-home charging events. However, some drivers used DC fast chargers more than others and may have relied on fast charging to meet their need for driving range.

- Although all vehicles in this study had access to home charging, some vehicles rarely charged at home. Instead, they relied on frequent away-from-home charging during the day. This demonstrates the viability of publicly accessible and/or workplace charging infrastructure for drivers of electric vehicles without access to home charging.

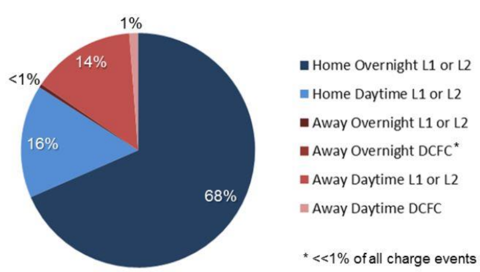


Figure 1. Percent of charging events performed by location, power level, and time of day.

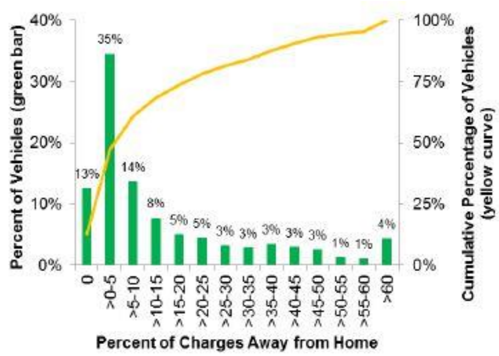


Figure 9.7 Key Findings of the EV Project by INL[6]

In addition to INL's work on PEV charging, in 2013, the Institute of Transportation Studies at the University of California, Davis (ITS-Davis) published a white paper titled, *California Statewide Charging Assessment Model for Plug-in Electric Vehicles: Learning from Statewide Travel Survey*.[7] This research focused on how different infrastructure types/locations can enable more BEV driving. (See Figure 9.8).

- If all statewide vehicles were 80 mile range BEVs and began the day with a full charge, 71 percent of miles (95 percent of home-based tours) are possible with home charging alone. Travel that requires some charging accounts for a corresponding 29 percent of miles (5 percent of tours). See chart below.
- Workplace charging can enable about 7 percent more electric vehicle miles traveled (eVMT), public Level 2 at stops greater than 1.5 hours could provide an additional 4 percent of eVMT, and DC fast charging could provide an additional 12 percent of eVMT.
- Scenarios show that for a 30 mile range PHEV, 61 percent of miles could be completed with home charging alone.[4]

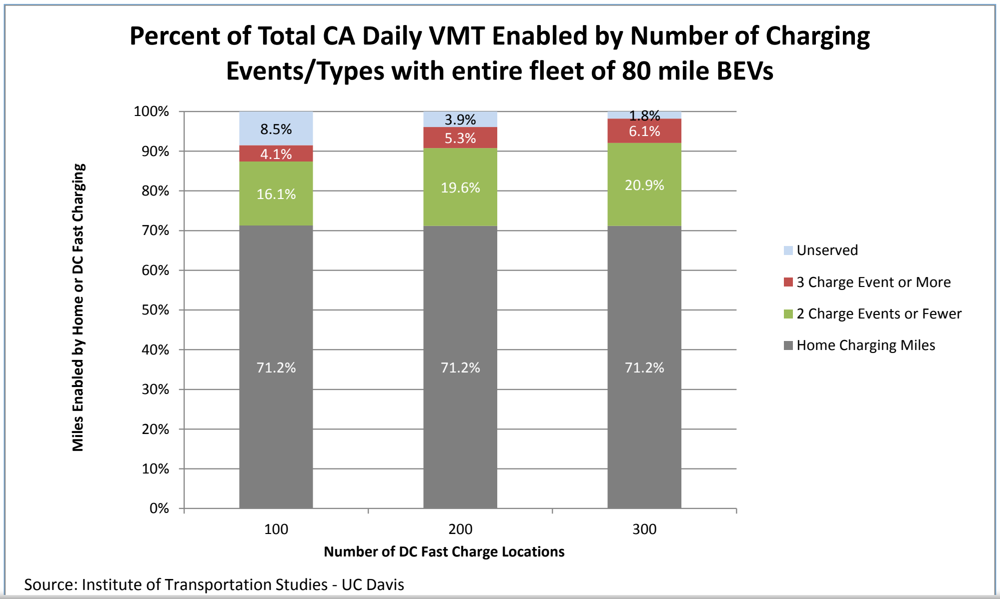


Figure 9.8 Key Findings of the UC Davis White Paper on EV Charging

Building upon the body of knowledge developed by INL, UC Davis and others, the California Energy Commission (CEC) sponsored the National Renewable Energy Laboratory (NREL) to conduct a PEV Infrastructure analysis for California. This analysis was developed with the goal of facilitating charging infrastructure for 1.5 million ZEVs on California roadways by 2025 as envisioned by California Governor Jerry Brown's Executive Order B-16-2012 in March 2012. Key findings from NREL's assessment are described in Figure 9.9 below.

- Entities should identify their objectives for installing EVSE before trying to determine EVSE numbers, types (such as, Level 1, Level 2, or fast charge), and locations.
- Near-term PEV charging will occur primarily at home, so this is the greatest opportunity for charging infrastructure support for the next few years. Other outstanding near-term infrastructure opportunities include workplaces and multiunit dwellings where management has indicated support for infrastructure and surveys indicate likely PEV adoption; garaged fleet locations that have or will have significant numbers of PEVs; and crowded airport and commuter parking locations, provided certain conditions are met.
- In many cases, there should be a reasonable belief that installed EVSE will be used by significant numbers of PEVs; however, there are compelling reasons to consider installing EVSE infrastructure besides expected short-term use. Some of these reasons address safety and convenience concerns, as well as building consumer confidence in PEVs and associated infrastructure.

Figure 9.9 Key Findings of NREL's California Statewide PEV Infrastructure Assessment

Ultimately, uncertainty regarding "where people charge" will be managed with the growth of various charging infrastructure investments and pricing policies. At this time, there does not appear to be a clear trend or convergence for where non-home based charging will occur. However, the following factors will likely continue to influence where charging occurs:

- PEV vehicle technology (especially driving range and rate of charging) influencing the need and convenience of daily, nightly, or travel corridor charging
- Employers increasingly providing workplace charging[8]
- Many public chargers currently operating for free may eventually implement fees to charge, (again, no clear trend has yet been established but a wide range of fees and non-fee structures are being explored depending on the site host business model)
- Electric utilities are beginning to make direct investment in the PEV infrastructure (see section 9.2.4.5) and may distribute the costs over a large ratepayer population
- DC Fast charge networks are growing rapidly and may affect usage of Level 2 EVSEs

9.2.3 Installation Costs and Equipment Costs

One factor driving PEV adoption rates is the cost savings related to fuel. Electricity is cheaper than gasoline on a per-mile basis; refueling a PEV may require additional equipment and installation costs. This section will explore costs related to capital equipment and installation for PEV refueling.

As referenced in section 9.2.2, the majority of PEV drivers predominantly charge at home. Approximately 85 percent of charging events occur at home and much of that is at Level 1. Since Level 1 cord-sets typically are included with PEVs, and many homes have a 120V power outlet in close proximity to the PEV, a large portion of PEV drivers incur no additional expense related to EVSE purchase or EVSE installation costs.

9.2.3.1 Installation Costs (Residential and Non-Residential)

In November 2015, the U.S. DOE released a report titled, *Costs Associated With Non-Residential Electric Vehicle Supply Equipment*. This report provides the most recent compilations of EVSE costs and factors influencing cost trends. This report was a synthesis of various studies on the subject in addition to data collected from EVSE owners, electric utilities, manufacturers, and installers. One study included in this synthesis was a 2013 report from the Electric Power Research Institute (EPRI) titled *Electric Vehicle Supply Equipment Installed Cost Analysis*.

The 2015 U.S. DOE report identified several cost drivers associated with the installation of Level 2 EVSEs. These drivers include:

- Trenching or boring to install electrical conduit from the transformer to the electrical panel or from the electrical panel to the EVSE;
- Upgrading the electrical panel to create dedicated circuits for each EVSE;
- Upgrading the electrical service to provide sufficient electrical capacity for the site;
- Locating EVSE on parking levels above or below the level with electrical service;
- Meeting accessibility requirements such as ensuring the parking spaces are level.

Figure 9.10 shows some important messages from the reports:

- It is important to work with the electric utility early in the process to minimize costs, optimize the electrical design, and eliminate scheduling bottlenecks.
- Level 2 commercial sites that required special work such as trenching or boring were about 25 percent more costly than those that did not need special work.
- Fundamental EVSE Electrical Needs:
  1. A dedicated circuit for each EVSE unit on the electrical panel.
  2. Sufficient electrical capacity from the utility connection to the electrical panel.
  3. Sufficient electrical capacity at the panel.
- Assuming $100 per foot to trench through concrete, lay the conduit, and refill, it would cost $5,000 to trench 50 feet.
- Upgrading the electrical service for future EVSE loads and installing conduit to future EVSE locations during the initial EVSE installation can result in significant future cost savings.

Figure 9.10 Important Messages from the 2013 EPRI and 2015 DOE Reports

The 2015 U.S. DOE report identifies labor costs associated with non-residential EVSE installation as a variable but ultimately based on the contractor's hourly rate and the time it takes to perform the work. These costs are affected by the contractor's experience and typical labor rates in the geographic location.

Residential installation costs for Level 2 EVSEs can vary significantly by geographic region. This may be attributed to varying labor rates and material costs across regions, as well as the condition and age of existing housing stock. For example, the EPRI report suggests that between 10 and 20 percent of the installations studied required electrical upgrades.[9] These upgrades and associated costs are less necessary in newer construction where higher capacity electrical panels are more common. Additionally, installation costs are lowest when a home has an existing 240V receptacle on a dedicated circuit. Figure 9.11 from the EPRI report illustrates the geographic installation costs for Level 2 EVSEs in 12 regions across the United States.

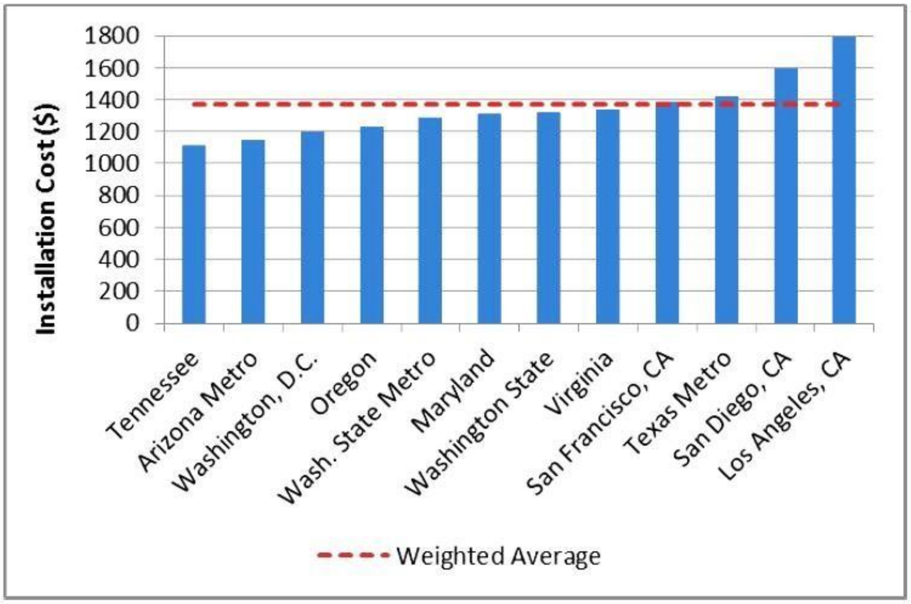


Figure 9.11 Average Residential Level 2 Installation Costs by Metro Area[10]

9.2.3.2 Installation Costs Trends

EVSE installation costs have been trending downward since 2009. As mentioned, many of the installations included in the EPRI study and the EV Project were part of demonstration programs that required prevailing wages to be paid. These programs are phasing out, and in a competitive market it is expected that labor rates will decrease 15 - 25 percent. Additionally, with the expected increase in the number of EVSE installations, the resulting competition for these projects and associated large scale material procurements should help continue the downward trend in installation costs.[11]

9.2.3.3 EVSE Equipment Costs

The aforementioned 2015 U.S. DOE report includes recent EVSE equipment costs and factors influencing cost trajectories.

Cost drivers for EVSEs include charging level and amperage, number of charging ports or connectors, mounting option, advanced features such as network communication, point of sale capability, access control features (radio frequency identification (RFID)), and intended use (home vs commercial). As a result EVSE costs can vary greatly depending upon the manufacturer and the cost drivers included with a specific EVSE installation. In the November 2015 U.S. DOE report, the costs for EVSE non-residential equipment were estimated using a variety of sources. The findings summarized in Table 9.2 and Figure 9.12 show similar cost estimates for the equipment itself and, for example, represent a range of approximately $400-$6,500 for Level 2 EVSE equipment and an additional $3,000, on average, for installation of the equipment.

Table 9.2 EVSE Unit Cost and Installation Cost Range[12]

EVSE Type	EVSE Unit* Cost Range (single port)	Average Installation Cost (per unit)	Installation Cost Range (per unit)
Level 1	$300-$1,500	not available	$0-$3,000** *Source: Industry Interviews*
Level 2	$400-$6,500	~$3,000 *EV Project (INL 2015b)*	$600-$12,700 *EV Project (INL 2015b)*
DCFC	$10,000-$40,000	~$21,000 *EV Project (INL 2015d)*	$4,000-$51,000 *EV Project (INL 2015d) and (OUC 2014)*

**EVSE unit costs are based on units commercially available in 2015.*

***The $0 installation cost assumes the site host is offering an outlet for PEV users to plug in their Level 1 EVSE cordsets and that the outlet already has a dedicated circuit.*

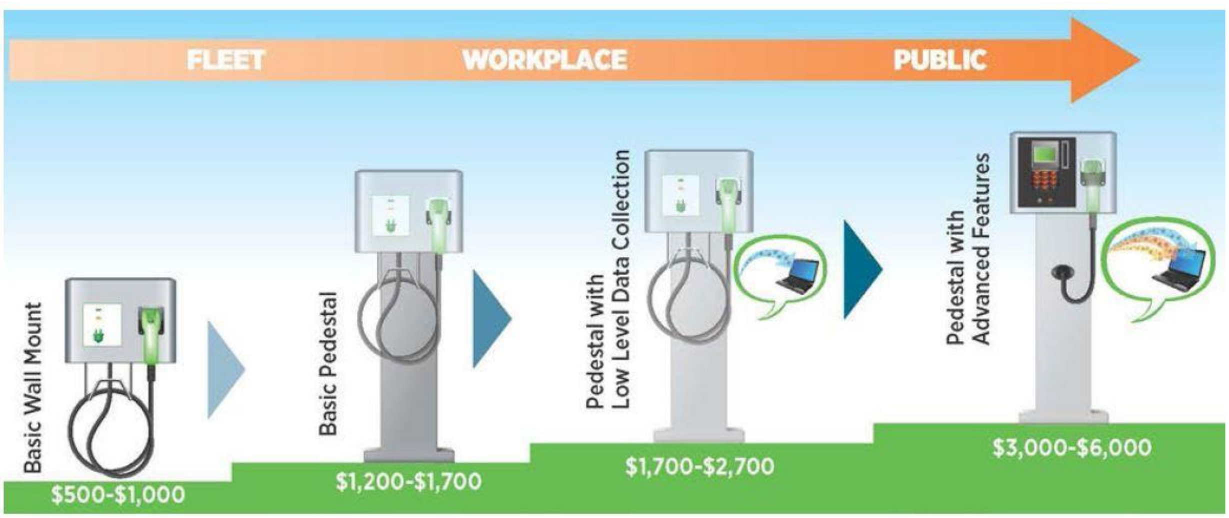


Figure 9.12 Range of Level 2 Equipment Costs by Type

Source: *Costs Associated With Non-Residential Electric Vehicle Supply Equipment*. U.S. DOE, November 2015. Image from Kristina Rivenbark, New West Technologies

9.2.3.4 Equipment Costs Trends

From 2012, the first full year of PEV sales, the global market for PEVs has grown from approximately 30,000 vehicles to nearly 500,000 in 2015, an impressive compound annual growth rate of 102 percent.[13] This expansion in PEV sales has led to solid growth in the EVSE market. Navigant Research expects the global market for EVSE to grow from around 425,000 units in 2016 to 2.5 million in 2025. These include sales of all EVSE units—residential and commercial and Level 1, Level 2, DC fast charging, and wireless charging. While the EVSE market will continue to grow as long as the PEV market grows, it is growing at a slightly higher rate than PEVs.[14]

Figure 9-13 below illustrates that global sales of commercial and residential EVSEs are projected to grow to approximately 2.5 million units annually by 2025.[15]

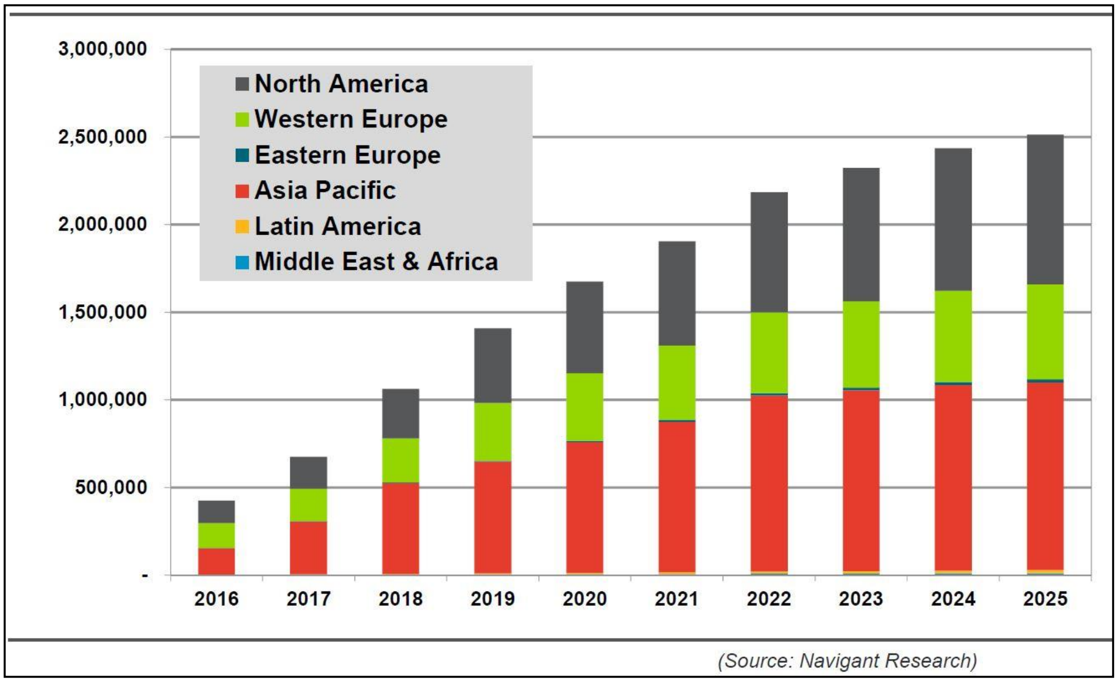


Figure 9.13 Projected Global EVSE Annual Sales by Region: 2016-2025

The cost of commercial and residential EVSE has declined in recent years through technology development and through economies of scale. A Level 2 residential EVSE, formerly priced between $900 - $1,000 in 2013, is currently priced in the $500-$600 range for basic units, and is expected to fall below $500 in the near term. As robust as the residential EVSE market forecasts are, the growth in the commercial EVSE market is expected to be even stronger. The same market forces that are applying downward price pressure on residential EVSE will also apply to commercial EVSE.

9.2.4 <u>Status of National PEV Infrastructure</u>

9.2.4.1 Number of Connectors and Stations

When analyzing PEV infrastructure, it is important to distinguish between the number of connectors, the number of stations, and the number of vehicles that may charge at a station simultaneously. As mentioned in section 9.2.1.1, a connector is defined as the hardware that physically attaches to a vehicle. A "station" is a physical location that contains at least one EVSE with at least one connector on a dedicated electrical circuit. However, an EVSE may have multiple connectors and may be able to charge multiple vehicles simultaneously. A typical station contains multiple EVSEs, with multiple connectors, on multiple circuits. The physical layout of a parking facility or the on-site power management systems may limit the number of vehicles that charge simultaneously.

Another important distinction when referring to PEV infrastructure is the identification of a station as either "private" or "public." Consistent with the most common usage, this report refers to a public station as one that is publicly accessible while a private station designation refers to one that does not allow access to the general public (e.g., located behind a gate or other method that limits access). Common examples of private stations include workplace or company fleet vehicle charging locations restricted to employee access. Public stations include those that are located in places like parking garages and shopping centers. For this report, Tesla supercharger DC fast charge stations are considered public stations even though usage is currently limited to Tesla vehicle owners.

The Alternative Fuels Data Center (AFDC), managed by NREL, has compiled a comprehensive database on Alternative Fuel Stations. The AFDC database includes extensive information of PEV infrastructure including number of stations, number of connectors, locations of stations, connector types, and power level of EVSEs. Further information on public and private stations is included. The value from a singular, national database is of such importance that California law requires station operators to report a station's location and other attributes directly to NREL for inclusion in this database.[16] The database shows that currently there are over 12,000 public and private PEV charging stations across the United States with over 38,000 connectors.[17] Table 9.3 and Figure 9.14 break down these numbers into further detail.

Table 9.3 Number of Non-Residential Connectors (June 6, 2016)

Publically Accessible Connectors and Stations				
	Level 1	Level 2	DC Fast Charge	Total
California Connectors	647	8,186	880	9,713
National Connectors[1]	2,977	26,859	3,738	33,574
National Stations[2]	1,546	12,176	1,760	13,649
Privately Accessible Connectors and Stations[3]				
	Level 1	Level 2	DC Fast Charge	Total
California Connectors	416	1,582	18	2,016
National Connectors[1]	702	4,633	32	5,367
National Stations[2]	145	2,408	23	2,455
Total (Public and Private) Connectors and Stations				
National Connectors	3,679	31,492	3,770	38,941
National Stations	1,691	14,584	1,783	16,104

[1]National numbers include California numbers

[2]A station may include multiple charging types, therefore station total is not a direct summation of types.

[3]Does not include home charging

As of 6/6/2016

Source: Alt Fuels Data Center (US DOE)

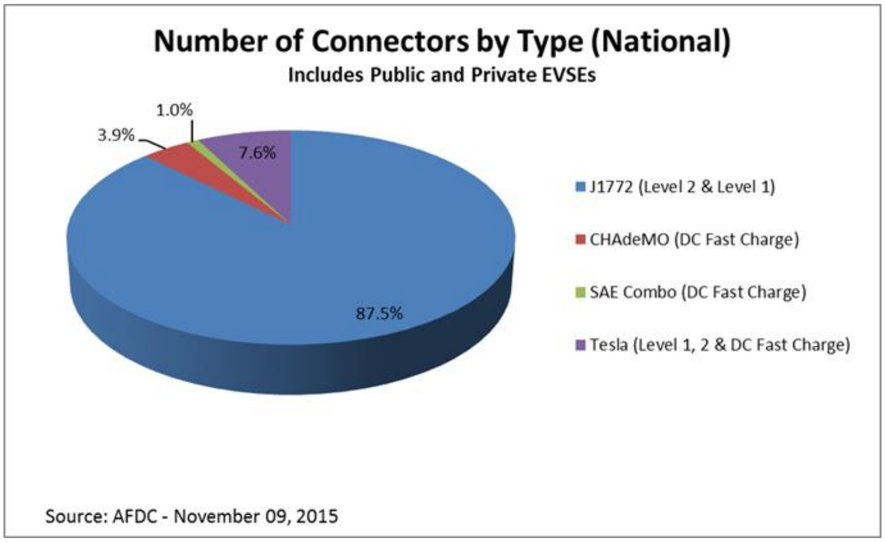


Figure 9.14 Comparison of EVSE Connector Types

9.2.4.2 Trends, Growth

The U.S. DOE's AFDC maintains detailed records of public and private charging stations and connectors dating back to the 1990s. Figure 9.15 and Figure 9.16, created using this database, clearly show that since the 2010 TAR, PEV infrastructure has increased substantially. In 2010, there were approximately 206 public and private Level 2 charging stations and 347 Level 2 connectors. As of May 2016, there are over 14,000 public and private Level 2 charging stations and nearly 31,000 Level 2 connectors. That represents nearly a 70 fold increase in the number of connectors and stations in the past 5 years.

Of the 14,000 Level 2 charging stations, nearly 12,000 are public stations while the remaining stations are private. As noted above, public and private in the context of EV infrastructure refers to the type of access to the station, not ownership. With regards to ownership of the stations, approximately 56 percent of Level 2 and DC fast charge stations are currently owned, operated or networked by one of the four largest private entities in the EV infrastructure market.[18]

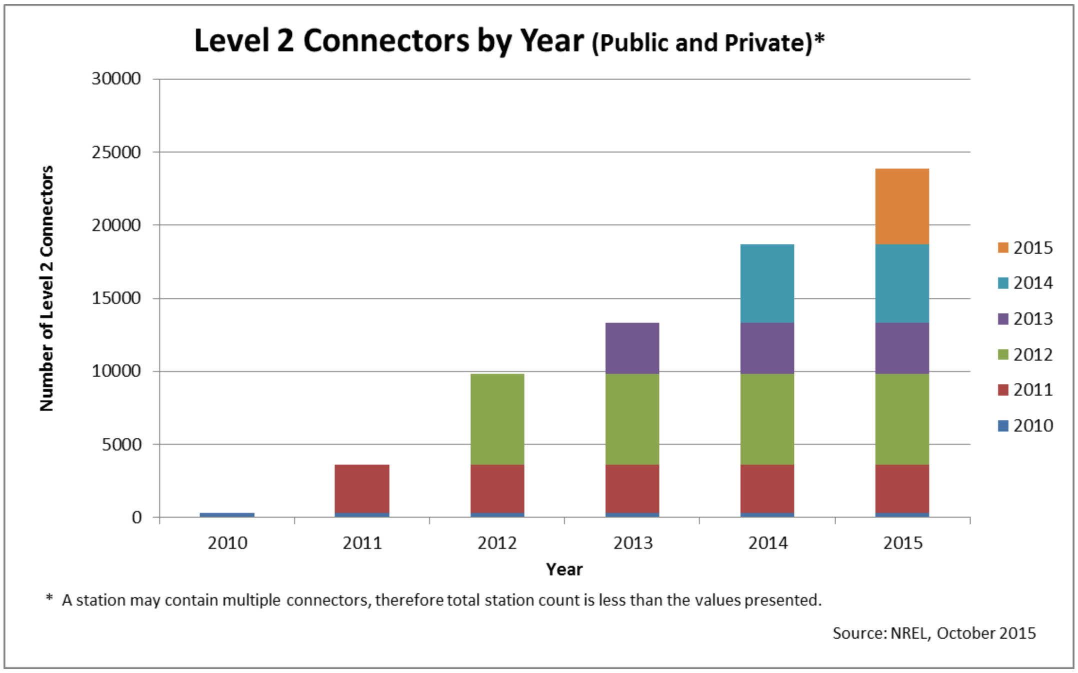


Figure 9.15 Annual Growth of Level 2 Connectors[19]

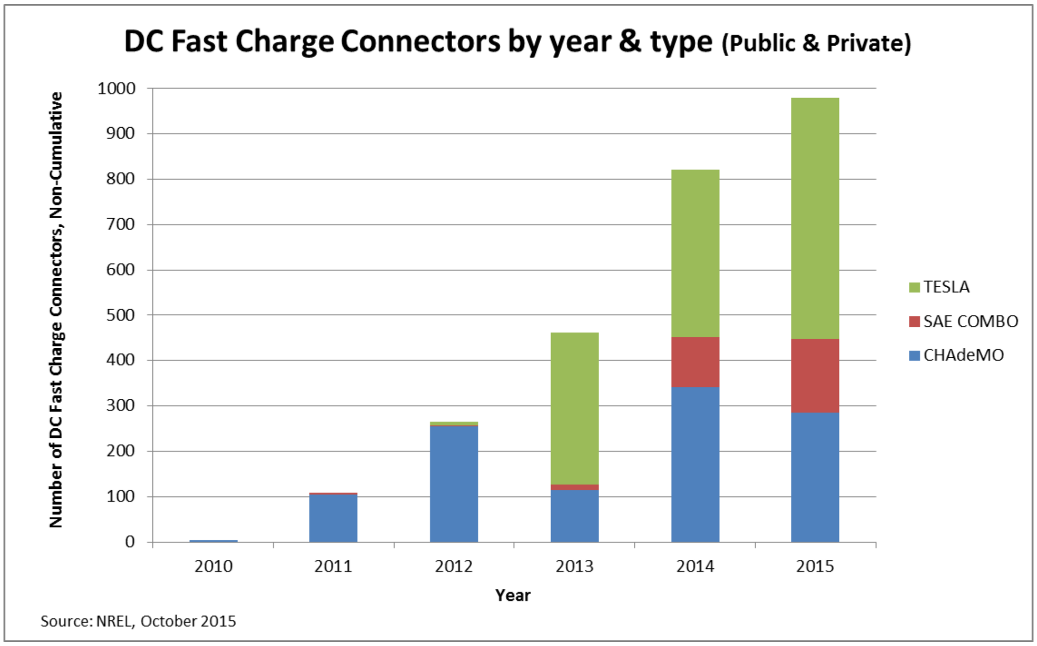


Figure 9.16 Annual Growth of DC Fast Connectors

9.2.4.3 Networks and Corridors

The data in section 9.2.4.1 and section 9.2.4.2 detail an initial assessment of national PEV infrastructure. The current PEV infrastructure landscape is robust, and the trends indicate it will continue with strong growth.

Equally important to the number of charging stations and connectors is the geographic location of the stations. Compared to traditional technologies, most current PEVs have a limited electric range making a strategic network of charging stations critical for interregional or interstate travel. As detailed below, several strategic charging networks or corridors are planned, under development, or are operational. For a map of current charging stations nationwide, see the AFDC database.[20]

9.2.4.3.1 West Coast Electric Highway (Baja California to British Columbia)

California, Oregon, and Washington are partnering with the Canadian province of British Columbia to construct the "West Coast Electric Highway," an extensive network of DC fast charging stations located every 25 to 50 miles along Interstate 5 and other major roadways in the Pacific Northwest. The goal is to provide a seamless consumer experience for PEV drivers traveling from Baja California to British Columbia (BC to BC) and all points in between. Recently, the CEC awarded $8.87 million to four companies to install DC fast charging stations on nine corridor segments to fill the gaps between the Oregon border and Baja California. The CEC also released a second competitive $9.97 million Grant Funding Opportunity to construct DC fast charge stations on additional interregional corridors in California.[21]

9.2.4.3.2 Northeast Electric Vehicle Network (D.C. to Northern New England)

A coalition of 12 Mid-Atlantic and New England states and the District of Columbia have joined forces to implement the Northeast Electric Vehicle Network. This network will pave the way for the deployment of an anticipated 200,000 electric vehicles (EVs) and facilitate PEV travel from D.C. to Maine. Already, more than 1,700 charging stations are publicly available in this region.[22]

9.2.4.3.3 Tesla Super Charging Network (Coast to Coast)

Tesla Motors has constructed the most extensive network of DC fast charging stations in the nation. With over 500 stations and nearly 2,000 connectors, Tesla's proprietary network provides coast-to-coast mobility to Tesla drivers.[23] Although this charging station network is limited to Tesla vehicles, it provides a model for OEM-based charging networks.

9.2.4.3.4 FAST Act - Nationwide Alternative Fuel Corridors

In December 2015, President Obama signed the Fixing America's Surface Transportation (FAST) Act. This bill not only authorized funding for traditional surface transportation projects, but section 1413 of the bill requires the U.S. Department of Transportation (DOT) to designate corridors to improve mobility of passenger and commercial vehicles that employ electric, hydrogen fuel cell, propane, and natural gas fueling technologies across the U.S. by December 2016. Although the bill does not provide direct funding for alternative fuel infrastructure, the U.S. DOT can support these corridors through technical assistance, analytical support, peer review, marketing and branding. In addition, this bill amended the Congestion Mitigation and Air Quality Improvement (CMAQ) Program to give priority to designated EV and CNG corridors. This bill facilitates the planning activities required in the construction and implementation of nationwide PEV corridors.

9.2.4.4 Challenges and Opportunities with PEV Infrastructure

The PEV infrastructure environment, in its current state, has been in development and refinement for nearly a decade, and many of the initial challenges have been met: technical standards, communication protocols, signage and design guidelines have all been adopted. In addition to its "Workplace Charging Challenge," which aims to achieve a tenfold increase in the number of U.S. employers offering workplace charging by 2018, the U.S. DOE, through its Clean Cities coalition, has awarded $8.5 million to projects in 24 States and the District of Columbia. The CEC has funded $40 million for over 7,700 charging stations in California as well as PEV Community Readiness grants for $5.7 million to help local communities prepare for PEVs and charging infrastructure.[24]

As a result of meeting these initial milestones, consumer acceptance and private capital market involvement have followed. However, challenges and opportunities surrounding PEV infrastructure exist and the following paragraphs detail some of the more prominent issues.

9.2.4.4.1 Challenge – Multi-Unit Development (MuD)

Electric utilities estimate that over 80 percent of all current PEV charging occurs at home, usually in a garage with access to electrical power.[25] However, nationwide, approximately 36 percent of households reside in rental housing with 60 percent of those households living in Multi-unit Dwellings (MuDs). Most MuDs do not provide EVSE or access to electrical power in proximity to parking.[26] In order to expand the PEV market, access to EVSE in MuDs is important; however, many challenges still exist and stakeholders are beginning to address them. These include:

- Physical Facilities: Age, existing electrical infrastructure, and physical layout of parking within a MuD all present unique challenges in installing and operating PEV infrastructure.
- Diversity: MuDs are comprised of a variety of structures from modern, urban high-rise buildings to sprawling, midrise suburban apartment complexes to low-density townhome condominiums. Given this physical diversity, there is no universal solution or standardized cost for providing EVSE access in MuDs.
- Economics: Costs associated with installing, maintaining, and operating EVSE needs to be accounted for; however, equitable distribution of these costs among building occupants, PEV drivers, and the building owner remains a challenge.

9.2.4.4.2 *Challenge - Increasing Battery Capacity*

Vehicle battery costs are declining while energy density is increasing.[27] Currently, most BEVs sold today have a range under 100 miles; the most common BEV on the road today, the Nissan Leaf, has a range of 84-107 miles depending upon model year.[28] Tesla vehicles are the primary exception, offering a range in excess of 200 miles but at a much higher price. However, several automakers, including General Motors and Tesla, have announced plans to deploy affordable BEVs with larger battery packs and ranges over 200 miles at a price near $30,000 after federal incentives. These developments hold the potential to alter the need for, and use of, public charging infrastructure in ways unknown. For example, larger battery packs will take longer to charge which may increase the demand for DC fast charging and decrease the demand for Level 1 and Level 2 public charging. However, it is also likely that longer range PEVs will charge less often which may also impact public charging infrastructure. These uncertainties require on-going analysis of the PEV market and charging behavior.

9.2.4.4.3 *Challenge and Opportunity – Inductive Charging*

The current PEV charging standards and protocols involve connected, conductive charging. PEV batteries are charged by physically attaching the vehicle to a power source via the EVSE. Currently, this physical connection is essential to almost all PEV charging.

However, some automakers, third party vendors, and charging providers have begun to develop wireless, inductive charging. Inductive charging uses an electromagnetic field to transfer energy between the vehicle and the power source where no physical connection is required. This has the potential to revolutionize charging and charging infrastructure by literally “cutting the cord.” Inductive charging technology can facilitate charging in non-traditional locations such as stop lights, along curbs, or even along routes while the vehicle is in motion. Although, current inductive charging systems may have lower efficiency, the technology is developing and the convenience may be worth slightly higher charge rates to many users. In addition, it is likely that the ease and convenience of inductive charging will draw drivers of conventional vehicles into PEVs. How these wireless inductive charging systems are designed, developed, installed, and utilized by drivers presents uncertainty and an opportunity in the PEV infrastructure landscape.

9.2.4.4.4 Opportunity - Vehicle Grid Integration (VGI)

PEVs store a large amount of energy in their on-board batteries. Current EVSE and charging specifications and protocols are intended to facilitate the one-way power transfer from the electrical grid to the vehicle. However, new protocols and standards are being developed and tested to facilitate the two-way transfer of energy from the vehicle back to the grid; this is referred to as Vehicle to Grid Integration (VGI). VGI holds the potential to assist electric utilities in meeting their peak power demands by tapping a new source of power storage − a large PEV fleet. Many programs across the nation are in place to study VGI including programs in California, Delaware, and at the U.S. Department of Defense. The CEC, in coordination with the California Independent System Operator developed a Vehicle Integration Roadmap[29] in 2014 to outline a way to develop solutions that enable PEVs to provide grid services while still meeting consumer driving needs.[30]

9.2.4.4.5 Opportunity - Utility Demand Response

In broad terms, electrical power on the grid comes from central electric generation facilities. This electricity is purchased by an electric utility and resold to its customers. Although most utility bills make the cost of electricity appear relatively uniform, the actual cost to procure electricity from a generator can vary greatly. Prices can spike (or fall) quickly and with little notice. Factors that affect the price of electrical power include temperature, weather, time of day, demand for power, availability of operational power plants, and many others.

PEVs charge when they are parked, and most vehicles, including PEVs, are parked 96 percent of the time.[31] Therefore, a PEV doesn't need to be charging at all times when it is parked. This fact, coupled with emerging technologies that allow an electric utility to communicate with advanced EVSEs and control the power transfer, gives utilities a unique opportunity. Utilities could effectively manage PEV power demands in the broader context of regional grid operation, power generation and supply, local transformer capacity, and price fluctuations. The next generation of networked EVSEs provides a valuable opportunity for utilities to operate more efficiently and effectively.

9.2.4.5 Further Analysis and Developments

Commercial OEM-built PEVs have been around for nearly two decades while more recent, modern advanced battery technology PEVs have been on the market for approximately five years. Over that time, vehicle technology has changed dramatically and is still continuing to evolve. With regards to the technology adoption curves for PEVs, the market is currently transitioning from the "innovators" (a.k.a. first adopters) phase to the "early adopters" (a.k.a. fast followers) phase. As a result of this transition and technology advancement, charging behavior has changed and is continuing to evolve. Further study of charging patterns and behavior, optimal charging network configuration, and public charging infrastructure sufficiency, are warranted and currently being investigated by many stakeholders. The following is a partial list of additional analysis and implementation efforts in the area of PEV infrastructure which should yield results that will enhance the current level of understanding in this topic and enable even more efficient investment in public charging infrastructure:

- As mentioned in section 9.2.2, NREL conducted a statewide PEV infrastructure analysis for the CEC. The CEC has recently contracted with NREL to use this analysis as a basis to create an actionable plan that will prioritize specific charging locations and guide regional PEV infrastructure planning and other stakeholder actions in California. The recommendations from these studies can be utilized by other states interested in promoting ZEVs in their jurisdiction. The CEC also funded 12 PEV planning regions which will each develop charging infrastructure plans along with other critical actions to prepare for increasing numbers of PEVs. The lessons learned from these planning activities can be used by local agencies in other states.

- The California Public Utilities Commission (CPUC), the entity that regulates Investor Owned Utilities (IOU) and sets rate tariffs in California, has approved Phase 1 pilot projects by two IOUs and is reviewing a proposal by a third IOU. Combined, the two approved pilot projects aim to install up to 5,000 public charge stations or related infrastructure. When these proposals come to fruition, not only will the large number of new charging stations transform the current PEV infrastructure landscape, but the introduction of electric utilities into the infrastructure marketplace could be transformative. The U.S. DOE EV Everywhere program is working with other states to encourage similar actions and several states have already commenced action. Examples are included below:

- The State of Oregon has introduced SB 1547 (Beyer), which allows their PUC to direct electric companies to file applications for programs to accelerate transportation electrification, including customer rebates for electric vehicle charging and related infrastructure.

- The New York Power Authority (NYPA), and others, are collaborating in an initiative called ChargeNY which aims to reach 3,000 PEV charging stations to support an expected 30,000 - 40,000 PEVs on the road in New York by 2018

- In March 2016, Utah lawmakers enacted SB 115 (Snow), the Sustainable Transportation and Energy Plan (STEP). STEP establishes a five-year pilot program, under which regulators will authorize the State's power company, Rocky Mountain Power, to spend up to $2 million per year on electric vehicle infrastructure.

California enacted SB 350 (de Leon) which directs the CPUC to guide the IOUs' investments in the widespread transportation electrification including the deployment of charging infrastructure. This law is significant for several reasons: it will allow IOUs to ultimately commence "phase 2" electrification programs if they are determined to meet specific requirements, thereby potentially greatly expanding infrastructure for PEVs and other mobile sources in California. In addition, SB 350 defines how ratepayers benefit from transportation electrification (reduced emissions, reduced impacts to public health and the environment, increased use of alternative fuels, renewable energy integration, and economic benefits), and therefore can participate, through utility rates, in the funding of electrification programs.

9.2.4.6 Status of Public PEV Infrastructure Network

The question of infrastructure sufficiency is an important topic in regards to facilitating the expansion of the PEV market to assist in meeting federal GHG and CAFE standards. Specifically, how does the current infrastructure landscape and trajectory meet the needs of current and projected vehicle fleets and, within that fleet, what role will PEVs play in meeting federal rules?

When addressing this question of infrastructure sufficiency in the context of PEV adoption, it is important to distinguish between BEVs, which inherently rely on charging infrastructure to operate and PHEVs, which can run exclusively on gasoline and only require charging infrastructure to operate electrically. Intuitively, it is less likely that PHEV adoption rates are as dependent upon robust EV infrastructure as BEVs. Given this important distinction, the question of infrastructure sufficiency will be addressed for BEVs by examining a snapshot of current BEV numbers in relationship to the EV landscape and trends, and comparing that relationship to work performed by NREL for the CEC. Although the majority of PEV charging occurs at home, data related to the availably of home charging infrastructure (e.g., 110V outlets in home garages) is extremely limited. Therefore, the analysis of EV infrastructure sufficiency is focused on public and workplace charging.

A recent CEC contract with NREL looked at the question of sufficiency. NREL analyzed two potential charging scenarios --a “home dominant” charging scenario and a “high public access” charging scenario. Based upon these two scenarios and the composition of California’s current and projected BEV and PHEV fleet, NREL calculated that the minimum ratio of non-home based charge points (both workplace and public) to PEVs is 0.14 per PEV in the home dominate scenario and 0.24 per PEV in the high public access scenario.

Applying these ratios on a national scale, infrastructure development at its current pace appears to be sufficient in meeting today’s charging demands of BEVs. As of April 2016, a cumulative total of over 227,000 BEV and nearly 214,000 PHEV sales were recorded nationwide.[32] Studies have shown that, on average, over 80 percent of all charging events occur at home. Using the home dominant NREL ratio of 0.14 charge points per BEV, the nation would need approximately 31,700 charge points for the current BEV fleet. At the end of May 2016 there were over 38,000 public and private charge points[33] (i.e. connectors) nationwide. Therefore, the existing charging network appears sufficient for the existing BEV fleet. However, if the PHEV fleet were added to the existing BEV fleet, the combined fleet of 441,000 vehicles would, under NREL's methodology, requires approximately 61,000 charge points nationwide. While the existing workplace and public charging network falls short of that number, the existing and forecasted sales of PHEVs demonstrate that public infrastructure is less critical for PHEV adoption.

Currently, PEV sales are a small percentage of overall light duty vehicle sales and public charging infrastructure is sufficient to meet the current demand of BEVs in a home dominant charging scenario. However, as PEV technology becomes more broadly accepted and less expensive, and as automakers increase PEV production, infrastructure will need to continue to keep pace with demand. Although this development is not a guarantee, there is evidence to suggest it will sufficiently expand. Some private electric utilities are eager to enter the PEV infrastructure market with large investments which has the potential to significantly increase the number of charge points. In addition, with today’s relatively small PEV fleet, private companies have established business models to compete in the PEV infrastructure market. As the PEV fleet grows, those business models should become even more viable. Using current technology, the current number of public and private charge points may need to be expanded by nearly a factor of 10 to provide sufficient charging capacity (as defined by the home dominant NREL ratio of

0.14) for the combined number of BEVs and PHEVs projected by 2025 in this Draft TAR. However, as section 9.2.4.2 details, there has been a nearly 70 fold increase in the number of connectors and stations in the past five years. And, this includes PHEVs which, as noted above, are far less likely to be as dependent on charging infrastructure. Lastly, developments such as longer range BEVs, high power charging, and inductive charging will alter the current charging paradigm which may lessen the ratio of public chargers per PEV, thereby decreasing the projected charger network needs.

The current national charging infrastructure network continues to grow with investment in infrastructure by government, corporations, private capital markets, and electric utilities. There are infrastructure challenges as noted earlier (e.g., multi-unit dwellings), but they are systematically being addressed, and infrastructure is progressing sufficiently to support the scale of the electric vehicle market projected in this Draft TAR to be necessary to comply with the national GHG standards.

9.2.4.7 Summary of PEV Infrastructure

With over 16,000 (14,550 Level 2 and over 1,700 DC fast charger) public and private electric charging stations with a total of over 38,000 connectors,[34] the national PEV infrastructure network is off to a robust start and continued strong growth is forecasted. Although there are remaining challenges, the initial challenges with technical specifications, communication protocols, and operability standards have largely been addressed. Over $250 million of private capital has entered the infrastructure market,[35] supported by emerging business cases for charging networks. New challenges are being addressed and, as referenced herein, tremendous opportunities in PEV infrastructure are on the horizon. Given the overall strength of the PEV infrastructure landscape (as detailed in section 9.2.4.6), infrastructure is progressing sufficiently to support vehicles with PEV technology to be used in meeting the 2022-2025 national program GHG and CAFE standards. However, PEV infrastructure needs are expected to be greater in states with ZEV regulations than in states where only federal GHG and CAFE standards are applicable.

9.3 Hydrogen Infrastructure Overview

Hydrogen (typically in the form of a compressed gas) is the primary fuel source for the Fuel Cell Electric Vehicle (FCEV). Hydrogen is abundant as a constituent of readily-available natural resources, though it does not naturally occur in its elemental form. In spite of this challenge, many methods exist or are in development for its extraction from various resources, including renewable energy sources. The success of the FCEV as a commercial product will rely on the development of a fueling infrastructure network that can provide that hydrogen with a retail experience meeting the expectations of today’s gasoline-fueled vehicle drivers. Significant progress has been made towards this goal in recent years, with a network of 51 stations currently under construction in California (a growth of 41 stations in addition to the 10 reported in the 2010 TAR[36]) to support the initial market. FCEVs are another vehicle technology option that makes use of an all-electric drivetrain, providing zero tailpipe emissions. In contrast to the plug-in electric vehicles discussed previously, FCEVs provide power to their electric motors by generating the necessary electricity onboard (as opposed to receiving electricity from an external source, through a plug). The FCEV accomplishes this through the electrochemical conversion of hydrogen and air into electricity, water, and a small amount of heat.

Hydrogen fueling stations are designed to provide hydrogen to FCEV drivers in accordance with design specifications of the FCEV onboard hydrogen storage tanks. Designs have evolved over the past decade, but the prevailing on-board storage form across the industry has largely converged on gaseous hydrogen compressed to a pressure of 70 MegaPascals (MPa). At this pressure, hydrogen can be stored onboard in sufficient quantities to provide drivers with driving range equivalent to typical gasoline-fueled vehicles without significant concessions in other vehicle features in order to accommodate the storage tanks. As such, hydrogen fueling stations are designed to dispense hydrogen at this high pressure, using fueling protocols that allow the station to provide a complete, safe, reliable, and accurately metered fill in a time on par with current gasoline stations, typically around three minutes for light duty vehicles.

Figure 9.17 provides a glimpse of the diversity in hydrogen production processes currently in use, based on the developments in California, where many fueling stations are in operation or currently in development.[37] The figure shows shares of production pathways for hydrogen provided to all stations proposed in the most recent round of California's hydrogen fueling station grant program and for California's operating and planned network, including stations awarded in that program. The full mix shown in the 2015 network includes stations from the research and demonstration era of hydrogen infrastructure development, which are expected to continue to provide limited service for some time. The differences in the shares between the full network mix and the grant applications may be indicative of changing emphases in technology development. For example, electrolyzers make up a much greater portion of the 2014 applications than the full network, potentially indicating a trend for increasing participation of this technology than was utilized in the demonstration-era stations. Similar variations in the mix of hydrogen production technologies may be expected to continue over time as the respective technologies develop and push the hydrogen industry to the most appropriate and cost-effective solutions.

The diversity of hydrogen production shown in Figure 9.17 is indicative of the latest state of production and delivery technology and innovation in the hydrogen industry. This figure, based on counts of stations, shows the shares of hydrogen production methods in applications to the most recent round of California's grant program and the funded hydrogen fueling network in the state.[38] Stations deployed in earlier years of the network development also had smaller daily fueling capacities on average than the newer stations. More recently, hydrogen fueling station developers have proposed and built stations relying on a wider array of hydrogen production methods, with stations ranging in size from 100 kg/day up to 350 kg/day.[39] Concurrently, stations have been designed to meet more rigorous technical specifications that facilitate a retail experience. It is expected that the hydrogen stations currently being built in California will serve as the first examples of true retail stations with designs that can be largely reproduced or easily modified for future expansion and establishment of regional fueling networks in other parts of the country.

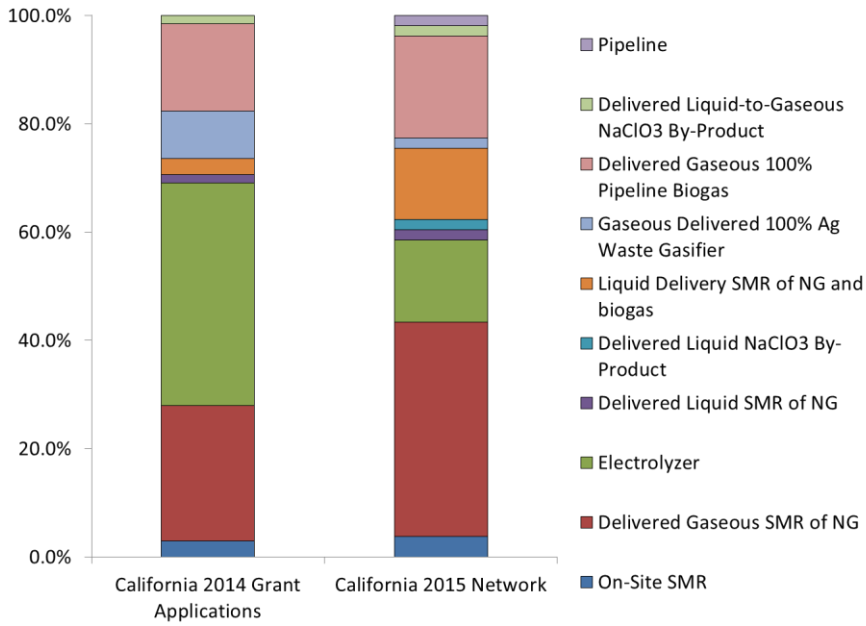


Figure 9.17 Hydrogen Production Methods in California

Hydrogen dispensed from fueling stations to FCEVs is provided in gaseous form, but a variety of solutions exist for storage of larger volumes at the station. Gaseous hydrogen may be stored in large cylinders installed at the station, often at various pressures up to or exceeding 70 MPa. Other stations store the hydrogen as a liquid, gasifying the hydrogen prior to dispensing to a vehicle. Additionally, hydrogen may be delivered to the station from a central production facility in either gaseous or liquid form or it may be produced on-site from methods like Steam Methane Reformation (SMR), electrolysis (electrically-driven separation of water into hydrogen and oxygen), or tri-generation. Tri-generation is a process utilizing a stationary fuel cell and an opportunity fuel like a wastewater treatment facility's digester gas to generate electricity, heat, and hydrogen for vehicle fueling. When hydrogen is delivered from central production facilities, it may originate from a number of processes including SMR, electrolysis, by-product from industrial or chemical processes, biogas and biomass conversion, and other technologies currently under development. Finally, hydrogen may be delivered via a direct pipeline link from a major production facility. In California, this has been demonstrated at the Torrance station, where an existing supply line between a hydrogen production facility and an oil refinery was accessed to divert a stream of hydrogen to the vehicle fueling station. In the future, the source of hydrogen provided via pipelines could continue to serve a variety of end uses, but it is also likely that some of the source hydrogen will be produced at central facilities specifically with the intent of fueling FCEVs.

9.3.1 Hydrogen Network Development and Status

FCEVs are currently envisioned to be introduced to the public fleet across the nation in a series of releases that will coincide with development of fueling infrastructure. In the past, the regions where these first releases are likely to be concentrated have been referred to as network "clusters." As FCEV and fueling infrastructure markets progress, these clusters will be connected by stations along major long-distance travel corridors, and smaller secondary clusters will be established as the demand and capability to fuel FCEVs spreads beyond the initial cluster areas. This strategy has begun to be exhibited in California, where the California Fuel Cell Partnership (CaFCP) explicitly detailed such a strategy, focusing on five early adopter clusters (two in the northern and three in the southern portion of the state), with various smaller clusters, connector, and destination stations developing around the state.[40] This strategy has been adopted in past State funding programs, and newer analyses and programs continue to identify the need for stations in some of the very same regions identified by the cluster paradigm.

Similar development strategies are likely to be carried out in other areas of the nation where there will be a high early adopter market demand for FCEVs. In most cases, these high demand areas will be in or near major urban areas, with other clusters developing as the demand spreads outward from these focal regions. Thus, the network of nationwide stations will likely develop in smaller regions, established primarily to support the daily needs of the first adopter FCEV market. Connector stations will then link these major clusters and establish travel corridors for further development. As these first clusters grow and spread to become interconnected with a widening market for FCEVs, they will become more regional in scale and provide service coverage to increasing portions of the nation's population. During this development, these networks will be connected by long-distance connector stations, allowing for inter-regional and nationwide travel via FCEV with ample opportunity for fueling.

Figure 9.17 shows the current status of development for the hydrogen fueling network in California.[41] An early semblance of the clustering paradigm is visible in the stations located in Los Angeles, Orange County, and around the San Francisco Bay in the northern part of the state. The station shown in Coalinga will serve as a connector enabling travel between the clusters in the northern and southern halves of the states. Meanwhile, destination stations will be in place in areas like Truckee and Santa Barbara to support vacation travel for FCEV drivers. The California Air Resources Board (ARB) estimated that the 51 stations in operation or development in 2015 (50 are shown in the map; a recent relocation has resulted in a station project converting into an upgrade for a legacy station) will be able to provide sufficient fueling capability for approximately 12,000 - 15,000 FCEVs.[42] Assuming no decrease in State funding, ARB also estimated that a total of 86 stations could be built by 2021 and 100 by 2023. In December 2015, a more nuanced projection accounting for potential reductions in station costs projected that 100 stations could be built by 2020, as long as the FCEV introduction rate was at least as fast as the ARB estimate.[43] If the introduction of FCEVs were to be delayed for 4 years, then station rollout would correspondingly decelerate, and 100 stations would not be built until 2024.[44] However, in all analyses thus far performed by the State of California, the demand for hydrogen to fuel FCEVs is projected to exceed the dispensing capacity if station deployment is limited only to the AB 8-related funds currently in use. The State's estimate for the timing of insufficient dispensing capacity depends on the assumed scenario and ranges from 2019 to 2026. In response, State agencies have initiated dialog on addressing this potential shortfall by working with stakeholders to demonstrate the market opportunity and increase the magnitude of private investment in the state's hydrogen infrastructure network.

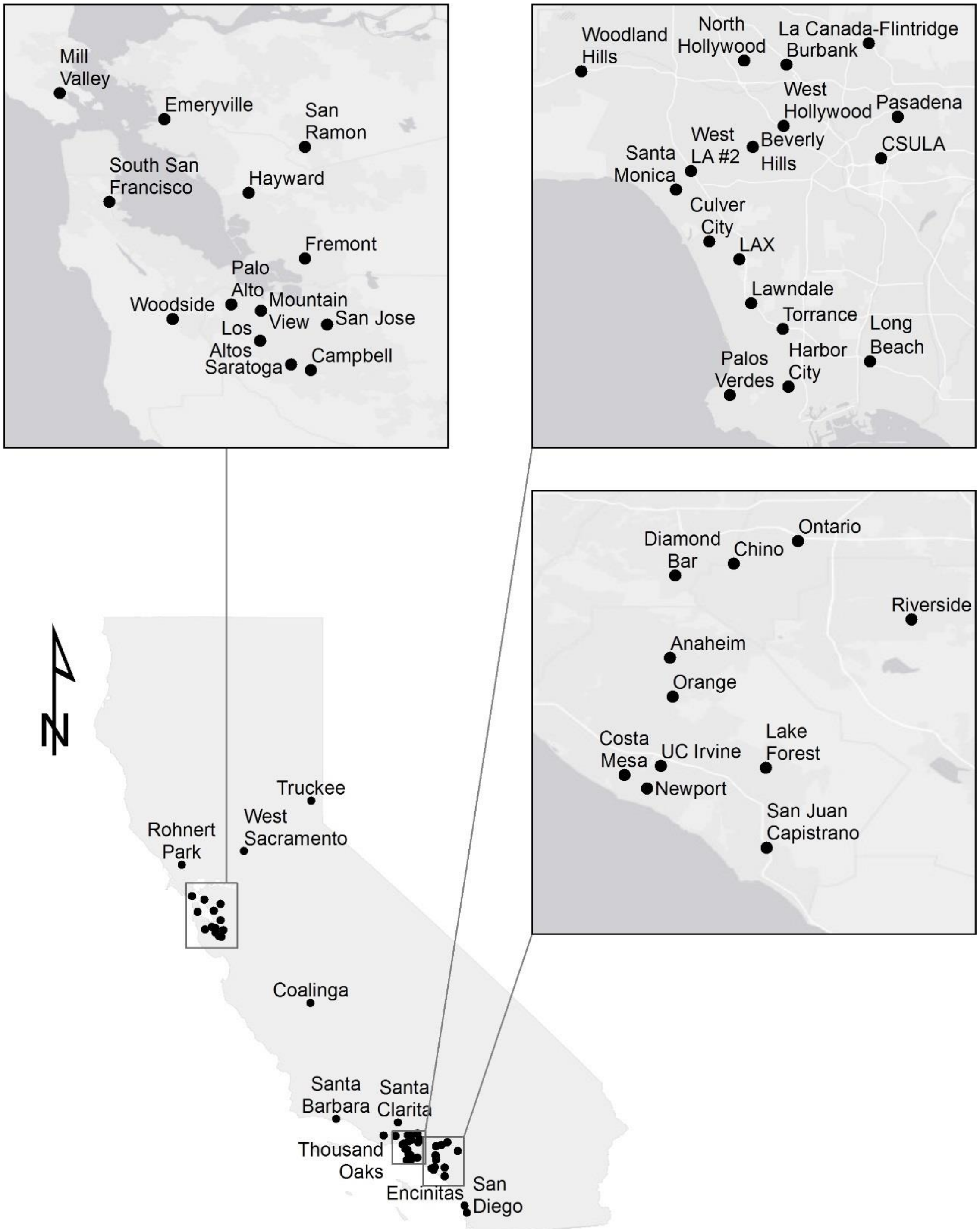


Figure 9.18 Locations of California's Funded and Operational Network of 50 Hydrogen Fueling Stations[45]

It is the goal of the State's financial support to set in place enough stations that customers have sufficiently convenient access to stations and sufficient confidence in availability of hydrogen fueling locations to decide to purchase or lease a FCEV instead of a traditional combustion-powered vehicle. Given the early state of both the FCEV and infrastructure markets, the financial incentive is meant to increase the financial viability of the earliest stations, when the risk is greatest and the fueling throughput lowest. This will help keep more stations open longer, allowing auto manufacturers time to develop the FCEV technology and introduce vehicles that meet all of a retail customer's expectations, as is currently beginning to happen. Eventually, as both the FCEV and fueling station industries mature, the stations will be financially self-sufficient and more attractive to private investment; at this point, the market opportunities are expected to dictate the rate of growth of both markets and the State will be able to reduce its financial participation.

Following the sales trajectories of Figure 5-46 in Chapter 5, approximately 125,000 FCEVs may be expected on California's roads by 2025, with approximately 37,000 new vehicle sales in that year. Effectively, the annual rate of installation of new fueling capacity by 2025 needs to be greater than the full amount of capacity included in the first 100+ stations expected to be funded by the State by through AB 8. This should signal a significant market opportunity to station developers and private financers with an interest in hydrogen and FCEVs. However, individual assessments of risk and market opportunity will play a predominant role in determining how rapidly the need will be met, as State funding is not expected to play as significant of a role in 2025 as it does now. Further discussion of the costs and financial evaluations of deploying hydrogen fueling infrastructure is included in section 9.3.4.

Outside of California, the Alternative Fuels Data Center, maintained by the United States Department of Energy (U.S. DOE), indicates that two other stations are currently operational (one in Connecticut and one in South Carolina) and one station is in development in Massachusetts.[46] Additionally, U.S. DOE opened a 70 MPa station in Golden, Colorado for use in research studies[47] coinciding the event with National Hydrogen and Fuel Cell Day on October 08, 2015.

In addition to these stations, a number of activities across the nation are currently or soon will be underway to establish and increase coverage provided by hydrogen fueling stations in the expected early adopter markets. Connecticut is currently seeking applications for grant funding of up to two stations in the Hartford area.[48] Air Liquide and Toyota have announced a partnership to establish a dozen fueling stations in the northeast states.[49] Finally, H2USA (a public-private partnership established by U.S. DOE to address the challenges of establishing the FCEV market in the USA) is developing a plan for fueling station development across the northeast, emphasizing fleet vehicles as the first market, with the intent of expanding into a retail consumer-centric network model.[50]

9.3.2 Retail Experience

Until very recently, many of the existing and funded hydrogen fueling stations have been largely demonstration and/or research stations. These stations have been critical in providing insights for station design, construction, and operation while still providing essential fueling service to pre-commercial FCEV drivers. However, as fully commercial launches of FCEV models have now begun (e.g., the Hyundai Tucson Fuel Cell and Toyota Mirai) and more are planned for the near future (e.g., the Honda Clarity Fuel Cell expected in 2016), the stations will need to provide fueling service to a wider, more retail-oriented user base. Over the past few years, and often times directly as a result of experiences gained at the earlier demonstration stations, new protocols and standards have been developed that will ensure future FCEV drivers have consistent, reliable, retail-like experiences when filling their vehicles. Hydrogen quality standards (SAE J2719[51]) and dispenser fueling protocols (SAE J2601[52]) are examples of recent advancements that will shape industry-wide development and implementation of fueling station equipment and ultimately provide consistent and reliable fueling experiences to FCEV drivers.

Additionally, a number of state and national efforts have and will provide tools that can ensure stations adhere to these and other standards. In California, the Hydrogen Field Standard (HFS), developed by NREL under contract with the California Division of Measurement Standards and funded by the California Energy Commission, has allowed for the certification of dispensers' metering accuracy. HFS was developed based on a need for a discrete method to verify that dispensers could measure and dispense hydrogen accurately. The California Department of Food and Agriculture's (CDFA) Division of Measurement Standards (DMS) has jurisdiction over the retail sale of motor vehicle fuels and has adopted by reference the methods for sale and accuracy standards contained in National Institute of Standards and Technology (NIST) Handbooks 44[53] and 130.[54] NIST set the national hydrogen accuracy standard at 1.5 percent acceptance and 2 percent for in-use or maintenance tolerance.

Workshops and early field testing indicated the 1.5 percent/2 percent NIST standards were technologically infeasible with existing metering technology, so CDFA adopted temporary tiered accuracy classes of 3 percent, 5 percent, and 10 percent[55]. This approach allowed the near-term retail sale of hydrogen to consumers and provided time for industry to improve dispenser metering methods. In the past year, several dispensers have been tested and certified using the HFS, including the world's first dispenser certified to be accurate enough to sell hydrogen to the consumer by the kilogram at the station located on the Los Angeles campus of the California State University. Future station designs that incorporate type-certified dispensers will require less-intensive accuracy testing during the commissioning process.

The Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) project has developed the Hydrogen Station Equipment Performance (HyStEP) device. The device is designed to carry out various certification tests outlined in the CSA Hydrogen Gas Vehicle (HGV) 4.3, 2015.[56] These tests will be able to certify that a station's dispenser is capable of providing safe, fast, and repeatable fills according to the protocols defined in SAE J2601. The device has been validated in a research setting at NREL in Colorado and at retail stations in California; it is now being used to perform validation testing of the operational stations in California's fueling network. There, it will be used to test stations currently in service and newly-constructed stations as they are completed. The device is trailer-mounted and has been purposely designed with the intent of traveling not only within the state of California, but across the nation as stations and networks are developed in other regions.

With these devices, and others currently under consideration or development, state and national stakeholders are gaining the capability to provide increasing confidence to consumers that their fueling experience will be safe, reliable, and consistent. At the same time, industry stakeholders have recently placed considerable effort into precisely defining additional features to enhance the customer experience and allow a station to be considered "retail." For example, many demonstration stations were placed behind card-key locks and thus not freely accessible to any public driver in the vicinity. Additionally, given that a legal means was not yet in place to sell hydrogen directly to consumers, stations did not have a Point-of-Sale system and customer payment was managed through access agreements as opposed to the on-demand purchase enabled by cash, debit, and credit card sales typical of today's gasoline stations. With the deployment of commercial vehicles, vehicle manufacturers expect that truly retail public stations will not limit the customer base of their service.

9.3.3 Hydrogen Fueling Station Capacity

Given the limited number of FCEVs currently on the road and the demonstration nature of many of the stations built to date, most hydrogen fueling installations have been designed with a smaller capacity than is anticipated to become the norm in the future. In 2014, ARB compared the composition of the existing and funded hydrogen fueling network in California to the state's gasoline fueling network in terms of capacity. ARB reported that the state's gasoline fueling infrastructure was comprised of very different types of fueling stations; the top 1 percent of stations (in terms of volume of gasoline sold) were typically seven times as large as the average station in the state. In addition, over 50 percent of the gasoline was sold by only the top 21 percent of stations.[57] Thus, the gasoline fueling infrastructure contains a large number of comparatively small stations and a small number of very large stations.

Thus far, the hydrogen infrastructure development has not been as heterogeneous. This is partially due to the early development stage; all these stations have served a similar demonstration and pre-commercial market purpose. In the case of gasoline stations, the progress of development has led to station designs that are more tailored to different roles within the network (such as connector, destination, etc.). Over half of the hydrogen fueling stations built and planned have been designed with a capacity in the range of 150 to 200 kg/day, with the largest stations designed for 350 kg/day. The average for the state currently stands at 180 kg/day, also the most common design capacity in the state. Thus far, station capacities are mainly a function of the hydrogen source; the composition of California's network is: 31 180 kg/day gaseous delivery (or combination of on-site production and gaseous delivery) stations, 7 350 kg/day liquid delivery stations, and 8 on-site electrolysis stations ranging from 100 to 130 kg/day.

From its comparison to gasoline infrastructure, ARB concluded that hydrogen fueling stations would not only need to grow larger in design capacity, but also become more diversified and specially-designed for various network roles. While today's gasoline stations provide on average 24 times the fueling capacity of a hydrogen station on an energy basis, the largest 1 percent of gasoline stations can provide 80 times as much energy per day as the largest hydrogen station designs. As a result, hydrogen stations with the highest capacities in the network will need to show the greatest growth in order to provide the same magnitude of service as the largest gasoline stations. This growth in capacity will likely be a smooth transition over time, requiring careful balancing of the financial constraints of greater capital investment, potential for greater revenue due to greater throughput, and coordination with the timing of FCEV rollouts and sales.

9.3.4 Hydrogen Fueling Station Costs

Hydrogen fueling infrastructure is currently in a period of transition from research and demonstration to full retail and commercial market development. This transition period has meant that hydrogen fueling stations built in prior years have largely been hand-constructed, individually designed stations. Conversely, newer stations currently being constructed in California and other parts of the nation (and the world) are becoming increasingly standardized in their design. Given this transitional period, there is currently a degree of uncertainty in the likely costs to build and operate a hydrogen fueling station in a fully-developed, retail-service

FCEV and hydrogen fueling market. However, as part of its infrastructure development program, California recently released the first of its annual reports that evaluate the costs and timing of building the currently-funded hydrogen fueling stations and the expectations for stations to be funded up to the goal of at least 100 stations. The 2015 Joint Agency Staff Report on Assembly Bill 8: Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California[58] discussed the costs and construction timelines observed over the course of California's experience with installing hydrogen fueling stations. In particular, the report assessed the costs for three station types that are representative of the majority of the stations currently in California's planned network and are expected to continue to play major roles in the ongoing network development.

Based on grant funding applications and follow-up interviews with awardees, estimates of costs for the currently funded station network in California were developed for the Joint Assessment.[59] Representative values for three common station designs are summarized in Table 9.4, based on the information provided in the report. Note that some of the values reported are estimates generated for stations still in construction, and some underlying cost values may be based on one or a few stations and all stations are being developed in the early years of network development. As in Figure 9.19, these costs may decline over the coming years. As the State continues to co-fund stations and learn more about the development costs, estimates and trends will likely become more precise and predictable.

Table 9.4 Representative Hydrogen Fueling Station Costs[60]

Hydrogen Source	Capacity (kg/day)	Total Capital Costs ($ Million)	Equipment Costs ($ Million)	Construction Costs ($ Million)	Other Costs* ($ Million)
Delivered Gaseous	180	2.01	1.60	0.28	0.13
Delivered Liquid	350	2.80	1.93	0.60	0.27
On-Site Electrolysis	100	3.21	2.38	0.46	0.37

*Other Costs include Engineering and Design, Permitting, Commissioning, and Project Management and Overhead

Based on information available from station grant funding applications, invoices, and follow-up meetings with station developers, the 2015 cost assessment estimated the current costs of development for each of these stations. It is important to note that any such estimation is only representative; many variable costs included in the overall estimate may significantly alter the assessment for an individual station. These costs are "all-in" capital costs, including engineering, permitting, equipment procurement, construction, commissioning, and other factors. These costs do not include operations and maintenance costs, which would include the cost to procure hydrogen, rent, variable electrical and potentially natural gas energy costs, and others.

These costs are representative of today's technology, the relatively small number of stations in development (compared to expectations for the future), and the still-developing supply chain for manufacture of the equipment. In future years, as the rollout of FCEVs progress, larger numbers of stations (and likely of larger rated capacity) will be needed and it is expected that continued development of the equipment technology and the material supply chains will enable decreasing capital costs on an individual station basis, as shown in Figure 9.19. Economies of scale suggest larger reductions are possible for larger capacity stations. Note that although shown in Figure 9.19, no retail station currently funded or in operation in the United States has a capacity above 400 kg/day; stations with the larger capacities are expected to become more favorable and common as the volumes of vehicles on the road significantly increase in later years.

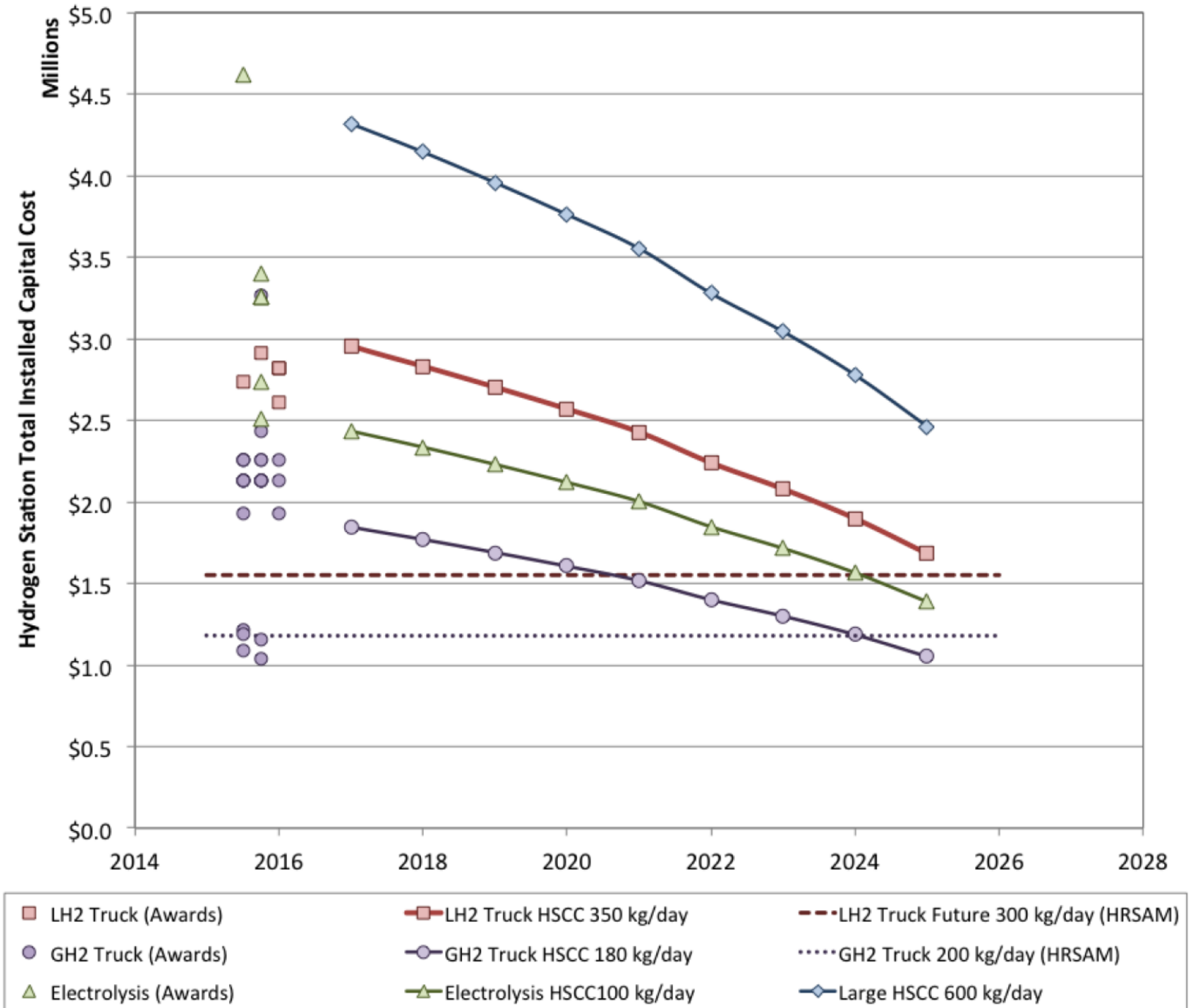


Figure 9.19 Projections for Cost Reductions in Hydrogen Fueling Infrastructure[61]

Operations costs also play a major role in the overall financial viability of hydrogen fueling stations. Especially during the early period of the FCEV market launch, the operations costs can actually be the dominating concern for a station's viability. Small numbers of vehicles translate to low utilization of the station and restricted hydrogen sales revenue, which provides the means of paying for variable operating costs and amortized capital costs. In addition to the uncertainty in the near-term demand for hydrogen fueling, there is also uncertainty in the price to procure hydrogen and the eventual market price that can be charged for hydrogen. Currently, hydrogen is most often sold to other industries in much larger quantities and at much lower pressures than are needed at today's FCEV fueling stations. This "merchant hydrogen" price is thus not likely representative of the price that hydrogen fueling station operators will need to pay. In the 2015 Assessment,[62] estimates of delivered hydrogen cost to the stations varied from $8.91/kg in 2015 to $7.64/kg in 2025; retail sale price to the consumer was estimated to decrease from $14/kg in

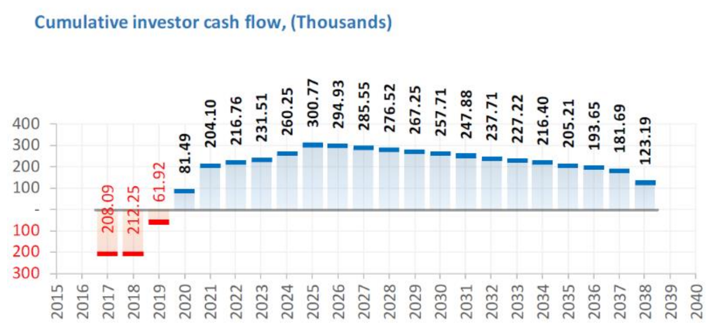
2015 to $11.11/kg in 2025, all based on prior work and information from current stations developers. A sample of the assessment and major financial indicators for the gaseous delivery station is included in Figure 9.20. In the figure, the cost of delivered hydrogen is clearly a major portion of the overall costs to the station (note that cash flows are shown in levelized terms). Also note the importance of the capital and production incentives (as modeled through the AB 8 program); the analysis found that with current technology and vehicle deployment projections, these incentives play a major role in the financial viability of the early station network.

Station specification

Station type	Delivered gas	
Station capacity (kg/day)		180
Vintage year		2018
SERA Scenario		Expected
Station cost (all-in)	$	1,561,000
Station capital incentives	$	1,249,000
O&M incentive (for 3 years)	$	100,000

Financial performance benchmark

IRR		29.6% √
Profitability index		1.7
NPV after-tax, nominal @ 10% discount	$	116,000
First year of positive EBITD		4
Real levelized retail margin ($/kg)	$	3.49
Price of H2 to yield 10% IRR ($/kg)	$	9.52



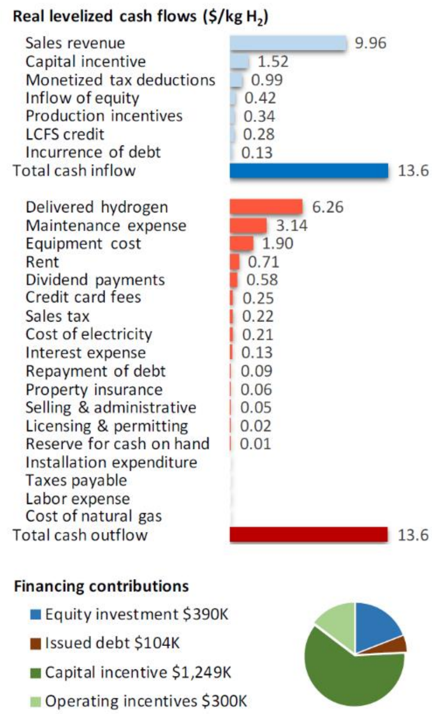


Figure 9.20 Sample Financial Evaluation of a 180 Kg/Day Delivered Gaseous Hydrogen Fueling Station Based on Experience in California[63]

9.3.5 Paradigms for Developing Networks

While there is broad acceptance of some form of the cluster-connector-destination style of fueling station placement and planning, significant and varied work has been targeted towards the specific implementation of the strategy and translating the general concept into a plan that can be implemented by state and local agencies. One of the earliest examples is STREET (Spatially and Temporally Resolved Energy and Environment Tool) developed by the Advanced Power and Energy Program at the University of California, Irvine.[64] This tool represented an innovation in providing detailed spatial resolution in pinpointing ideal locations for hydrogen fueling stations, based on projections of geographic distribution of the early adopter market. A fundamental function of the STREET model is to determine the appropriate number and location of stations to provide localized service coverage equivalent to the national average of coverage provided by gasoline stations, thereby providing the same measure of convenience to the driver. The tool was instrumental in the development of a roadmap to meeting the CaFCP-defined clusters and served the State of California for a number of years to help quantify the desirability of proposed station locations. With STREET and stakeholder discussions led by the CaFCP, it was determined that 68 stations would be necessary to launch the first adopter FCEV market.[65]

More recently ARB has developed the California Hydrogen Infrastructure Tool (CHIT), which shares some fundamental features with STREET and other models. At its core, CHIT identifies the areas with a large early market potential for FCEVs and compares this to an estimation of the coverage provided by existing and funded stations.[66] CHIT has been designed as a tool that allows ARB and CEC to annually identify the areas with the greatest need for additional station coverage, and emphasizes infrastructure planning rather than optimization. By determining areas of greatest need for additional station coverage, CHIT provides a basis for structuring State infrastructure funding programs while also allowing flexibility for station developers to build proposals with more finely detailed information for specific sites that could meet the identified early adopter market needs. Thus, it fills a need for evaluation in grant funding programs, as opposed to the optimization scheme that takes a central role in STREET. Figure 9.21and Figure 9.22 show STREET and CHIT's coverage assessment outputs.

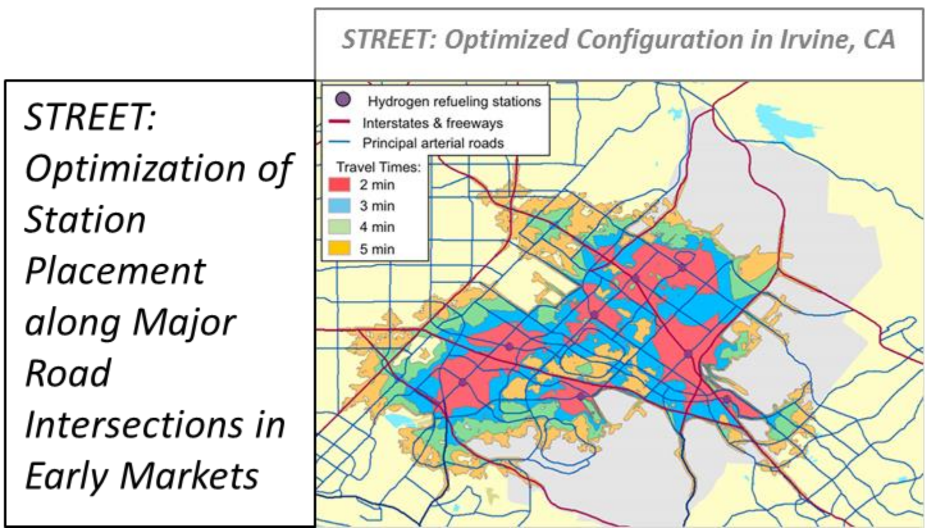


Figure 9.21 Optimization of Coverage in STREET

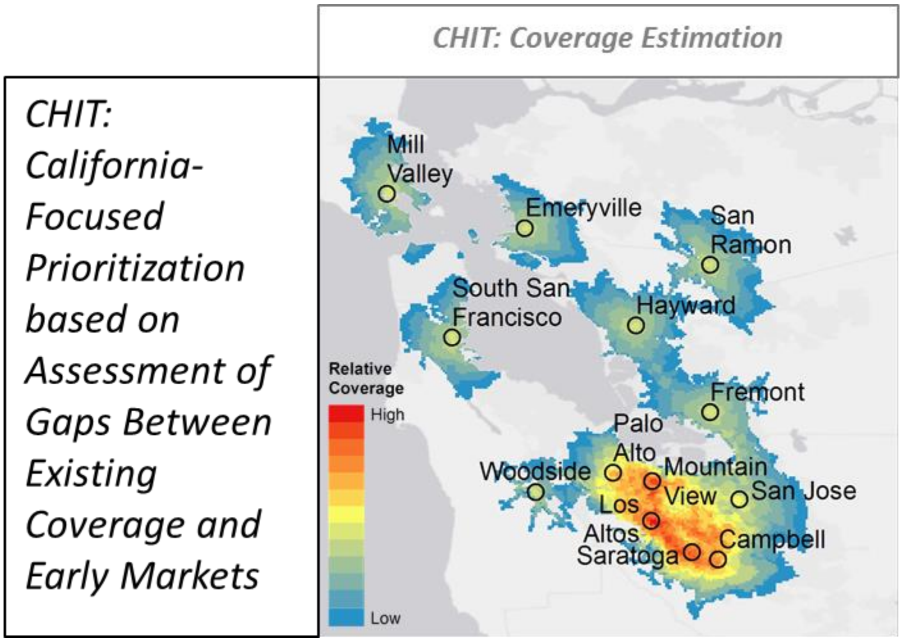


Figure 9.22 Multiple-Station Coverage Estimation in CHIT

On the national scale, the National Renewable Energy Laboratory has been developing the Scenario Evaluation, Regionalization, and Analysis (SERA) tool to study likely scenarios of hydrogen infrastructure development and deployment.[67] The tool incorporates findings and direct functionalities from a number of other hydrogen fueling station and vehicle choice models from various DOE efforts in order to provide a full-spectrum analysis of potential nationwide growth in FCEV adoption and complementary fueling station establishment. Among other factors, the model emphasizes the assessment of an Early Adopter Metric in determining the order and magnitude of development of hydrogen fueling stations in Urbanized Areas (as defined by the U.S. Census Bureau), and more recently incorporates an analysis to determine timing and placement of connector stations between regional clusters once they reach critical size(s). The consideration given to the model's various factors is flexible, allowing researchers to assess scenarios that emphasize proximity to early adopter markets, proximity to established fueling infrastructure, the strength of incentive programs, or other fundamental considerations. In addition to the scheduling, siting, and capacity specification capabilities, the model also provides a means for assessing or optimizing the financial case for individual stations and the network. Figure 9.23 shows projections of network size and phase-in date from analysis of a scenario with successful launch of FCEVs nationwide.

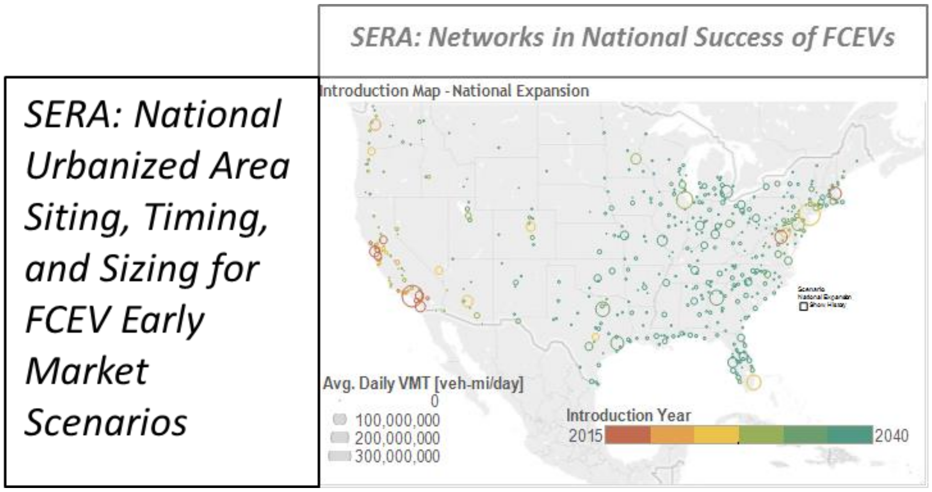


Figure 9.23 Nationwide Identification and Timing of Urban Areas for FCEV Markets in SERA

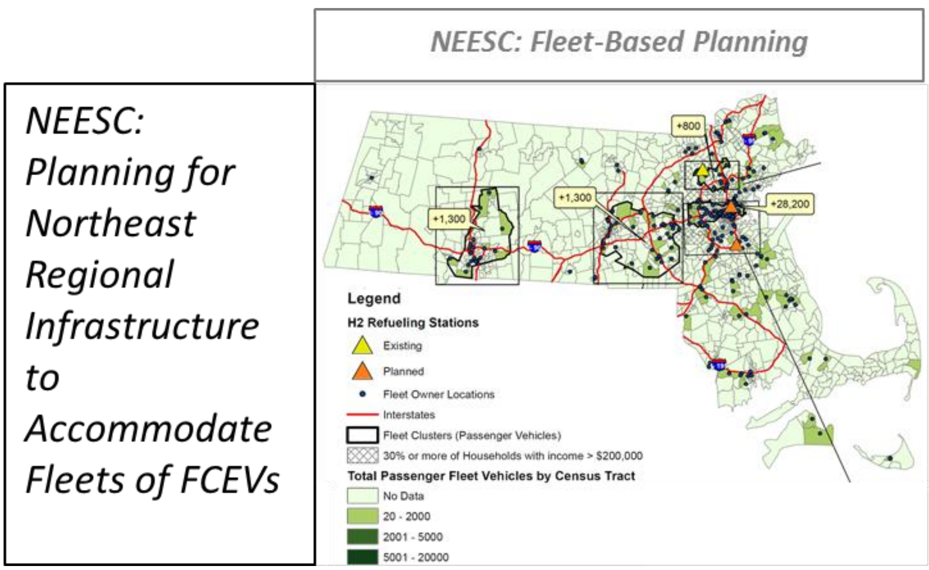


Figure 9.24 Fleet-Based Planning for Infrastructure Networks in the Northeast States Produced by NEESC

Finally, the Northeast Electrochemical Energy Storage Cluster (NEESC) has been working in partnership with NREL and H2USA to develop a plan for refueling station locations for nine states in the Northeast: Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, and Maryland. The planning has involved a fleet-centric approach to determining the best locations for the early market.[42, 68] Under this paradigm, fleets (corporate and/or government passenger vehicle fleets) and individual consumers will be able to fuel at the stations; however, the fleet vehicles may be able to provide a more consistent and greater utilization of the fueling stations in the early years. Over time, the mix of vehicles utilizing the stations is anticipated to shift towards individual retail customers while still serving the needs of both markets. Figure 9.24 shows the planning methods used by NEESC, which emphasize demographic information, known vehicle fleet locations, and transportation data to plan station locations to meet primarily fleet-based needs.

A number of other paradigms for building a robust hydrogen infrastructure network have also provided valuable insights for planning and anticipating the regional and national need. Modeling has been completed to demonstrate the benefit to network flexibility that could be afforded by a larger number of mobile refuelers with the ability to act as dispatch able temporary or semi-permanent stations.[69,70] Other work emphasizes the importance of local demographics and traffic patterns, especially near major highway access points, for fine-tuned optimization of station placement.[71] Origin-Destination studies further analyze traffic patterns, seeking to take advantage of data available from case studies of local drivers' travel routes in order to find station locations optimized by their proximity to the major travel routes, rather than to the homes, of the early market adopters.[72,73,74] Other examples of station placement planning have been detailed in the literature, but an exhaustive review is beyond the scope of this report and the concepts presented here have had demonstrable effects on considerations in current and past fueling station planning.

9.3.6 Challenges and Opportunities for Hydrogen Fueling Stations

While development of hydrogen fueling networks has been concentrated in California, future expansion is anticipated in other early market areas of the nation. As previously mentioned, the northeast states currently have multiple efforts underway including a grant program in Connecticut, development of a multi-state regional plan, and anticipated station development through private partnerships (Toyota-Air Liquide). As these and other networks become established and continue to grow, the development of local, statewide, and regional hydrogen fueling networks is likely to evolve to meet the changing needs of the network.

In particular, it is anticipated that the paradigm for locating new stations will shift from providing maximum coverage to the early adopters to providing maximum fueling capacity for broadening markets. A number of factors will motivate this shift. The first is that economies of scale are expected to dictate that larger stations will provide more favorable business cases to the station developers and operators. With the revenue gains afforded by larger throughput, station operators will be able to capture shorter payback periods and will likely be able to provide hydrogen at lower retail prices than with a smaller station. Additionally, the increasing volume of FCEV production and sales will necessitate greater capacities of hydrogen fueling in the future. If the network cannot serve the projected growing numbers of vehicles, there will be a risk that vehicle introduction rates will be curbed in order to avoid stressing the network and diminishing the customer experience. However, the timing and implementation of a transition to larger capacity stations will need to be carefully gauged; larger capacity stations will individually require greater capital investment. The result would be fewer stations built with an equivalent investment, potentially limiting the effectiveness of that investment to provide increased coverage. This transition from coverage-focused to capacity-focused investment is not expected to be abrupt; instead, a smooth transition that balances capacity and coverage appropriately will likely lead to a more successful network.

In addition to station capacity, it is expected that stations will continue to become more technically capable. In California and Connecticut, performance requirements such as back-to-back fills capability have been specified. This ensures customers will not need to wait for station equipment to be ready to fuel their vehicle when they arrive during the busiest, peak traffic times of the day. The number of back-to-back fills and the speed of the fills are expected to be refined over the coming years and each is likely to improve as technology progresses and increased demand warrants more stringent performance standards. Part of this development will also be the move from single-hose designs that are currently the norm to stations with multiple dispensers that can fuel multiple vehicles simultaneously. Projecting further out, stations will also progress from the current model of co-location of individual hydrogen fueling islands on gasoline station property to development of stations fully dedicated to hydrogen.

Nearly all hydrogen fueling stations developed to date have received financial assistance via some form of government grant funding. This has been a necessary step in order to accelerate the technological and market development of FCEVs and hydrogen fueling. The aim of the government programs that supply these funds (like Assembly Bill 8 in California and EV Connecticut) is to provide support to a developing industry and relieve some of the initial investment risk. However, it is also the goal that the supported industry will become self-sufficient and see real returns on investment without government assistance within a reasonable timeframe. As a benchmark, AB 8 in California has set 100 State-funded stations as an evaluation point for determining whether the FCEV and hydrogen market is self-sufficient. As fueling networks continue to develop, there will be an expectation that the business cases for new stations will continue to improve through reduced risk, reduced costs, and increased revenue provided by a growing customer base. Once early uncertainties and risks are overcome, new stations will be able to be built with increasing proportions of private funds.

The progress to-date in California and planned for the Northeast is working to ensure that sufficient fueling infrastructure exists to support the needs of the early FCEV market. By catalyzing this early fueling network development, government and private industry are making the necessary developments to allow FCEVs to enter the retail commercial market and have success in widespread consumer adoption. The current networks and planning target this specific near-term need, but these developments are crucial for establishing the FCEV market's potential as a major aspect of achieving greenhouse gas emission reduction goals. The success of these efforts will enable a national expansion of the FCEV market, fulfilling expectations of the future role of the vehicles in the nation's fleet.

For the stations that have been built to date, implementation of renewable hydrogen sourcing has posed a financial challenge. Recognizing the increased cost of generating hydrogen through entirely renewable methods (such as solar and/or wind-powered electrolysis, reformation of biogas, and conversion or biomass), the California Energy Commission has previously provided greater funding incentive for stations that demonstrate a 100 percent renewable fuel pathway. It has long been a vision for the industry that renewable generation methods become less expensive, enabling the economic viability of a hydrogen infrastructure network that will be supplied by increasing volumes of renewably-sourced hydrogen.

There exists a particularly notable potential to accelerate this industry development by implementation of the power-to-gas paradigm. In this type of system, hydrogen plays a central role as an energy carrier, providing energy storage for renewable electricity that would otherwise be curtailed at times of low demand. The renewably-produced hydrogen can then be integrated with local and regional natural gas pipeline systems potentially for enrichment of the energy content of the gas or for long-distance transportation of hydrogen, and providing fuel to FCEVs. This integrated approach is currently being researched by a number of organizations worldwide and efforts are underway to demonstrate the viability of the concept at real-world scales of energy demand. For example, there are approximately 30 power to gas projects in Germany in various stages of planning and operation.[75]

9.4 Fueling Infrastructure for Other Alternative Fuel Vehicles

As discussed in Chapters 12 and 13, and consistent with the agencies' projections in the 2012 final rule, the agencies project that OEMs will be able to comply with the standards without large-scale development and commercialization of alternative fuel vehicle technologies. While the discussion above focused on infrastructure for electric and hydrogen-fueled vehicles, which can achieve significant reduction in GHGs, it is also possible that vehicle manufacturers will continue to market some light-duty vehicles using alternative fuels other than electricity and hydrogen in the U.S. There are already a large number of flex fuel vehicles (FFVs), capable of fueling on either gasoline or ethanol (E85), in the marketplace. In addition, there is existing infrastructure capable of delivering blends of conventional fuels and biofuels; this existing capacity is being enhanced by investment in additional capacity, including through investment by USDA, matched by state and private sector investment. It is also possible that there may continue to be gradual growth in the numbers of natural gas vehicles, primarily compressed natural gas (CNG) vehicles, into the foreseeable future if favorable market conditions continue.

To the extent that some manufacturers produce alternative fueled vehicles in the coming years, sufficient fueling infrastructure will continue to be needed for purchasers of those vehicles. For the two largest alternative fuel vehicle segments, CNG and E85, fueling infrastructure has continued to grow to support vehicle fleet growth. Numbers of CNG stations have continued to rebound from a decline during the recent recession years, increasing each year since 2009 and reaching an all-time high of over 1,600 stations currently, over 900 of which are available to the public. (The remainder of current CNG stations provide fuel to dedicated fleets of vehicles, usually heavy-duty vehicles, and are not available for fueling light-duty CNG vehicles). The number of gasoline stations that provide E85 has increased from under 800 stations in 2006 to over 3,100 stations today, over 2,800 of which are available to the public.[76] Also, the U.S. Department of Agriculture's Biofuels Infrastructure Partnership now underway could increase the number of E85 stations.[77]

9.5 Summary of Alternative Fuel Infrastructure

In aggregate, the status of alternative fuel infrastructure could be characterized as sufficient, growing, or robust. Moreover, the agencies' initial assessment for this Draft TAR is that the MY2022-2025 standards can be met largely through continued advancements in gasoline vehicle technologies, with the only alternative fuels needed to meet the MY2022-2025 standards being a very small fraction of PEVs (see Chapters 12 and 13). As a result, infrastructure does not present a barrier for alternative fuel vehicles to be used in meeting the 2022-2025 national program GHG and CAFE standards. Of course, the agencies recognize that, apart from the standards, auto manufacturers may decide to pursue alternative fueled vehicles for other reasons, such as market demand.

Although the majority of PEV charging occurs at home and home-based charging is an option for many PEV drivers, national PEV infrastructure in public and work locations is progressing appropriately. With over 12,000 public and private stations and over 38,000 connectors, public charging needs are being addressed, additional public charge stations are opening weekly, and strong growth is forecasted. With vehicle grid integration, inductive charging, and vehicle to grid bi-direction power flow, tremendous opportunities in PEV infrastructure are on the horizon. These opportunities coupled with a growing PEV market will further the commercial infrastructure market and ultimately the availability of PEV infrastructure.

The preceding section discusses existing infrastructure and trends for ethanol (E85) and natural gas.

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Chapter 10: Economic and Other Key Inputs Used in the Agencies' Analyses

10.1 The On-Road Fuel Economy "Gap"

10.1.1 The "Gap" Between Compliance and Real World Fuel Economy

Real world tailpipe CO_2 emissions are higher, and real world fuel economy levels are lower, than the corresponding values from EPA standards compliance tests. This is because laboratory testing cannot reflect all of the factors that can affect real world operation, and, in particular, the city and highway tests used for compliance do not encompass the broad range of driver behavior and climatic conditions experienced by typical U.S. drivers.[A] In the rulemakings that established the National Program standards through MY2025, EPA and NHTSA applied a 20 percent fleet-wide fuel economy "gap," i.e., that average, fleet-wide real world fuel economy would be 20 percent lower than EPA compliance test values.[B] This 20 percent value was based on data from MY2004-2006.[1] For example, a vehicle with a fuel economy compliance test value of 30 mpg would be projected to have a real world fuel economy of 30 multiplied by 0.8 (equivalent to a 20 percent reduction) or 24 mpg. The inverse of 0.8 is 1.25, and a vehicle with a CO_2 emissions compliance test value of 300 grams/mile would be projected to have a real world CO_2 emissions value of 300 multiplied by 1.25 or 375 grams/mile.

More recent data suggests that the gap between 2-cycle compliance test and 5-cycle methodology values may have increased very slightly in the last decade. For example, the use of final MY2014 and projected MY2015 data suggest that the fuel economy gap between 2-cycle data and 5-cycle data may now be approximately 21 percent.[2] EPA believes that further analysis is needed before incorporating such small changes into calculations of the overall gap. In addition, some analysis suggests that the gap between 2-cycle compliance tests and real world fuel economy may be increasing in recent years, but the evidence is not conclusive.[3] One factor which has clearly changed and can be quantified is ethanol content in gasoline. When the 20 percent fuel economy gap was first projected in 2005-2006, ethanol accounted for a small fraction of the gasoline pool. For this Draft TAR analysis, EPA adjusts for projected differences in the energy content due to increased ethanol penetration of retail gasoline relative to test fuel for MY2022 and beyond.. Ethanol contains about 35 percent less energy than gasoline, on a volumetric basis, and EPA projects that average in-use gasoline will contain about 3.5 percent less energy in 2025 than it did in the 2005-2006 timeframe. Using the "base" 20 percent fuel economy gap between 2-cycle and 5-cycle data and the projected impact of the ethanol increase in 2025 yields an effective gap of 23 percent (or a fuel economy factor of 0.77), and this is the

[A] EPA has recognized that the "2-cycle" city and highway tests are not representative of real world fuel economy performance for over 30 years. From MY 1985 through MY2007, EPA based new vehicle window labels on the fuel economy compliance test values adjusted downward by 10% for the city test and by 22% for the highway test. Beginning in MY2008, EPA has based vehicle labels on a 5-cycle methodology that includes three additional tests (reflecting high speed/high acceleration, hot temperature/air conditioning, and cold temperature operation) as well as a 9.5% downward fuel economy adjustment for other factors not reflected in the 5-cycle protocol.

[B] Note that this is an average fleet-wide value, in reality the true fuel economy gap is data driven and will be lower for some vehicles and higher for other vehicles. In general, all things being equal, today's data suggests that the gap is generally smaller for lower-fuel economy vehicles and greater for higher-fuel economy vehicles.

overall fuel economy gap that we use in this report. Multiplying 2-cycle fuel economy by 0.77 yields projected real world fuel economy.[C]

The fuel economy gap is data driven, so any 2025 projection involves uncertainty. EPA expects that, all other things being equal, as average fuel economy increases over time, the gap would likely increase as well. On the other hand, it is also possible that powertrain designs will be designed to be more robust in the future, which would impact the gap in the opposite direction. EPA will continue to monitor the relevant data on this issue.

10.1.2 Real World Fuel Economy and CO_2 Projections

Except when noted, CO_2 emissions and fuel economy values cited in this report represent standards compliance values. As discussed above, real world tailpipe CO_2 emissions are higher, and real world fuel economy levels are lower, than the corresponding values from EPA standards compliance tests.

This has led to widespread public confusion as there are two sets of fuel economy "books," one for fuel economy standards compliance (mandated by statute for cars) and one for the vehicle label estimates that EPA provides to consumers to estimate real world fuel economy. The projected real world fuel economy values shown below are the most meaningful fuel economy values for citizens and reporters as they provide a good comparison with label values, EPA Fuel Economy Trends report values, vehicle dashboard display values, and fuel economy calculations performed by some drivers, and also correspond to real world fuel consumption and CO_2 emissions.

Table 10.1 through 10.3 show EPA's best projections of the real world CO_2 emissions and fuel economy values associated with the projected CO_2 standards compliance emissions levels presented throughout this report, as well as how "the numbers add up," for cars, trucks, and the combined car/truck fleet, respectively. These values use as a starting point the projected industry-wide CO_2 2-cycle targets. The first step is to "back out" the impact of the direct air conditioner refrigerant credits, since reducing leakage and/or substituting lower-GHG refrigerants will not increase real world fuel economy. Backing out these credits requires adding the value of the air conditioner refrigerant credits to the target values, as doing so increases the CO_2 value and decreases the projected real world fuel economy level. The sum of the 2-cycle target and the "backed out" air conditioner refrigerant credits is the "fuel economy-relevant adjusted 2-cycle CO_2 emissions value," shown as the effective CO_2 value in the tables which can also be expressed as an effective mpg by dividing it into 8887 (which represents the number of grams of CO_2 that results from the combustion of a gallon of test gasoline). The second step is to multiply the adjusted 2-cycle, or effective mpg value by 0.77, the fuel economy "gap" factor discussed above. This step converts from the adjusted 2-cycle mpg to a real world, on-road mpg value. On-road tailpipe CO_2 emissions are projected by dividing the real world mpg value into 8488 (which represents the number of grams of CO_2 that results from the combustion of a gallon of retail gasoline). Subtracting back the A/C leakage credit value provides an on-road CO_2 equivalent (CO_2 e) value as shown.

[C] The corresponding CO_2 "gap" is 1.24, i.e., multiplying 2-cycle tailpipe CO_2 by 1.24 yields projected real world CO_2 emissions. This 1.24 factor is actually less than the 1.25 factor used in the past because of the lower carbon content of ethanol.

Table 10.1 EPA Projections for Fleet-wide CO_2 Standards Compliance and On-road Performance for Cars

	2-Cycle							Adjustments to 2-Cycle to Reflect Real World Impacts			On-road			
MY	CO_2 Target (g/mi)	CO_2 Target As MPG	A/C Leakage Credit (g/mi)	A/C Efficiency Credit (g/mi)	Off-cycle Credit (g/mi)	Tailpipe CO_2 (g/mi)	MPG	A/C Efficiency & Off-cycle Credits (g/mi)	Effective CO_2 (g/mi)	Effective MPG	Gap	On-road MPG	On-road Tailpipe CO_2 (g/mi)	On-road CO_2e (g/mi)
2021	171	51.9	13.8	5.0	0.6	191	46.6	5.6	185	48.1	.773	37.1	229	215
2022	165	53.9	13.8	5.0	0.7	184	48.2	5.7	179	49.8	.773	38.4	221	207
2023	159	56.0	13.8	5.0	0.9	178	49.8	5.9	173	51.5	.773	39.8	213	200
2024	153	58.2	13.8	5.0	1.0	173	51.5	6.0	167	53.3	.773	41.2	206	192
2025	147	60.3	13.8	5.0	1.1	167	53.2	6.1	161	55.2	.773	42.6	199	186

Note: The on-road values reflect adjustments for both the historical 2-cycle-to-5-cycle gap as well as the projected ethanol content in retail gasoline, and corresponding energy content. The on-road CO_2 is calculated by dividing 8488, the estimated CO_2 grams/gallon from combustion of a gallon of retail gasoline, by the on-road MPG. The on-road CO_2 e column subtracts from the on-road tailpipe CO_2 values the A/C leakage value to yield a value that reflects overall real world CO_2 e emissions performance.

Table 10.2 EPA Projections for Fleet-wide CO_2 Standards Compliance and On-road Performance for Trucks

	2-Cycle							Adjustments to 2-Cycle to Reflect Real World Impacts			On-road			
MY	CO_2 Target (g/mi)	CO_2 Target As MPG	A/C Leakage Credit (g/mi)	A/C Efficiency Credit (g/mi)	Off-cycle Credit (g/mi)	Tailpipe CO_2 (g/mi)	MPG	A/C Efficiency & Off-cycle Credits (g/mi)	Effective CO_2 (g/mi)	Effective MPG	Gap	On-road MPG	On-road Tailpipe CO_2 (g/mi)	On-road CO_2e (g/mi)
2021	242	36.7	17.2	7.2	2.3	269	33.1	9.5	259	34.3	.773	26.5	321	304
2022	232	38.3	17.2	7.2	2.6	259	34.3	9.8	250	35.6	.773	27.5	309	292
2023	223	39.9	17.2	7.2	2.9	250	35.6	9.9	240	37.0	.773	28.6	297	280
2024	214	41.6	17.2	7.2	3.2	241	36.8	10.4	231	38.5	.773	29.7	286	269
2025	206	43.2	17.2	7.2	3.5	233	38.1	10.7	223	39.9	.773	30.8	276	258

Note: The on-road values reflect adjustments for both the historical 2-cycle-to-5-cycle gap as well as the projected ethanol content in retail gasoline, and corresponding energy content. The on-road CO_2 is calculated by dividing 8488, the estimated CO_2 grams/gallon from combustion of a gallon of retail gasoline, by the on-road MPG. The on-road CO_2 e column subtracts from the on-road tailpipe CO_2 values the A/C leakage value to yield a value that reflects overall real world CO_2 e emissions performance.

Table 10.3 EPA Projections for Fleet-wide CO_2 Standards Compliance and On-road Performance for the Fleet

	2-Cycle							Adjustments to 2-Cycle to Reflect Real World Impacts			On-road			
MY	CO_2 Target (g/mi)	CO_2 Target As MPG	A/C Leakage Credit (g/mi)	A/C Efficiency Credit (g/mi)	Off-cycle Credit (g/mi)	Tailpipe CO_2 (g/mi)	MPG	A/C Efficiency & Off-cycle Credits (g/mi)	Effective CO_2 (g/mi)	Effective MPG	Gap	On-road MPG	On-road Tailpipe CO_2 (g/mi)	On-road CO_2e (g/mi)
2021	206	43.1	15.5	6.1	1.5	229	38.8	7.6	222	40.1	.773	30.9	274	259
2022	198	44.9	15.5	6.1	1.7	221	40.2	7.8	213	41.6	.773	32.1	264	249
2023	190	46.8	15.5	6.1	1.9	213	41.7	8.0	205	43.3	.773	33.4	254	239
2024	182	48.8	15.4	6.1	2.1	206	43.2	8.2	198	45.0	.773	34.7	245	229
2025	175	50.8	15.4	6.0	2.3	199	44.7	8.4	190	46.7	.773	36.0	236	220

Note: The on-road values reflect adjustments for both the historical 2-cycle-to-5-cycle gap as well as the projected ethanol content in retail gasoline, and corresponding energy content. The on-road CO_2 is calculated by dividing 8488, the estimated CO_2 grams/gallon from combustion of a gallon of retail gasoline, by the on-road MPG. The on-road CO_2e column subtracts from the on-road tailpipe CO_2 values the A/C leakage value to yield a value that reflects overall real world CO_2e emissions performance.

EPA projects the industry-wide real world fuel economy associated with the MY2025 GHG standards to be 36 mpg. This value provides a good comparison with average label and Fuel Economy Trends values.

10.2 Fuel Prices and the Value of Fuel Savings

Fuel prices and the projection of fuel prices remain critical in the analysis of GHG and fuel economy standards. EPA has continued to use the methodology described in section 4.2 of the 2012 Joint Technical Support Document, with some notable updates. EPA continued to rely on the fuel price projections from the U.S. Energy Information Administration's (EIA) Annual Energy Outlook (AEO) for this analysis, updated to the AEO 2015 Reference Case. The Reference case projection is a business-as-usual trend estimate, given known technology and technological and demographic trends. EIA has published annual projections of energy prices and consumption levels for the U.S. economy since 1982 in its Annual Energy Outlook reports. These projections have been widely relied upon by federal agencies for use in regulatory analysis and for other purposes. Since 1994, EIA's annual forecasts have been based upon the agency's National Energy Modeling System (NEMS), which includes detailed representation of supply pathways, sources of demand, and their interaction to determine prices for different forms of energy. In addition to the AEO 2015 Reference Case as the central case, EPA has also included the AEO 2015 low and high fuel price cases as sensitivities. A comparison of these cases is presented below in Table 10.4.

Table 10.4 Gasoline Prices for Selected Years in Various AEO 2015 Cases

	2025	2030	2040
AEO 2015 Reference Case	$ 2.95	$ 3.20	$ 3.90
AEO 2015 "Low" Case	$ 2.40	$ 2.45	$ 2.60
AEO 2015 "High" Case	$ 4.56	$ 5.05	$ 6.33

The retail fuel price forecasts presented in AEO 2015 span the period from 2012 through 2040. Measured in constant 2013 dollars, the AEO 2015 Reference Case projections of retail gasoline prices during calendar year 2025 is $2.95 per gallon, rising gradually to $3.90 by the year 2040 (these values include federal and state taxes). However, valuing fuel savings over the full lifetimes of passenger cars and light trucks affected by the standards for MYs 2012-25 requires fuel price forecasts that extend through approximately 2060, approximately the last year during which a significant number of MY2025 vehicles will remain in service. Due to the difficulty in accurately projecting fuel prices over this long time span, EPA has assumed constant fuel prices after the year 2040 for the Draft TAR analysis.

The AEO 2016 Early Release (AEO 2016ER) was released in June 2016, as the agencies' Draft TAR analyses were well underway. While there are some differences between the AEO 2015 and AEO 2016ER fuel price projections, especially in earlier years, the projection prices are similar over the 2022 and beyond timeframe. Moreover, the AEO 2016ER fuel price projections fall well within the range of the AEO 2015 low and high fuel price sensitivity cases analyzed as part of Chapter 12.4. The agencies plan to update their analyses based on the latest available AEO projections for later steps of the midterm evaluation and CAFE rulemaking process.

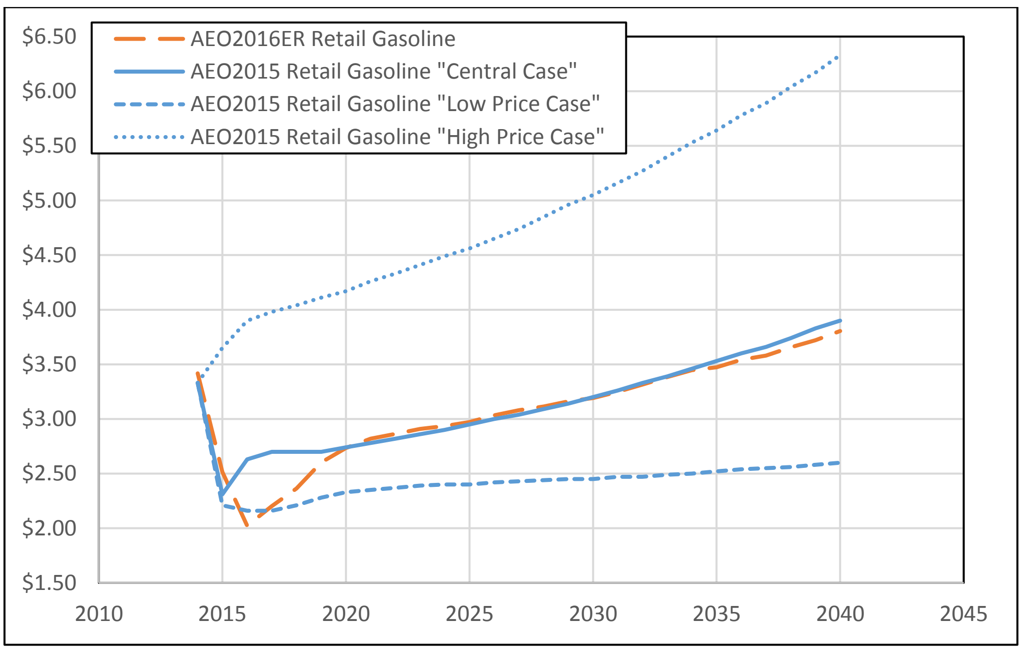

Figure 10.1 Comparing AEO 2015 and AEO 2016 Early Release Retail Fuel Price Projections

The value of fuel savings resulting from improved fuel economy and reduced GHG emissions to buyers of light-duty vehicles is determined by the retail price of fuel, which includes federal, state, and any local taxes imposed on fuel sales. Total taxes on gasoline, including federal, state, and local levies, averaged $0.41 per gallon during 2013, while those levied on diesel averaged $0.48. Because fuel taxes represent transfers of resources from fuel buyers to government agencies, rather than real resources that are consumed in the process of supplying or using fuel, their value must be deducted from retail fuel prices to determine the value of fuel savings resulting from more stringent fuel efficiency and GHG standards to the U.S. economy. When calculating the value of fuel saved by an individual driver, however, these taxes are included as part of the value of realized fuel savings. Over the entire period spanned by the agencies' analysis, this difference causes each gallon of fuel saved to be valued by about $0.39 (in constant 2013 dollars) more from the perspective of an individual vehicle buyer than from the overall perspective of the U.S. economy.

10.3 Vehicle Mileage Accumulation and Survival Rates

EPA's analysis of benefits from fuel economy and GHG standards for passenger cars and light trucks, including GHG reductions, oil reductions, and fuel savings, begin by estimating the resulting changes in fuel use over the entire lifetimes of affected cars and light trucks. The change in total fuel consumption by vehicles produced during each of these model years is calculated as the difference in their total lifetime fuel use over the entire lifetimes of these vehicles as compared to a reference case.

EPA's approach for this analysis remains largely the same as that found in the 2012 FRM TSD, Chapter 4.2. Since the FRM, EPA has updated a few key inputs related to vehicle lifetime survival rates and total vehicle miles traveled (VMT), as described in Table 10.5 and Table 10.6 below. These updates were made in order to align this analysis with inputs developed in conjunction with the EPA MOVES 2014a model[4], which has integrated new activity and population data sources from R.L. Polk, FHWA, and the EIA Annual Energy Outlook following the release of the FRM.[5] Additionally, the MOVES model is also already used as part of other EPA rulemaking analyses, allowing this analysis to take advantage of updates from those efforts. Methodologies for the derivation of fuel savings and related benefits (including future year projections, VMT growth factor, and fuel cost per mile) from these inputs remain identical to those found in the FRM TSD.

Table 10.5 Updated Vehicle Survival Rates (from MOVES 2014a)

VEHICLE AGE	ESTIMATED SURVIVAL FRACTION (CARS)	ESTIMATED SURVIVAL FRACTION (LIGHT TRUCKS)
0	1.000	1.000
1	0.997	0.991
2	0.994	0.982
3	0.991	0.973
4	0.984	0.960
5	0.974	0.941
6	0.961	0.919
7	0.942	0.891
8	0.920	0.859
9	0.893	0.823
10	0.862	0.784
11	0.826	0.741
12	0.788	0.697
13	0.718	0.651
14	0.613	0.605
15	0.510	0.553
16	0.415	0.502
17	0.332	0.453
18	0.261	0.407
19	0.203	0.364
20	0.157	0.324
21	0.120	0.288
22	0.092	0.255
23	0.070	0.225
24	0.053	0.198
25	0.040	0.174
26	0.030	0.153
27	0.023	0.133
28	0.013	0.117
29	0.010	0.102
30	0.007	0.089
31	0.002	0.027

Table 10.6 2011 Mileage Schedule (from MOVES 2014a)

VEHICLE AGE	ESTIMATED VMT CARS	ESTIMATED VMT LIGHT TRUCKS
0	13,843	15,962
1	13,580	15,670
2	13,296	15,320
3	12,992	15,098
4	12,672	14,528
5	12,337	14,081
6	11,989	13,548
7	11,630	13,112
8	11,262	12,544
9	10,887	12,078
10	10,509	11,595
11	10,129	11,131
12	9,748	10,641
13	9,370	10,153
14	8,997	9,691
15	8,629	9,239
16	8,270	8,797
17	7,922	8,383
18	7,586	8,009
19	7,265	7,666
20	6,962	7,358
21	6,679	7,089
22	6,416	6,862
23	6,177	6,684
24	5,963	6,556
25	5,778	6,481
26	5,623	6,466
27	5,499	6,466
28	5,410	6,466
29	5,358	6,466
30	5,358	6,466
TOTAL	**278,134**	**310,610**

10.4 Fuel Economy Rebound Effect

10.4.1 Accounting for the Fuel Economy Rebound Effect

The rebound effect generally refers to the additional energy consumption that may arise from the introduction of a more efficient, lower cost energy service which offsets, to some degree, the energy savings benefits of that efficiency improvement.[6,7,8] In the context of light-duty vehicles (LDVs), rebound effects might occur when an increase in vehicle fuel efficiency encourages people to drive more as a result of the lower cost per mile of driving. Because this additional driving consumes fuel and generates emissions, the magnitude of the rebound effect is one determinant of the actual fuel savings and emission reductions that will result from adopting stricter fuel economy or GHG emissions standards.

The rebound effect for personal vehicles can in theory be estimated directly from the change in vehicle use, in terms of vehicle miles traveled (VMT), which results from a change in vehicle fuel efficiency.[D] In practice, any attempt to quantify this "VMT rebound effect" (sometimes also labeled the "direct rebound effect," or "direct VMT rebound effect") is complicated by the difficulty in identifying an applicable data source from which the response to a significant improvement in fuel efficiency can be estimated. Analysts instead often estimate the VMT rebound indirectly as the change in vehicle use that results from a change in fuel cost per mile driven or a change in fuel price. When a fuel cost per mile approach is used, it does not distinguish the relative contributions of changes in fuel efficiency and changes in fuel price to the rebound effect, since both factors are determinants of fuel cost per mile.[E]

When expressed as positive percentages, the elasticities of vehicle use with respect to fuel efficiency or per-mile fuel costs (or fuel prices) give the percentage increase in vehicle use that results from a doubling of fuel efficiency (e.g., 100 percent increase), or a halving of fuel consumption or fuel price. For example, a 10 percent rebound effect means that a 20 percent reduction in fuel consumption or fuel price (and the corresponding reduction in fuel cost per mile) is expected to result in a two percent increase in vehicle use.

While we focus on the VMT rebound effect in our analysis of this program, there are at least two other types of rebound effects discussed in the transportation policy and economics literature. In addition to direct VMT rebound effect, there is the "indirect" rebound effect, which typically refers to the purchase of other goods or services that consume energy with the costs savings from energy efficiency improvements. The last type of rebound effect is labeled the "economy-wide" rebound effect. This effect refers to the increased demand for energy throughout the whole economy in response to the reduced market price of energy that happens as a result of energy efficiency improvements.

Research on indirect and economy-wide rebound effects is scant, and we have not identified any studies that attempt to quantify indirect or economy-wide rebound effects that result from improvements in the energy efficiency of LDVs. In particular, the agencies are not aware of any

[D] Vehicle fuel efficiency is more often measured in terms of fuel consumption (gallons per mile) rather than fuel economy (miles per gallon) in rebound estimates.

[E] Fuel cost per mile is equal to the price of fuel in dollars per gallon divided by fuel economy in miles per gallon (or multiplied by fuel consumption in gallons per mile), so this figure declines when a vehicle's fuel efficiency increases.

data to indicate that the magnitude of indirect or economy-wide rebound effects would be significant for this National Program. Therefore, the rebound effect discussed in this section refers solely to the effect of increased fuel efficiency on vehicle use. The terms, "VMT rebound effect," "direct VMT rebound effect," and "rebound effect" can be used interchangeably, and they need to be distinguished from other rebound effects that could potentially impact the fuel savings and emissions reductions from our standards such as the "indirect rebound effect." To restate, the rebound effect discussed in this section refers solely to the effect of increased fuel efficiency on vehicle use.

This section surveys previous studies on the LDV rebound effect, summarizes recent work on the rebound effect, and explains the basis for the 10 percent rebound effect EPA and NHTSA are using for the Draft TAR analyses.

10.4.2 Summary of Historical Literature on the LDV Rebound Effect

It is important to note that a majority of the studies previously conducted on the rebound effect rely on data from the 1950–1990s. While these older studies provide valuable information on the potential magnitude of the rebound effect, studies that include more recent information (e.g., data within the last decade) may provide more reliable estimates of how the standards will affect future driving behavior. Recent studies on LDV rebound effects that have become available since the 2012 final rule are summarized in Section 10.4.3 below.

Estimates based on aggregate U.S. vehicle travel data published by the U.S. Department of Transportation, Federal Highway Administration, covering the period from roughly 1950 to 1990, have found long-run rebound effects on the order of 10–30 percent. Some of these studies are summarized in the following two Tables.

Table 10.7 Estimates of the Rebound Effect Using U.S. Aggregate Time-Series Data on Vehicle Travel

Author (year)	Short-Run	Long-Run	Time Period
Mayo & Mathis (1988)	22%	26%	*1958-84*
Gately (1992)	9%	9%	*1966-88*
Greene (1992)	Linear 5-19% Log-linear 13%	Linear 5-19% Log-linear 13%	*1957-89*
Jones (1992)	13%	30%	*1957-89*
Schimek (1996)	*5-7%*	*21-29%*	*1950-94*

Source: Sorrell and Dimitropolous (2007) table 4.6.[9]

Table 10.8 Estimates of the Rebound Effect Using U.S. State Level Data

Author (year)	Short-Run	Long-Run	Time Period
Haughton & Sarkar (1996)	9-16%	22%	*1973-1992*
Small and Van Dender (2005 and 2007a)	4.5% 2.2%	22.2% 10.7%	*1966-2001* *1997-2001*
Hymel, Small and Van Dender (2010)	*4.7%* *4.8%*	*24.1%* *15.9%*	*1966-2004* *1984-2004*

Source: Sorrell and Dimitropolous (2007) table 4.7 and the agencies' addition of recent work by Small and Van Dender (2007a) and Hymel, Small, and Van Dender (2010).

While studies using national (Table 10.7) and state level (Table 10.8) data have found relatively consistent long-run estimates of the rebound effect, household surveys display more variability (Table 10.9). One explanation is that these studies consistently find that the magnitude of the rebound effect differs according to the number of vehicles a household owns, and the average number of vehicles owned per household differs among the surveys used to derive these estimates. Still another possibility is that it is difficult to distinguish the impact of fuel cost per mile on vehicle use from that of other, unobserved factors. For example, commuting distance might influence both the choice of the vehicle as well as VMT. Residential density may also influence both fuel cost per mile and VMT, since households in urban areas are likely to simultaneously face both higher fuel prices and shorter travel distance. Also, given that household data tends to be collected on an annual basis, there may not be enough variability in the fuel price data to estimate the magnitude of the rebound effect.[10]

Table 10.9 Estimates of the Rebound Effect Using U.S. Survey Data

Author (year)	Estimate of Rebound Effect	*Time Period*
Goldberg (1996)	0%	*CES 1984-90*
Greene, Kahn, and Gibson (1999a)	23%	*EIA RTECS* *1979-1994*
Pickrell & Schimek (1999)	4-34%	*NPTS 1995* *Single year*
Puller & Greening (1999)	49%	*CES 1980-90* *Single year, cross-sectional*
West (2004)	87%	*CES 1997* *Single year*
West and Pickrell (2011)	9-34%	*NHTS 2009* *Single year*

Source: Sorrell and Dimitropolous (2007). The agencies added a more recent study by West and Pickrell (2011).

It is important to note that some of these studies actually quantify the price elasticity of gasoline demand (e.g., Puller & Greening (1999)[11]) or the elasticity of VMT with respect to the price of gasoline (e.g., Pickrell & Schimek (1999)[12]), rather than the elasticity of VMT with respect to fuel efficiency or the fuel cost per mile of driving. These latter measures more closely match the definition of the fuel economy rebound effect. In fact, most studies cited above do not estimate the direct measure of the fuel economy rebound effect (i.e., the increase in VMT attributable to an increase in fuel efficiency).

Another important distinction among studies of the rebound effect is whether they assume that the effect is constant, or varies over time in response to the absolute levels of fuel costs, personal income, or household vehicle ownership. Most studies using aggregate annual data for the U.S. assume a constant rebound effect, although some of these studies test whether the effect can vary as changes in retail fuel prices or average fuel efficiency alter fuel cost per mile driven. Many studies using household survey data estimate significantly different rebound effects for households owning varying numbers of vehicles, with most finding that the rebound effect is larger among households that own more vehicles.[F]

In addition to the studies listed above, Bento et al. (2009)[13] combined demographic characteristics of more than 20,000 U.S. households, the manufacturer and model of each vehicle they owned, and their annual usage of each vehicle from the 2001 National Household Travel Survey with detailed data on fuel economy and other attributes for each vehicle model obtained from commercial publications. The authors aggregated vehicle models into 350 categories representing combinations of manufacturer, vehicle type, and age, and use the resulting data to estimate the parameters of a complex model of households' joint choices of the number and types of vehicles to own, and their annual use of each vehicle.

Bento et al. estimate the effect of vehicles' operating cost per mile, including fuel costs – which depend in part on each vehicle's fuel economy – as well as maintenance and insurance expenses, on households' annual use of each vehicle they own. Combining the authors' estimates of the elasticity of vehicle use with respect to per-mile operating costs with the reported fraction of total operating costs accounted for by fuel (slightly less than one-half) yields estimates of the rebound effect. The resulting values vary by household composition, vehicle size and type, and vehicle age, ranging from 21 to 38 percent, with a composite estimate of 34 percent for all households, vehicle models, and ages. The smallest values apply to new luxury cars, while the largest estimates are for light trucks and households with children, but the implied rebound effects differ little by vehicle age.

Wadud et al. (2009)[14] combine data on U.S. households' demographic characteristics and expenditures on gasoline over the period 1984-2003 from the Consumer Expenditure Survey with data on gasoline prices and an estimate of the average fuel economy of vehicles owned by individual households (constructed from a variety of sources). They employ these data to explore variation in the sensitivity of individual households' gasoline consumption to differences in income, gasoline prices, the number of vehicles owned by each household, and their average fuel economy. Using an estimation procedure intended to account for correlation among unmeasured characteristics of households and among estimation errors for successive years, the

[F] Six of the household survey studies evaluated in Table 10.6 found that the rebound effect varies in relation to the number of household vehicles. Of those six studies, four found that the rebound effect rises with higher vehicle ownership, and two found that it declines. The four studies with rebound estimates that increase with higher household vehicle ownership are: Greene, D., and Hu, P., "The Influence of the Price of Gasoline on Vehicle Use in Multi-vehicle Households," Transportation Research Record 988, pp. 19-24, ; Hensher, D., Milthorpe, F. and Smith, N., "The Demand for Vehicle Use in the Urban Household Sector: Theory and Empirical Evidence," Journal of Transport Economics and Policy, 24:2 (1990), pp. 119-137; Walls, M., Krupnick A., and Hood, H., "Estimating the Demand for Vehicle-Miles Traveled Using Household Survey Data: Results from the 1990 Nationwide Personal Transportation Survey," Discussion Paper ENR 93-25, Energy and Natural Resources Division, Resources for the Future, Washington, D.C., 1993; and West, R. and Pickrell, D., "Factors Affecting Vehicle Use in Multiple-Vehicle Households," 2009 National Household Travel Survey Workshop, June 2011.

authors explore variation in the response of fuel consumption to fuel economy and other variables among households in different income categories, and between those residing in urban and rural areas.

Dividing U. S. households into five equally-sized income categories, Wadud et al. estimate rebound effects ranging from 1-25 percent, with the smallest estimates (8 percent and 1 percent) for the two lowest income categories, and significantly larger estimates for the middle (18 percent) and two highest income groups (18 and 25 percent). In a separate analysis, the authors estimate rebound effects of seven percent for households of all income levels residing in U.S. urban areas, and 21 percent for rural households.

West and Pickrell (2011)[15] analyzed data on more than 100,000 households and 300,000 vehicles from the 2009 Nationwide Household Transportation Survey to explore how households owning multiple vehicles chose which of them to use and how much to drive each one on the day the household was surveyed. Their study focused on how the type and fuel economy of each vehicle a household owned, as well as its demographic characteristics and location, influenced household members' decisions about whether and how much to drive each vehicle. They also investigated whether fuel economy and fuel prices exerted similar influences on vehicle use, and whether households owning more than one vehicle tended to substitute use of one for another – or vary their use of all of them similarly – in response to fluctuations in fuel prices and differences in their vehicles' fuel economy.

Their estimates of the fuel economy rebound effect ranged from as low as nine percent to as high as 34 percent, with their lowest estimates typically applying to single-vehicle households and their highest values to households owning three or more vehicles. They generally found that differences in fuel prices faced by households who were surveyed on different dates or who lived in different regions of the U.S. explained more of the observed variation in daily vehicle use than did differences in vehicles' fuel economy. West and Pickrell also found that while the rebound effect for households' use of passenger cars appeared to be quite large – ranging from 17 percent to nearly twice that value – it was difficult to detect a consistent rebound effect for SUVs.

In addition, some recent studies (Small and Van Dender (2007), Hymel, Small, and Van Dender (2010), (2012)), using both state-level and national data, conclude that the rebound effect varies directly in response to changes in personal income, as well as fuel costs. These more recent studies published between 2007 and 2012 indicate that the rebound effect has decreased over time as incomes have risen and, until recently, fuel costs as a share of total monetary travel costs have generally decreased.[G] One theoretical argument for why the rebound effect should vary over time is that the responsiveness to the fuel cost of driving will be larger when it is a larger proportion of the total cost of driving. For example, as incomes rise, the responsiveness to the fuel cost per mile of driving will decrease if people view the time cost of driving – which is likely to be related to their income levels – as a larger component of the total cost.

Small and Van Dender (2007)[16] combined time series data for each of the 50 states and the District of Columbia to estimate the rebound effect, allowing the magnitude of the rebound to

[G] While real gasoline prices have varied over time, fuel costs (which reflect both fuel prices and fuel efficiency) as a share of total vehicle operating costs declined substantially from the mid-1970s until the mid-2000s when the share increased modestly (see Greene (2012)). With the recent decline in world petroleum prices, total vehicle operating costs have declined recently as well.

vary over time. For the time period from 1966–2001, their study found a long-run rebound effect of 22.2 percent, which is consistent with previously published studies. But for the five year period (1997–2001) estimated in their study, the long-run rebound effect decreased to 10.7 percent. Furthermore, when the authors updated their estimates with data through 2004, the long-run rebound effect for the most recent five year period (2000–2004) dropped to six percent.[17]

Hymel, Small and Van Dender (2010)[18] extended the Small and Van Dender model by adding congestion as an endogenous variable. Although controlling for congestion increased their estimates of the rebound effect, Hymel, Small and Van Dender also found that the rebound effect was declining over time. For the time period from 1966–2004, they estimated a long-run rebound effect of 24 percent, while for 2004 they estimated a long-run rebound effect of 13 percent.

Research conducted by David Greene (2012)[19] under contract with EPA further appears to support the theory that the magnitude of the rebound effect "is by now on the order of 10 percent."[H] Like Small and Van Dender, Greene finds that the VMT rebound effect could decline modestly over time as household income rises and travel costs increase. Over the entire time period analyzed (1966–2007), Greene found that fuel prices had a statistically significant impact on VMT, while fuel efficiency did not, which is similar to Small and Van Dender's prior finding. From this perspective, if the impact of fuel efficiency on VMT is not statistically significant, the VMT rebound effect could be zero. When Small and Van Dender tested whether the elasticity of vehicle travel with respect to the price of fuel was equal to the elasticity with respect to the rate of fuel consumption (gallons per mile), they found that the data could not reject this hypothesis. Therefore, Small and Van Dender estimated the rebound effect as the elasticity of travel with respect to fuel cost per mile.

In contrast, Greene's research rejected the hypothesis of equal elasticities for gasoline prices and fuel efficiency. In spite of this result, Greene also tested Small and Van Dender's formulation which allows the elasticity of fuel cost per mile to decrease with increasing per capita income. The results of estimation using national time series data confirmed the results obtained by Small and Van Dender using a time series of state level data. When using Greene's preferred functional form, the projected rebound effect is approximately 12 percent in 2008, and drops to 10 percent in 2020 and to nine percent in 2030.

Since there has been little variation in fuel economy in the data over time, isolating the impact of fuel economy on VMT can be difficult using econometric analysis of historical data. Therefore, studies that estimate the rebound effect using time-series data often examine the impact of gasoline prices on VMT, or the combined impact of both gasoline prices and fuel economy on VMT, as discussed above. However, these studies may overstate the potential impact of the rebound effect resulting from this rule, if people are more responsive to changes in fuel price than the variable directly of interest, fuel economy.

There is some evidence in the literature that consumers are more responsive to an increase in prices than to a decrease in prices. At the aggregate level, Dargay and Gately (1997) and

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[H] p. 15, Greene, D., Rebound 2007: Analysis of U.S. light-duty vehicle travel statistics. Energy Policy (2010), doi:10.1016/j.enpol.2010.03.083.

Sentenac-Chemin (2012)[20] have provide some evidence that demand for transportation fuel is asymmetric. In other words, given the same size change in prices, the response to a decrease in gasoline price is smaller than the response to an increase in gasoline price. Gately (1993)[21] has shown that the response to an increase in oil prices can be on the order of five times larger than the response to a price decrease. Furthermore, Dargay and Gately and Sentenac-Chemin also find evidence that consumers respond more to a large shock than a small, gradual change in fuel prices. Since these standards would decrease the cost of driving gradually over time, it is possible that the rebound effect would be much smaller than some of the historical estimates included in the literature. Greene also notes that the resultant data from such gradual changes could make discernment of such an effect difficult.

10.4.3 Review of Recent Literature on LDV Rebound since the 2012 Final Rule

A number of recent studies examining LDV rebound effects have been undertaken since EPA/NHTSA's review of the LDV rebound literature for 2012 final rule. Only a limited amount of work has been conducted to examine the rebound effect of electric vehicles so most of the studies of light-duty vehicle rebound effects focus on a change in gasoline prices. Below is a brief summary of the results of these recent studies.

Using data on household characteristics and vehicle use from the 2009 Nationwide Household Transportation Survey (NHTS), Su (2012)[22] analyzes the effects of locational and demographic factors on household vehicle use, and investigates how the magnitude of the rebound effect varies with vehicles' annual use. Using variation in the fuel economy and per-mile cost of and detailed controls for the demographic, economic, and locational characteristics of the households that owned them (e.g., road and population density) and each vehicle's main driver (as identified by survey respondents), the author employs specialized regression methods to capture the variation in the rebound effect across ten different categories of vehicle use.

Su estimated that the overall rebound effect for all vehicles in the sample averaged 13 percent, and that its magnitude varied from 11-19 percent among the ten different categories of annual vehicle use. The smallest rebound effects were estimated for vehicles at the two extremes of the distribution of annual use – those driven comparatively little, and those used most intensively — while the largest estimated effects applied to vehicles that were driven slightly more than average. Controlling for the possibility that high-mileage drivers respond to the increased importance of fuel costs by choosing vehicles that offer higher fuel economy narrowed the range of Su's estimated rebound effects slightly (to 11-17 percent), but did not alter the finding that they are smallest for lightly- and heavily-driven vehicles and largest for those with slightly above average use.

Linn (2013)[23] also uses the 2009 NHTS to develop a linear regression approach to estimate the relationship between the VMT of vehicles belonging to each household and a variety of different factors: fuel costs, vehicle characteristics other than fuel economy (e.g., horsepower, the overall "quality" of the vehicle), and household characteristics (e.g., age, income). Linn reports a fuel economy rebound effect with respect to VMT of between 20–40 percent.

One interesting result of the study is that when the fuel efficiency of all vehicles increases, which would be the long-run effect of rising fuel efficiency standards, two factors have opposing effects on the VMT of a particular vehicle. First, VMT increases when that vehicle's fuel efficiency increases. But the increase in the fuel efficiency of the household's other vehicles causes the vehicle's own VMT to decrease. Since the effect of a vehicle's own fuel efficiency is larger than the other vehicles' fuel efficiency, VMT increases if the fuel efficiency of all vehicles increases proportionately. Linn also finds that VMT responds much more strongly to vehicle fuel economy than to gasoline prices, which is at variance with the Hymel et al. and Greene results discussed above.

Like Su and Linn, Liu et al. (2014)[24] also employed the 2009 NHTS to develop an elaborate model of an individual household's choices about how many vehicles to own, what types and ages of vehicles to purchase, and how much combined driving to do using all of them. Their analysis used a complex mathematical formulation and statistical methods to represent and measure the interdependence among households' choices of the number, types, and ages of vehicles to purchase, as well as how intensively to use them.

Liu et al. employed their model to simulate variation in households' total vehicle use to changes in their income levels, neighborhood characteristics, and the per-mile fuel cost of driving averaged over all vehicles each household owns. The complexity of the relationships among the number of vehicles owned, their specific types and ages, fuel economy levels, and use incorporated in their model required them to measure these effects by introducing variation in income, neighborhood attributes, and fuel costs, and observing the response of households' annual driving. Their results imply a rebound effect of approximately 40 percent in response to significant (25-50 percent) variation in fuel costs, with almost exactly symmetrical responses to increases and declines.

Frondel and Vance (2013)[25] use panel estimation methods and household diary travel data collected in Germany between 1997 and 2009 to identify an estimate of a private transport rebound value. The study focuses on single-car households that did not change their car ownership over the maximum three years each household was surveyed. Failing to reject the null hypothesis of a symmetric price response, they find a rebound effect for single-vehicle households of 46–70 percent (though we discuss further below the limitations in applying findings of studies from other countries to U.S. rebound).

Gillingham (2014)[26] analyzed variation in the use of more than five million new vehicles purchased in California during the years 2001-03 over the first several years of their lifetimes, focusing particularly on the response of buyers' use of new vehicles to geographic and temporal variation in fuel prices. His sample consists predominantly of personal vehicles (87 percent), but also includes some purchased by businesses, rental car companies, and government. He estimates the effect of differences in the average of monthly fuel prices on their monthly average vehicle use over the time – at a county level, since being purchase – focusing his analysis on vehicles that have been purchased new and have been in service for six to seven years. The author also explores how the effect of fuel prices on vehicle use varies with vehicle use, buyer type and household income.

Gillingham relies exclusively on the effect of variation in fuel prices and does not involve vehicles' fuel economy. He reports an overall average effect of fuel prices on vehicle use that corresponds to a rebound effect of 22 percent, rising to 23 percent when he controls for the potential effect of gasoline demand on its retail price. He finds little evidence of variation in the rebound effect among buyer types. Based on the nature of his data and estimation procedure, he interprets his estimates as implying that vehicle use responds fully to changes in fuel prices after approximately two years.

Gillingham's results suggest that the vehicle-level responsiveness to fuel price increases with income. Gillingham hypothesizes that the increase in the per-vehicle rebound effect with higher incomes may relate to wealthier households having more discretionary driving or switching between flying and driving. Alternatively, wealthier households tend to own more vehicles and it is possible that within-household switching of vehicles to other more efficient vehicles in the household may account for the greater responsiveness at higher income levels.

Hymel and Small (2015)[27] revisit the simultaneous equations methodology of Small and Van Dender (2007) and Hymel, Small and Van Dender (2010) to see whether their previous estimates of the VMT rebound effect have changed by adding in more recent data from the late 2000 time period (e.g., 2005–2009). Consistent with previous results, the VMT rebound effect declines with increasing income and urbanization, and it increases with increasing fuel cost. By far the most important of these sources of variation is income, whose effect is large enough to greatly reduce the projected rebound effect for time periods of interest to current policy decisions. The best estimate of the long-run light-duty vehicle rebound effect over the years 2000–2009 is 17.8 percent, when evaluated at average values of income, fuel cost, and urbanization in the U.S. during that time period.

The recent study by Hymel and Small also finds a strengthening of the VMT rebound effect for the years 2003–2009 compared to the results for time periods from their previous research, suggesting that some additional unaccounted for factors have increased the rebound effect. Three potential factors are hypothesized to have caused the upward shift in the VMT rebound effect in the 2003–2009 time period: (1) media coverage, (2) price volatility, and (3) asymmetric response to price changes.[I] It should be noted that the while media coverage and volatility are important to understand the rebound effect based upon fuel prices, they may not be as relevant to the rebound effect due to fuel efficiency. These results show strong evidence of asymmetry in responsiveness to price increases and decreases. Results suggest that a rebound adjustment to fuel price rises takes place quickly; the rebound response elasticity is large in the year of, and the first year following, a price rise, then diminishes to a smaller value. The rebound response to price decreases occurs more slowly.

Hymel and Small find that there is an upward shift in the rebound effect of roughly 2.5 to 2.8 percentage points starting in 2003. Results suggest that the media coverage and volatility variables may explain about half of the upward shift in the LDV rebound effect in the 2003–2009 time period. Nevertheless, these influences are small enough in magnitude that they do not fully offset the downward trend in VMT response elasticities due to higher incomes and other factors. Hence, even assuming that the variables retain their 2003–2009 values into the indefinite future, they would not prevent a further diminishing of the magnitude of the rebound effect if incomes continue to grow at anything like historic rates.

West et al. (2015)[28] attempt to estimate the VMT rebound effect using household level data from Texas using a discontinuity in the eligibility requirements for the 2009 U.S. "Cash for

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[I] The media coverage variable is measured by constructing measures of media coverage based upon gas-price related articles appearing in the New York Times newspaper. Using the ProQuest historical database, they tally the annual number of article titles containing the words gasoline (or gas) and price (or cost). They then form a variable equal to the annual fraction of all New York Times articles that are gas-price-related. This fraction ranged from roughly 1/4000 during the 1960s to a high of 1/500 in 1974.

Clunkers" program, which incentivized eligible households to purchase more fuel-efficient vehicles. Households that owned "clunkers" with a fuel economy of 18 miles per gallon (MPG) or less were eligible for the subsidy, while households owning clunkers with an MPG of 19 or more were ineligible. The empirical strategy of the paper is to compare the fuel economy of vehicle purchases and subsequent vehicle miles traveled of "barely eligible" households to those households who were "barely ineligible."

The paper finds a meaningful discontinuity in the fuel economy of new vehicles purchased by Cash for Clunker-eligible households relative to ineligible households. Those authors report that the increases in fuel economy realized by households who scrapped low fuel economy vehicles in response to the substantial financial incentives offered under the federal "Cash for Clunkers" program were not accompanied by increased use of the higher-MPG replacement vehicles they purchased because of the vehicle's other attributes. Households chose to buy cheaper, smaller and lower-performing vehicles. As a result, they did not drive any additional miles after the purchase of the fuel efficient vehicle. They conclude there is no evidence of a rebound effect in response to improved fuel economy from the Cash for Clunkers program.

It may be difficult to generalize the VMT response from the Cash for Clunkers program to a program for LDV GHG/fuel economy standards. Throughout this and all previous analyses of the likely effects of federal regulations to require increased fuel economy and reduce vehicles' GHG emissions, EPA and NHTSA have stressed that manufacturers can achieve the required improvements without compromising the performance, passenger-, cargo-carrying, and towing capacity, safety, or other attributes affecting the utility buyers and owners derive from the vehicles they choose to purchase. The Cash for Clunkers program was a one-time program for a fixed fleet of existing vehicles with specific characteristics. Their study may not provide useful implications about the likely response of vehicle use to required increases in fuel economy that are achieved through temporary incentive programs offered during recessions.

More recently, De Borger et al. (2016)[29] analyze the response of vehicle use to changes in fuel economy among a sample of nearly 350,000 Danish households owning a single vehicle, of which almost one-third replaced it with a different model sometime during the period from 2001 to 2011. By comparing the change in households' driving from the early years of this period to its later years among those who replaced their vehicles during the intervening period to that among households who kept their original vehicles, the authors claim to isolate the effect of changes in fuel economy on vehicle use from those of other factors. Their data allow them to control for the effects of important household characteristics and vehicle features other than fuel economy on vehicle use. They use complex statistical methods to account for the fact that some households replacing their vehicles may have done so in anticipation of changes in their driving demands (rather than the reverse), as well as for the possibility that some households who replaced their cars may have done so because their driving behavior was more sensitive to fuel prices than other households.

De Borger et al. measure the rebound effect from the change in households' vehicle use in response to changes in fuel economy that are a consequence of their decisions to replace the vehicles they owned previously. Thus they are able to directly estimate the fuel economy rebound effect itself, in contrast to other research that relies on indirect measures. Their preferred estimates span a very narrow range – from 8 - 10 percent – and vary only minimally in response to different statistical estimation procedures. They also vary little depending on whether the data sample is restricted to households that replaced their vehicles, in which case the rebound effect is identified exclusively by their responses to changes in fuel economy of varying magnitudes, or also includes households that did not replace their vehicles, and is thus identified partly by differences between their responses to varying fuel economy and changes in driving among households with vehicles whose fuel economy remained unchanged. Finally, De Borger et al. find no evidence that the rebound effect is smaller among lower-income households than among their higher-income counterparts.

Gillingham et al. (2016)[30] undertake a summary and review of the general rebound literature including, for example, rebound effects from LDVs as well as electricity used in stationary applications. The literature suggests that differences in estimates of the rebound effect stem from its varying definitions, as well as variation in the quality of data and empirical methodologies used to estimate it. Gillingham et al. seek to clarify the definition of each of the channels of the rebound effect and critically assess the state of the literature that estimates its magnitude.

Gillingham et al. provide a list of what they consider to be relevant rebound elasticities that can provide guidance to policymakers, with a focus on studies of overall demand or household-level demand. According to the authors, the studies are selected both because they are more recent and use rigorous empirical methods such as panel data methods, experimental designs, and quasi-experimental approaches.

Of the selected studies, four focus on VMT elasticities for light-duty vehicles in developed countries. For the Frondel and Vance study (cited above), which reported a short-run elasticity of VMT demand for Germany for the time period from 1997–2009, Gillingham et al. chose the 46 percent value.[J] Barla (2009)[31] found a short-run elasticity of VMT for Canada from 1990–2004 of eight percent. Gillingham (2014) (cited above) found a California medium-run new vehicle elasticity of VMT demand for the time period 2001–2009 of 23 percent. Small and Van Dender (2007) (cited previously) found a U.S. short-run elasticity of VMT demand for the time period from 1966–2001 of roughly five percent.

It is not clear whether studies of LDV VMT rebound estimates for countries different from the U.S. would provide estimates that are appropriate to the U.S. context. For example, European countries have higher fuel prices and more transit options, both factors which would possibly produce a VMT rebound effect that is higher than in the U.S. The agencies are planning to undertake an updated literature review of recent studies on the rebound effect for LDVs.

10.4.4 Basis for Rebound Effect Used in the Draft TAR

As the preceding discussion indicates, there is a wide range of estimates for both the historical magnitude of the rebound effect and its projected future value, and there is some evidence that the magnitude of the rebound effect appears to be declining over time for those studies that look at VMT time trends. The recent literature is mixed, with some studies supporting relatively modest direct VMT rebound estimates and other studies suggesting a higher rebound effect. Some of these studies come to these varied conclusions despite using the same dataset. EPA and NHTSA use a single point estimate for the direct VMT rebound effect as an input to the

[J] Gillingham et al. believe that this value is derived by more successfully holding exogenous factors constant in the Frondel and Vance study.

agencies' analyses, although a range of estimates can be used to test the sensitivity to uncertainty about its exact magnitude. Based on a combination of historical estimates of the rebound effect and more recent analyses, an estimate of 10 percent for the rebound effect is used for evaluating the MY2022–2025 standards in this Draft TAR (i.e., we assume a 10 percent decrease in fuel cost per mile from the standards would result in a 1 percent increase in VMT).

As Table 10.7, Table 10.8, and Table 10.9 indicate, the 10 percent figure is on the low end of the range reported in previous research. Recent research by Small, Hymel and Van Dender, and Greene reports evidence that the magnitude of the rebound effect is likely to be declining over time as household incomes rise which would be consistent with Gillingham's (2014) results showing that individual-vehicle rebound increases with household income. The values that are more applicable to quantifying the impact of these standards are values based on overall aggregate rebound effects. West and Pickrell, Su, Linn and Liu et al., each using NHTS 2009 data, find rebound effect estimates varying from 11 percent to 40 percent.

Gillingham et al. (2016) cite four studies that focus on VMT elasticities for light-duty vehicles in developed countries. Two of the four studies (for the U.S. and Canada) have VMT elasticity values below the 10 percent figure. The study for California has per-vehicle rebound value of 23 percent, and does not reflect the reduced use of other vehicles in multi-vehicle household fleets. A study for Germany has a considerably higher value, roughly 46 percent. A recent study by De Borger at al. found a rebound value in the range of 10 percent for Denmark. As noted previously, it is not clear whether studies of VMT LDV rebound estimates for countries different from the U.S. would provide estimates that are appropriate to the U.S. context.

Most of the studies reviewed use changes in fuel prices or fuel cost/mile to derive estimates of the VMT rebound effect instead of using the actual variable of interest, changes in fuel economy, and its impact on VMT. It is not clear how reliable the use of changes in fuel prices/fuel costs are in attempting to estimate the impacts of changes in fuel economy on VMT.

As mentioned above, for the reasons described in Section 10.4.2, historical estimates of the rebound effect may overstate the effect of a gradual decrease in the cost of driving due to the standards. As a consequence, a value on the low end of the historical estimates is likely to provide a more reliable estimate of its magnitude during the period spanned by the analysis of the impacts of the MYs 2022–2025 standards. Studies which produce an aggregate measure of the rebound effect are most applicable to estimating the overall VMT effects of the LDV standards. The 10 percent estimate lies at the bottom of the 10–30 percent range of estimates for the historical, aggregate rebound effect in most research, and at the upper end of the 5–10 percent range of estimates for the future rebound effect reported in the relatively recent studies by Small, Hymel and Van Dender and Greene. Both Greene and Small, Hymel and Van Dender find that the rebound effect decreases as household incomes rise. As incomes rise, the value of time spent driving becomes a larger fraction of total travel costs so that vehicle use becomes less responsive to variations in fuel costs. Since the AEO 2015 projects that household incomes will be rising throughout the analysis period, the agencies believe that it is appropriate to factor in studies that account for income on the rebound effect. In summary, the 10 percent value was not derived from a single point estimate from a particular study, but instead represents a reasonable compromise between historical estimates of the rebound effect and forecasts of its projected future value, based on an updated review of the literature on this topic.

10.5 Energy Security Impacts

The National Program is designed to require improvements in the fuel economy of light-duty vehicles and, thereby, reduce fuel consumption and GHG emissions. In turn, the program helps to reduce U.S. petroleum imports. A reduction of U.S. petroleum consumption and imports reduces both financial and strategic risks caused by potential sudden disruptions in global oil supply, thus increasing U.S. energy security. This section summarizes EPA's estimates of U.S. oil import reductions and energy security benefits of the GHG/fuel economy vehicle standards for model years 2022–2025.

10.5.1 Implications of Reduced Petroleum Use on U.S. Imports

U.S. energy security is generally considered as the continued availability of energy sources at an acceptable, stable price. Most discussion of U.S. energy security revolves around the topic of the economic costs of U.S. dependence on oil imports. While the U.S. has reduced its consumption and increased its production of oil in recent years, it still relies on oil from potentially unstable sources outside of the U.S. and the U.S. oil price will remain tightly linked to the global oil market. In addition, oil exporters with a large share of global production have the ability to raise the price of oil by exerting the monopoly power associated with a cartel, the Organization of Petroleum Exporting Countries (OPEC), to restrict oil supply relative to demand. These factors contribute to the vulnerability of the U.S. economy to episodic oil shocks to either the global supply of oil or world oil price spikes.

In 2014, U.S. expenditures for imports of crude oil and petroleum products, net of revenues for exports, were $178 billion and expenditures on both imported oil and domestic petroleum and refined products totaled $469 billion (2013$) (see Figure 10.2).[32] Recently, as a result of strong growth in domestic oil production mainly from tight shale formations, U.S. production of oil has increased while U.S. oil imports have decreased. For example, from 2012 to 2015, domestic oil production increased by 44 percent while oil imports decreased by 24 percent.[33] While oil import costs have declined since 2011, total oil expenditures (domestic and imported) remained near historical highs through 2014. Post-2015 oil expenditures are projected (AEO 2015) to remain between double and triple the inflation-adjusted levels experienced by the U.S. from 1986 to 2002.

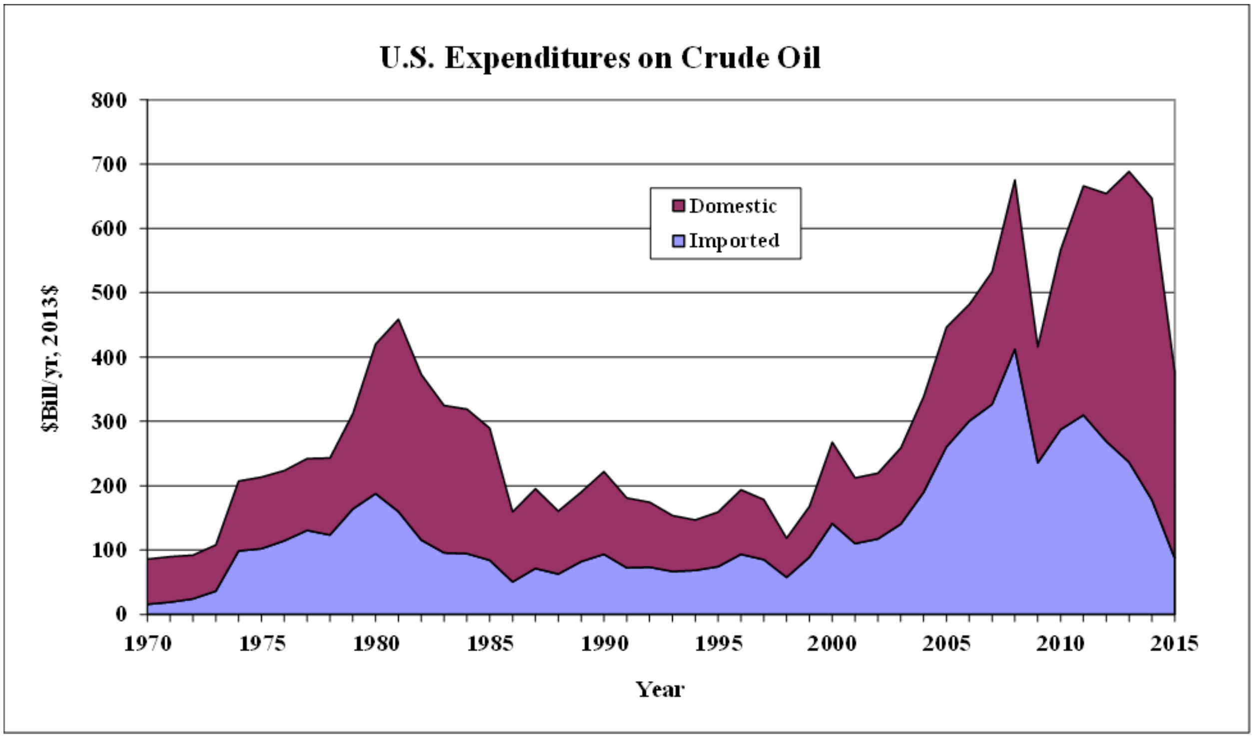

Figure 10.2 U.S. Expenditures on Crude Oil from 1970 through 2015[34]

Focusing on changes in oil import levels as a source of vulnerability has been standard practice in assessing energy security in the past, but given current market trends both from domestic and international levels, adding changes in consumption of petroleum to this assessment may provide better information about U.S. energy security. The major mechanism through which the economy sustains harm due to fluctuations in the (world) energy market is through price, which itself is leveraged through both imports and consumption. However, the United States, may be increasingly insulated from the physical effects of overseas oil disruptions, though the price impacts of an oil disruption anywhere will continue to be transmitted to U.S. markets. As of 2015, Canada accounted for 63 percent of U.S. net oil imports of crude oil and petroleum products.[35] The implications of the U.S. becoming a significant petroleum producer have yet to be discerned in the literature, but it can be anticipated that this will have some impact on energy security.

In 2010, just over 40 percent of world oil supply came from OPEC nations. The AEO 2015[36] projects that this share will stay high; dipping slightly from 37 percent by 2020 and then rising gradually to over 40 percent by 2035 and thereafter. Approximately 30 percent of global supply is from Middle East and North African countries alone, a share that is also expected to grow over the long term. Measured in terms of the share of world oil resources or the share of global oil export supply, rather than oil production, the concentration of global petroleum resources in OPEC nations is even larger. As another measure of concentration, of the 137 countries/principalities that export either crude or refined products, the top 12 have recently accounted for over 55 percent of exports.[37] Eight of these countries are members of OPEC, and a ninth is Russia.[K] In a market where even a 1–2 percent supply loss can raise prices noticeably, and where a 10 percent supply loss could lead to an unprecedented price shock, this regional concentration is of concern.[L] Historically, the countries of the Middle East have been the source of eight of the ten major world oil disruptions[38], with the ninth originating in Venezuela, an OPEC country, and the tenth being Hurricanes Katrina and Rita.

EPA uses a processed combination of the MOVES and OMEGA models, and DOT uses the CAFE model, to estimate the reductions in U.S. fuel consumption due to the LDV National Program. Based on a detailed analysis of differences in U.S. fuel consumption, petroleum imports, and imports of petroleum products, the agencies estimate that approximately 90 percent of the reduction in fuel consumption resulting from adopting improved GHG emission and fuel economy standards is likely to be reflected in reduced U.S. imports of crude oil and net imported petroleum products.[39] Thus, on balance, each gallon of fuel saved as a consequence of the LDV GHG/fuel economy standards is anticipated to reduce total U.S. imports of petroleum by 0.9 gallons. Based upon the fuel savings estimated by the models and the 90 percent oil import factor, the reduction in U.S. oil imports from the 2022–2025 LDV standards are estimated for selected years from 2022 to 2050 (in millions of barrels per day (MMBD) in Table 10.10 below. For comparison purposes, Table 10.10 also shows U.S. oil exports/imports, U.S. net product imports and U.S. net crude/product imports in selected years from 2022 to 2040, as projected by DOE in the Annual Energy Outlook 2015 Reference Case. U.S. Gross Domestic Product (GDP) is projected to grow by roughly 55 percent over the same time frame (e.g., from 2022 to 2040) in the AEO 2015 projections.

[K] The other three are Norway, Canada, and the EU, an exporter of product.

[L] For example, the 2005 Hurricanes Katrina/Rita and the 2011 Libyan conflict both led to a 1.8 percent reduction in global crude supply. While the price impact of the latter is not easily distinguished given the rapidly rising post-recession prices, the former event was associated with a 10-15 percent world oil price increase. There are a range of smaller events with smaller but noticeable impacts. Somewhat larger events, such as the 2002/3 Venezuelan Strike and the War in Iraq, corresponded to about a 2.9 percent sustained loss of supply, and was associated with a 28 percent world oil price increase. Compiled from EIA oil price data, IEA2012 [IEA Response System for Oil Supply Emergencies (http://www.iea.org/publications/freepublications/publication/EPPD_Brochure_English_2012_02.pdf) [EPA-HQ-OAR-2014-0827-0573] See table on P. 11.and Hamilton 2011 "Historical Oil Shocks," (http://econweb.ucsd.edu/~jhamilto/oil_history.pdfin [EPA-HQ-OAR-2014-0827-0598] Routledge Handbook of Major Events in Economic History*, pp. 239-265, edited by Randall E. Parker and Robert Whaples, New York: Routledge Taylor and Francis Group, 2013).

Table 10.10 Projected Trends in U.S. Oil Exports/Imports, and U.S. Oil Import Reductions Resulting from the Program in Selected Years from 2022 to 2050 (Millions of barrels per day (MMBD)

Year	U.S. Oil Exports	U.S. Oil Imports	U.S. Net Product Imports*	U.S. Net Crude & Product Imports	U.S. Reductions from Oil Imports
2022	0.63	6.47	-3.08	2.76	0.019
2023	0.63	6.61	-3.15	2.83	0.055
2024	0.63	6.63	-3.20	2.85	0.106
2025	0.63	6.72	-3.24	2.85	0.169
2030	0.63	7.07	-3.56	2.88	0.420
2035	0.63	7.98	-3.94	3.41	0.685
2040	0.63	8.21	-4.26	3.32	0.880
2050	**	**	**	**	1.119

Notes:
* Negative U.S. Net Product Imports imply positive exports.
**The AEO 2015 only projects energy market and economic trends through 2040.

10.5.2 Energy Security Implications

In order to understand the energy security implications of reducing U.S. oil imports, EPA has worked with Oak Ridge National Laboratory (ORNL), which has developed approaches for evaluating the social costs and energy security implications of oil use. The energy security estimates provided below are based upon a methodology developed in a peer-reviewed study entitled, "*The Energy Security Benefits of Reduced Oil Use, 2006-2015*", completed in March 2008. This ORNL study is an updated version of the approach used for estimating the energy security benefits of U.S. oil import reductions developed in a 1997 ORNL Report.[40] This approach has been used to estimate energy security benefits for the LDV GHG/fuel economy standards (2012–2016; 2017–2025) and the HDV GHG/fuel economy standards Phase I (2014–2018)/Phase II proposal (2018 and later). For EPA and NHTSA rulemakings, the ORNL methodology is updated periodically to account for forecasts of future energy market and economic trends reported in the U.S. EIA's AEO.

When conducting this analysis, ORNL considered the full cost of importing petroleum into the U.S. The full economic cost is defined to include two components in addition to the purchase price of petroleum itself. These are: (1) the higher costs for oil imports resulting from the effect of U.S. demand on the world oil price (i.e., the "demand" or "monopsony" costs); and (2) the risk of reductions in U.S. economic output and disruption to the U.S. economy caused by sudden disruptions in the supply of imported oil to the U.S. (i.e., macroeconomic disruption/adjustment costs).

For this Draft TAR, ORNL updated the energy security premiums by incorporating the most recent oil price forecast and energy market trends, particularly regional oil supplies and demands, from the AEO 2015 into its model.[41] Below are ORNL energy security premium estimates for the selected years from 2022 to 2050,[M] as well as a breakdown of the components

[M] AEO 2015 forecasts energy market trends and values only to 2040. The post-2040 energy security premium values are assumed to be equal to the 2040 estimate.

of the energy security premiums for each year. The components of the energy security premiums and their values are discussed below.

Table 10.11 Energy Security Premiums in Selected Years from 2022 to 2050, (2013$/Barrel)*

Year (range)	Monopsony (Range)	Avoided Macroeconomic Disruption/Adjustment Costs (Range)	Total Mid-Point (Range)
2022	$2.31 ($0.69 - $3.81)	$5.69 ($2.67 - $9.44)	$7.99 ($4.81 - $11.81)
2023	$2.33 ($0.71 - $3.92)	$5.75 ($2.75 - $9.70)	$8.09 ($4.94 - $12.15)
2024	$2.40 ($0.73 - $4.03)	$5.89 ($2.83 - $9.96)	$8.29 ($5.08 - 12.49)
2025	$2.59 ($0.76 - $4.14)	$6.30 ($2.92 - $10.22)	$8.89 ($5.22 - $12.83)
2030	$2.83 ($0.83 - $4.56)	$7.26 ($3.40 - $11.73)	$10.09 ($5.90 - $14.59)
2035	$3.78 ($1.10 - $6.17)	$8.47 ($3.99 - $13.58)	$12.26 ($7.28 - $17.59)
2040	$4.09 ($1.19 - $6.67)	$9.61 ($4.54 - $15.39)	$13.69 ($8.12 - $19.64)
2050	$4.09 ($1.19 - $6.67)	$9.61 ($4.54 - $15.39)	$13.69 ($8.12 - $19.64)

Note:
* The top values in each cell are the midpoints; the values in parentheses are the 90 percent confidence intervals.

10.5.2.1 Effect of Oil Use on the Long-Run Oil Price

The first component of the full economic costs of importing petroleum into the U.S. follows from the effect of U.S. import demand on the world oil price over the long-run. Because the U.S. is a sufficiently large purchaser of global oil supplies, its purchases can affect the world oil price. This monopsony power means that increases in U.S. petroleum demand can cause the world price of crude oil to rise, and conversely, that reduced U.S. petroleum demand can reduce the world price of crude oil. Thus, one benefit of decreasing U.S. oil purchases due to improvements in the fuel economy of light-duty vehicles is the potential decrease in the crude oil price paid for all crude oil purchased.

A variety of oil market and economic factors have contributed to lowering the estimated monopsony premium compared to monopsony premiums cited in the agencies' previous 2017–2025 LDV GHG/fuel economy rulemakings. Three principal factors contribute to lowering the monopsony premium: lower world oil prices, lower U.S. oil imports, and less responsiveness of world oil prices to changes in U.S. oil demand. Below we consider differences in oil market trends by comparing projections developed using the AEO 2012 (Early Release) and the AEO 2015. The AEO 2012 (Early Release) was used for the 2012 final LDV rule and the AEO 2015 is being used for this Draft TAR assessment, so the comparison gives a snapshot of how oil and energy markets have changed since the 2012 final rule.

The result of the comparison is that there has been a general downward revision in world oil price projections in the near term (e.g., a 35 percent reduction in 2020) and a sharp reduction in projected U.S. oil imports in the near term due to increased U.S. supply (i.e., a 60 percent reduction in U.S. oil imports by 2020 and a 58 percent reduction in 2025). Over the longer term, based upon the AEO 2015 projections, oil's share of total U.S. imports is projected to gradually increase after 2020 but still remain 50 percent below the AEO 2012 (Early Release) projected level in 2035.

Currently some OPEC countries (e.g., Saudi Arabia) are increasing oil supply in an attempt to price more expensive marginal suppliers, like the U.S., out of the market and regain market share, exacerbating the worldwide oil supply glut which has resulted in lowering the world oil price further. Lower world oil prices currently may reduce both production from existing domestic oil resources and investment in new domestic oil sources increasing U.S. oil import levels in the intermediate term.

Another factor influencing the monopsony premium is that U.S. demand on the global oil market is projected to decline, suggesting diminished overall influence and some reduction in the influence of U.S. oil demand on the world price of oil. This is a result of the U.S. being a smaller fraction of total world oil demand. Outside of the U.S., projected OPEC supply in the AEO 2015 remains roughly steady as a share of world oil supply compared to the AEO 2012 (Early Release). OPEC's share of world oil supply outside of the U.S. actually increases slightly. Since OPEC supply is estimated to be more price sensitive than non-OPEC supply, this means that AEO 2015 projected world oil supply is slightly more responsive to changes in U.S. oil demand. Together, these factors suggest that changes in U.S. oil import reductions have a somewhat smaller effect on the long-run world oil price than changes based on AEO 2012 (Early Release) estimates.

These changes in oil price and import levels lower the monopsony portion of energy security premium since this portion of the security premium is related to the change in total U.S. oil import costs that is achieved by a marginal reduction in U.S oil imports. Since both the price and the quantity of oil imports are lower, the monopsony premium component estimated in this assessment is 60–75 percent lower over the years 2025–2040 than the estimates based upon the AEO 2012 (Early Release) projections.

The literature on the energy security for the last two decades has routinely combined the monopsony and the macroeconomic disruption components when calculating the total value of the energy security premium. However, in the context of using a global value for the Social Cost of Carbon (SCC) the question arises: how should the energy security premium be used when some benefits from the rule, such as the benefits of reducing greenhouse gas emissions, are calculated from a global perspective? Monopsony benefits represent avoided payments by U.S. consumers to oil producers that result from a decrease in the world oil price as the U.S. decreases its demand for oil. Although there is clearly an overall benefit to the U.S. when considered from a domestic perspective, the decrease in price due to decreased demand in the U.S. also represents a loss to oil producing countries, one of which is the U.S.

Given the redistributive nature of this monopsony effect from a global perspective, it has been excluded in the energy security benefits calculations in past rulemakings. In contrast, the other portion of the energy security premium, the avoided U.S. macroeconomic disruption and adjustment cost that arises from reductions in U.S. petroleum imports, does not have offsetting impacts outside of the U.S., and, thus, is included in the energy security benefits. To summarize, the agencies have included only the avoided macroeconomic disruption portion of the energy security benefits to estimate the monetary value of the total energy security benefits.

There is disagreement in the literature about the magnitude of the monopsony component, and its relevance for policy analysis. Brown and Huntington (2013)[42], for example, argue that the U.S.'s refusal to exercise its market power to reduce the world oil price does not represent a proper externality, and that the monopsony component should not be considered in calculations of the energy security externality. However, they also note in their earlier discussion paper (Brown and Huntington 2010)[43] that this is a departure from the traditional energy security literature, which includes sustained wealth transfers associated with stable but higher-price oil markets.

On the other hand, Greene (2010)[44] and others in prior literature (e.g., Toman 1993)[45] have emphasized that the monopsony cost component is policy-relevant because the world oil market is non-competitive and strongly influenced by cartelized and government-controlled supply decisions. Thus, while sometimes couched as an externality, Greene notes that the monopsony component is best viewed as stemming from a completely different market failure than an externality (Ledyard 2008)[46], yet still implying marginal social costs to importers.

The Council on Foreign Relations[47] (i.e., "the Council") (2015) recently released a discussion paper that assesses NHTSA's analysis of the benefits and costs of CAFE in a lower-oil-price world. In this paper, the Council notes that while NHTSA cites the monopsony effect of the CAFE standards for 2017–2025, NHTSA does not include it when calculating the cost-benefit calculation for the rule. The Council argues that the monopsony benefit should be included in the CAFE cost-benefit analysis and that including the monopsony benefit is more consistent with the legislators' intent in mandating CAFE standards in the first place.

The recent National Academy of Science (NAS 2015) Report, "Cost, Effectiveness and the Deployment of Fuel Economy Technologies for Light-Duty Vehicles,"[48] suggests that the agencies' logic about not accounting for monopsony benefits is inaccurate. According to the NAS, the fallacy lies in treating the two problems, oil dependence and climate change, similarly. According to the NAS, "Like national defense, it [oil dependence] is inherently adversarial (i.e., oil consumers against producers using monopoly power to raise prices). The problem of climate change is inherently global and requires global action. If each nation considered only the benefits to itself in determining what actions to take to mitigate climate change, an adequate solution could not be achieved. Likewise, if the U.S. considers the economic harm its reduced petroleum use will do to monopolistic oil producers it will not adequately address its oil dependence problem. Thus, if the United States is to solve both of these problems it must take full account of the costs and benefits of each, using the appropriate scope for each problem." Based upon the assessment of the monopsony premium in the Council of Foreign Relations and NAS reports, we are seeking public input on whether it is appropriate to consider monopsony in the societal costs/benefits of the National Program.

There is also a question about the ability of gradual, long-term reductions, such as those resulting from the LDV GHG/fuel economy standards, to reduce the world oil price in the presence of OPEC's monopoly power. OPEC is currently the world's marginal petroleum supplier, and could conceivably respond to gradual reductions in U.S. demand with gradual reductions in supply over the course of several years as the fuel savings resulting from this Program grow. However, if OPEC opts for a long-term strategy to preserve its market share, rather than maintain a particular price level (as they have done recently in response to increasing U.S. petroleum production) reduced demand would create downward pressure on the global price. The Oak Ridge analysis assumes that OPEC does respond to demand reductions by reducing its supply over the long run, but there is still a price effect in the model because the supply reduction only partially offsets the demand reduction, enough to maintain supply share. Under the mid-case behavioral assumption used in the premium calculations, OPEC responds by gradually reducing supply to maintain *market share* (consistent with the long-term self-interested strategy suggested by Gately (2004, 2007)).[49]

It is important to note that the decrease in global petroleum prices resulting from this Program could spur increased consumption of petroleum in other sectors and countries, leading to a modest uptick in GHG emissions outside of the U.S. This increase in global fuel consumption could offset some portion of the GHG reduction benefits associated with these standards. The agencies have not quantified this increase in global oil consumption or GHG emissions outside the U.S. due to world oil price changes resulting from the standards. Recent research has quantified this type of effect in the context of biofuel policies (e.g., Drabik and de Gorter (2011)[50]; Rajagopal, Hochman and Zilberman (2011)[51]; Thompson, Whistance, and Meyer (2011))[52], pipeline construction (Erickson and Lazarus (2014))[53], and fuel economy policies (Karplus et al., (2015)[54]).

Quantifying resulting GHG emissions may be challenging because other fuels, with varying GHG intensities, could be displaced from the increasing use of oil worldwide, particularly outside of the transportation sector. For example, if a decline in the world oil price causes an increase in oil use in China, India, or another country's industrial sector, this increase in oil consumption may displace natural gas usage. Alternatively, the increased oil use could result in a decrease in coal used to produce electricity. We seek comment on whether it is appropriate to quantify changes in net global oil consumption and to consider the resulting GHG emissions in the societal costs/benefits of the Program. In particular, we are taking comments on any robust methodologies that could be used to look at these impacts, a discussion on the strengths and weaknesses of these methodologies, estimates of own and cross-price elasticities of demand for fossil fuels and their relative importance, and the appropriate level of regional and sectoral resolution for such an analysis.

10.5.2.2 Macroeconomic Disruption Adjustment Costs

The second component of the oil import premium, "avoided macroeconomic disruption/adjustment costs," arises from the effect of oil imports on the expected cost of supply disruptions and accompanying price increases. A sudden increase in oil prices triggered by a disruption in world oil supplies has two main effects: (1) it increases the costs of oil imports in the short-run and (2) it can lead to macroeconomic contraction, dislocation and Gross Domestic Product (GDP) losses. For example, ORNL estimates the combined value of these two factors to be $6.30/barrel when U.S. oil imports are reduced in 2025, with a range from $2.92/barrel to $10.22/barrel of imported oil reduced.

Since future disruptions in foreign oil supplies are an uncertain prospect, each of the disruption cost components must be weighted by the probability that the supply of petroleum to the U.S. will actually be disrupted. Thus, the "expected value" of these costs – the product of the probability that a supply disruption will occur and the sum of costs from reduced economic output and the economy's abrupt adjustment to sharply higher petroleum prices – is the relevant measure of their magnitude. Further, when assessing the energy security value of a policy to reduce oil use, it is only the change in the expected costs of disruption that results from the policy that is relevant. The expected costs of disruption may change from lowering the normal (i.e., pre-disruption) level of domestic petroleum use and imports, from any induced alteration in the likelihood or size of disruption, or from altering the short-run flexibility (e.g., elasticity) of petroleum use.

With updated oil market and economic factors, the avoided macroeconomic disruption component of the energy security premiums is somewhat lower compared to the avoided macroeconomic disruption premiums used in the 2017–2025 LDV GHG/fuel economy rule. Factors that contribute to moderately lowering the avoided macroeconomic disruption component are lower U.S. imports (slightly reducing the U.S.' global reliance on unstable supplies), lower real oil prices and slightly smaller price increases during prospective shocks. Oil price levels are 0–29 percent lower over the 2025–2040 period, and the likely increase in oil prices in the event of an oil shock are somewhat smaller, reflecting small increases in the responsiveness of global oil supply to changes in the world price of oil. However, over the 2025–2040 period AEO 2015 projected domestic oil demand, and real GDP levels, are little changed from AEO 2012 (Early Release). So oil remains an important input to the U.S. economy. Overall, the avoided macroeconomic disruption component estimates for the oil security premiums are 4–28 percent lower over the period from 2025–2040 based upon different projected oil market and economic trends in the AEO 2015 compared to the AEO 2012 (Early Release).

There are several reasons why the avoided macroeconomic disruption premiums change only moderately. One reason is that the projected macroeconomic sensitivity to oil price shocks is held unchanged from the historical average levels used in multiple prior estimates, since projected U.S. oil consumption levels and the expenditures on oil in the U.S. economy remain at comparatively high levels under both AEO 2012 (Early Release) and AEO 2015. Figure 10.3 below shows that under AEO 2015, projected U.S. real annual oil expenditures continue to rise after 2015 to over $800 billion (2013$) by 2035. The value share of U.S. oil use, labeled in the Figure below as U.S. oil expenditures as share of GDP, remains at three percent even as the economy grows, lower than the AEO 2012 (Early Release) projection of 4.4 percent declining to 3.5 percent. The value share of oil use in the AEO 2015 is still projected to be above the full historical average (2.8 percent for 1970–2010), and well above the historical levels observed from 1985 to 2005 (1.9 percent). A second factor is that oil disruption risks are little changed. The two factors influencing disruption risks are the probability of global supply interruptions and the world oil supply share from OPEC. Both factors are not significantly different from previous forecasts of oil market trends.

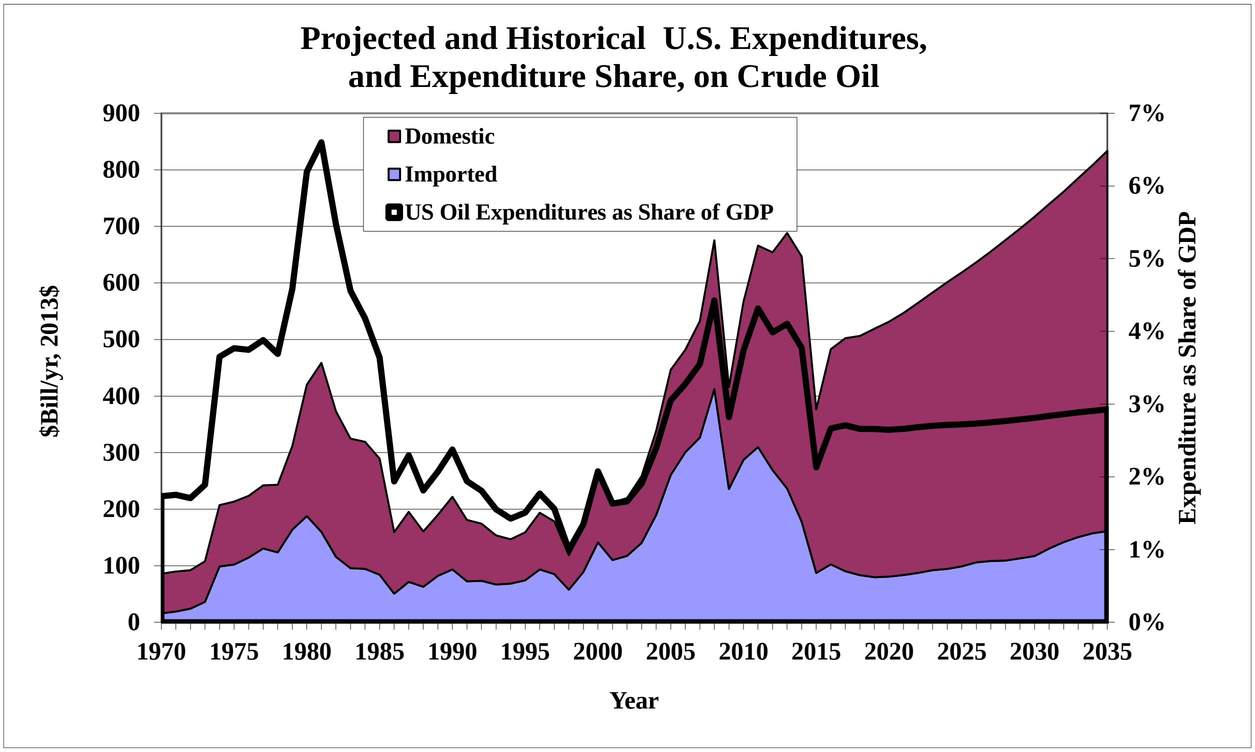

Figure 10.3 Projected and Historical U.S. Expenditures, and Expenditure Share, on Crude Oil[55]

The energy security costs estimated here follow the oil security premium framework, which is well established in the energy economics literature. The oil import premium gained attention as a guiding concept for energy policy around the time of the second and third major post-war oil shocks (Bohi and Montgomery (1982), EMF (1982)[56], Plummer (1982))[57] provided valuable discussion of many of the key issues related to the oil import premium as well as the analogous oil stockpiling premium. Bohi and Montgomery (1982)[58] detailed the theoretical foundations of the oil import premium and established many of the critical analytic relationships through their thoughtful analysis. Hogan (1981)[59] and Broadman and Hogan (1986, 1988)[60] revised and extended the established analytical framework to estimate optimal oil import premium with a more detailed accounting of macroeconomic effects.

Since the original work on energy security was undertaken in the 1980's, there have been several reviews on this topic. For example, Leiby, Jones, Curlee and Lee (1997)[61] provided an extended review of the literature and issues regarding the estimation of the premium. Parry and Darmstadter (2004)[62] also provided an overview of extant oil security premium estimates and estimated of some premium components.

The recent economics literature on whether oil shocks are the threat to economic stability that they once were is mixed. Some of the current literature asserts that the macroeconomic component of the energy security externality is small. For example, the National Research Council (2009) argued that the non-environmental externalities associated with dependence on foreign oil are small, and potentially trivial.[63] Analyses by Nordhaus (2007) and Blanchard and Gali (2010) question the impact of more recent oil price shocks on the economy.[64] They were motivated by attempts to explain why the economy actually expanded immediately after the last shocks, and why there was no evidence of higher energy prices being passed on through higher wage inflation. Using different methodologies, they conclude that the economy has largely gotten over its concern with dramatic swings in oil prices.

One reason, according to Nordhaus, is that monetary policy has become more accommodating to the price impacts of oil shocks. Another is that consumers have simply decided that such movements are temporary, and have noted that price impacts are not passed on as inflation in other parts of the economy. He also notes that real changes to productivity due to oil price increases are incredibly modest,[N] and that the general direction of the economy matters a great deal regarding how the economy responds to a shock. Estimates of the impact of a price shock on aggregate demand are insignificantly different from zero.

Blanchard and Gali (2010) contend that improvements in monetary policy (as noted above), more flexible labor markets, and lessening of energy intensity in the economy, combined with an absence of concurrent shocks, all contributed to lessen the impact of oil shocks after 1980. They find "… the effects of oil price shocks have changed over time, with steadily smaller effects on prices and wages, as well as on output and employment."[65] In a comment at the chapter's end, this work is summarized as follows: "The message of this chapter is thus optimistic in that it suggests a transformation in U.S. institutions has inoculated the economy against the responses that we saw in the past."

At the same time, the implications of the "Shale Oil Revolution" are now being felt in the international markets, with current prices at four year lows. Analysts generally attribute this result in part to the significant increase in supply resulting from U.S. production, which has put liquid petroleum production roughly on par with Saudi Arabia. The price decline is also attributed to the sustained reductions in U.S. consumption and global demand growth from fuel efficiency policies and previously high oil prices. The resulting decrease in foreign imports, down to about one-third of domestic consumption (from 60 percent in 2005, for example[66]), effectively permits U.S. supply to act as a buffer against artificial or other supply restrictions (the latter due to conflict or a natural disaster, for example).

However, other papers suggest that oil shocks, particularly sudden supply shocks, remain a concern. Both Blanchard and Gali's and Nordhaus work were based on data and analysis through 2006, ending with a period of strong global economic growth and growing global oil demand. The Nordhaus work particularly stressed the effects of the price increase from 2002–2006 that were comparatively gradual (about half the growth rate of the 1973 event and one-third that of the 1990 event). The Nordhaus study emphasizes the robustness of the U.S. economy during a time period through 2006. This time period was just before rapid further increases in the price of oil and other commodities with oil prices more-than-doubling to over $130/barrel by mid-2008, only to drop after the onset of the largest recession since the Great Depression.

Hamilton (2012)[67] reviewed the empirical literature on oil shocks and suggested that the results are mixed, noting that some work (e.g. Rasmussen and Roitman (2011) finds less evidence for economic effects of oil shocks, or declining effects of shocks (Blanchard and Gali

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[N] In fact, "… energy-price changes have no effect on multifactor productivity and very little effect on labor productivity." Page 19. He calculates the productivity effect of a doubling of oil prices as a decrease of 0.11 percent for one year and 0.04 percent a year for ten years. Page 5. (The doubling reflects the historical experience of the post-war shocks, as described in Table 7.1 in Blanchard and Gali, pp. 380) [EPA-HQ-OAR-2014-0827-0567].

2010), while other work continues to find evidence regarding the economic importance of oil shocks. For example, Baumeister and Peersman (2011) found that an oil price increase had a decreasing effect over time. But they note that with a declining price-elasticity of demand that a given physical oil disruption would have a bigger effect on price and a similar effect on output as in the earlier data. Hamilton observes that "a negative effect of oil prices on real output has also been reported for a number of other countries, particularly when nonlinear functional forms have been employed." Alternatively, rather than a declining effect, Ramey and Vine (2010) found "remarkable stability in the response of aggregate real variables to oil shocks once we account for the extra costs imposed on the economy in the 1970s by price controls and a complex system of entitlements that led to some rationing and shortages."[68]

Some of the recent literature on oil price shocks has emphasized that economic impacts depend on the nature of the oil shock, with differences between price increases caused by sudden supply loss and those caused by rapidly growing demand. Most recent analyses of oil price shocks have confirmed that "demand-driven" oil price shocks have greater effects on oil prices and tend to have positive effects on the economy while "supply-driven" oil shocks still have negative economic impacts (Baumeister, Peersman and Van Robays (2010)).[69] A recent paper by Kilian and Vigfusson (2014)[70], for example, assigned a more prominent role to the effects of price increases that are unusual, in the sense of being beyond range of recent experience. Kilian and Vigfusson also conclude that the difference in response to oil shocks may well stem from the different effects of demand- and supply-based price increases: "One explanation is that oil price shocks are associated with a range of oil demand and oil supply shocks, some of which stimulate the U.S. economy in the short run and some of which slow down U.S. growth (see Kilian (2009)). How recessionary the response to an oil price shock is thus depends on the average composition of oil demand and oil supply shocks over the sample period."

The general conclusion that oil supply-driven shocks reduce economic output is also reached in a recently published paper by Cashin et al. (2014)[71] for 38 countries from 1979-2011. "The results indicate that the economic consequences of a supply-driven oil-price shock are very different from those of an oil-demand shock driven by global economic activity, and vary for oil-importing countries compared to energy exporters", and "oil importers [including the U.S.] typically face a long-lived fall in economic activity in response to a supply-driven surge in oil prices" but almost all countries see an increase in real output for an oil-demand disturbance. Note that the energy security premium calculation in this analysis is based on price shocks from potential future supply events only.

By early 2016, world oil prices were sharply lower than in 2014. Future prices remain uncertain, but sustained markedly lower oil prices can have mixed implications for U.S. energy security. Under lower prices U.S. expenditures on oil consumption are lower, and the expenditures are a less prominent component of the U.S. economy. But sustained lower oil prices encourage greater oil consumption, and reduce the competitiveness of new U.S. oil supplies and alternative fuels. The AEO 2015 low-oil price outlook, for example, projects that by 2030 total U.S. petroleum supply would be 10 percent lower and imports would be 78 percent higher than the AEO 2015 Reference Case. Under the low-price case, 2030 prices are 35 percent lower, so that U.S. import expenditures are 16 percent higher.

A second potential proposed energy security effect of lower oil prices is increased instability of supply, due to greater global reliance on fewer suppling nations,[O] and because lower prices may increase economic and geopolitical instability in some supplier nations.[72,73,74] The International Monetary Fund reported that low oil prices are creating substantial economic tension for Middle East oil producers on top of the economic costs of ongoing conflicts, and noted the risk that Middle East countries including Saudi Arabia could run out of financial assets without a substantial change in policy.[75] The concern raised is that oil revenues are essential for some exporting nations to fund domestic programs and avoid domestic unrest.

Finally, despite continuing uncertainty about oil market behavior and outcomes and the sensitivity of the U.S. economy to oil shocks, it is generally agreed that it is beneficial to reduce petroleum fuel consumption from an energy security standpoint. It is not just imports alone, but both imports and consumption of petroleum from all sources and their role in economic activity, that may expose the U.S. to risk from price shocks in the world oil price. Reducing fuel consumption reduces the amount of domestic economic activity associated with a commodity whose price depends on volatile international markets.

The relative significance of petroleum consumption and import levels for the macroeconomic disturbances that follow from oil price shocks is not fully understood. Recognizing that changing petroleum consumption will change U.S. imports, this assessment of oil costs focuses on those incremental social costs that follow from the resulting changes in imports, employing the usual oil import premium measure. The agencies request comment on any published data or literature that could help inform how the agencies might attempt to incorporate the impact of changes in oil consumption, rather than imports exclusively, into our energy security analysis. Most helpful would be the provision of specific methodologies that could be utilized to estimate quantitatively how changes in oil consumption patterns influence energy security.

10.5.2.3 Cost of Existing U.S. Energy Security Policies

The last often-identified component of the full economic costs of U.S. oil imports are the costs to the U.S. taxpayers of existing U.S. energy security policies. The two primary examples are maintaining the Strategic Petroleum Reserve (SPR) and maintaining a military presence to help secure a stable oil supply from potentially vulnerable regions of the world. The SPR is the largest stockpile of government-owned emergency crude oil in the world. Established in the aftermath of the 1973/1974 oil embargo, the SPR provides the U.S. with a response option should a disruption in commercial oil supplies threaten the U.S. economy. It also allows the U.S. to meet part of its International Energy Agency obligation to maintain emergency oil stocks, and it provides a national defense fuel reserve. While the costs for building and maintaining the SPR are more clearly related to U.S. oil use and imports, historically these costs have not varied in response to changes in U.S. oil import levels. Thus, while the effect of the SPR in moderating price shocks is factored into the ORNL analysis, the cost of maintaining the SPR is excluded.

[O] Fatih Birol, Executive Director of the International Energy Agency warn that prolonged lower oil prices would trigger energy-security concerns by increasing reliance on a small number of low-cost producers "or risk a sharp rebound in price if investment falls short." "It would be a grave mistake to index our attention to energy security to changes in the oil price," Birol said. "Now is not the time to relax. Quite the opposite: a period of low oil prices is the moment to reinforce our capacity to deal with future energy security threats."

10.5.2.4 Military Security Cost Components of Energy Security

The agencies also attempted to assess the military security benefits components of energy security in this Draft TAR. The recent literature on the military components of energy security has included three broad categories of oil related military and national security costs all of which are hard to quantify and provide estimates of their costs. These include possible costs of U.S. military programs to secure oil supplies from unstable regions of the world, the energy security costs associated with the U.S. military's reliance on petroleum to fuel its operations and possible national security costs associated with expanded oil revenues to "rogue states."

Of these categories listed above, the one that is most clearly connected to petroleum use and is, in principle, quantifiable is the first, the cost of military programs to secure oil supplies and stabilize oil supplying regions. There is a developing literature on the measurement of these components of energy security but methodological and measurement challenges pose significant challenges to providing a robust estimate of this component of energy security.

Assessing the military component of the energy security cost has two major challenges: attribution and incremental analysis. The attribution challenge is to determine which military programs and expenditures can properly be attributed to oil supply protection, rather than some other objective. The incremental analysis challenge is to estimate how much the petroleum supply protection costs might vary if U.S. oil use were to be reduced or eliminated.

Since "military forces are, to a great extent, multipurpose and fungible" across theaters and missions (Crane et al. (2009))[76], and because the military budget is presented along regional accounts rather than by mission, the allocation to particular missions is not always clear. Approaches taken usually either allocate "partial" military costs directly associated with operations in a particular region, or allocate a share of total military costs (including some that are indirect in the sense of supporting military activities overall) (Koplow and Martin (1998)).[77]

The incremental analysis can estimate how military costs would vary if the oil security mission is no longer needed, and many studies stop at this point. It is substantially more difficult to estimate how military costs would vary if U.S. oil use or imports are partially reduced. Partial reduction of U.S. oil use diminishes the magnitude of the security problem, but there is uncertainty that supply protection forces and their costs could be scaled down in proportion (e.g. Crane et al. (2009))[78], and there remains the associated goal of protecting supply and transit for allies and important trade partners, and other importing countries, if they do not decrease their petroleum use as well.

The challenges of attribution and incremental analysis have led some to conclude that the mission of oil supply protection cannot be clearly separated from others, and the military cost component of oil security should be taken as near zero (Moore et al. (1997)).[79] For example, the Council on Foreign Relations takes the view that substantial foreign policy missions will remain over the next 20 years, even without the oil security mission entirely. Stern, on the other hand, argues that many of the other policy concerns in the Persian Gulf follow from oil, and the reaction to U.S. policies taken to protect oil.

Most commonly, analysts estimate substantial military costs associated with the missions of oil supply security and associated contingencies, but avoid estimating specific cost reductions from partial reductions in oil use. However, some relatively recent studies (Copulos (2003), Delucchi and Murphy (2008), Crane et al., Stern (2010))[80] seek to update, and in some cases significantly improve the rigor of analysis.

Delucchi and Murphy sought to deduct from the cost of Persian Gulf military programs, the costs associated with defending U.S. interests other than the objective of providing more stable oil supply and price to the U.S. economy. Excluding an estimate of cost for missions unrelated to oil, and for the protection of oil in the interest of other countries, Delucchi and Murphy estimated military costs for all U.S. domestic oil interests of between $24 and $74 billion annually.

Crane et al. considered force reductions and cost savings that could be achieved if oil security were no longer a consideration. After reviewing documents supporting recent defense resource allocations they concluded that the oil protection mission is prominent: "First, the United States does include the security of oil supplies and global transit of oil as a prominent element in its force planning." While they noted that the elimination of this mission of oil supply protection might not lead to complete reduction of those costs, they concluded there is very likely to be some cost reduction. Taking two approaches, and guided by post-Cold War force draw downs and by a top-down look at the current U.S. allocation of defense resources, they concluded that $75–$91 billion, or 12–15 percent of the current U.S. defense budget, could be reduced if the oil protection mission were completely eliminated.

Stern presents an estimate of military cost for Persian Gulf force projection, addressing the challenge of cost allocation with an activity-based cost method. He used information on actual naval force deployments rather than budgets, focusing on the costs of carrier deployment. As a result of this different data set and these assumptions regarding allocation, the estimated costs are much higher, roughly 4 to 10 times, than other recent estimates. For the 1976–2007 time frame, Stern estimated an average military cost of $212 billion and for 2007, $500 billion.

A study by the National Research Council (NRC) (2013)[81] attempted to estimate the military costs associated with U.S. imports and consumption of petroleum. The NRC cites estimates of the national defense costs of oil dependence from the literature that range from less than $5 billion to $50 billion per year or more. Assuming a range of approximate range of $10 billion to $50 billion per year, the NRC divided national defense costs by a projected U.S. consumption rate of approximately 6.4 billion barrels per year (EIA, 2012). This procedure yielded a range of average national defense cost of $1.50–$8.00 per barrel (rounded to the nearest $0.50), with a mid-point of $5/barrel (in 2009). However, as discussed above, it is unclear that incremental reductions in either U.S. imports, or consumption of domestic petroleum, would produce incremental changes to the military expenditures related to the oil protection mission (Crane, et al.). The agencies continue to review newer studies and literature to better estimate the military components of the energy security benefits associated with this Draft TAR, but as of this date, have not been able to identify a robust methodology that can be used to quantify the military cost component of energy security.

10.6 Non-GHG Health and Environmental Impacts

This section discusses the economic benefits from reductions in health and environmental impacts resulting from non-GHG emission reductions (such as criteria and toxic air pollutants) that can be expected to occur as a result of the light-duty 2022-2025 GHG standards. CO_2 emissions are predominantly the byproduct of fossil fuel combustion processes that also produce criteria and hazardous air pollutant emissions. The vehicles that are subject to this program are also significant sources of mobile source air pollution such as direct PM, NO_X, VOCs and air toxics, which are regulated by separate emissions standards programs. The program will affect exhaust emissions of these pollutants from vehicles and will also affect emissions from upstream sources that occur during the refining and distribution of fuel. Changes in ambient concentrations of ozone, $PM_{2.5}$, and air toxics that will result from the program are expected to affect human health by reducing premature deaths and other serious human health effects, as well as other important improvements in public health and welfare. Children especially benefit from reduced exposures to criteria and toxic pollutants, because they tend to be more sensitive to the effects of these respiratory pollutants. Ozone and particulate matter have been associated with increased incidence of asthma and other respiratory effects in children, and particulate matter has been associated with a decrease in lung maturation.

It is important to quantify the co-pollutant-related health and environmental impacts associated with the GHG standards because a failure to adequately consider these ancillary impacts could lead to an incorrect assessment of the standards' costs and benefits. Moreover, the health and other impacts of exposure to criteria air pollutants and airborne toxics tend to occur in the near term, while most effects from reduced climate change are likely to occur only over a time frame of several decades or longer.

For purposes of this Draft TAR, EPA has applied PM-related benefits per-ton values to its estimated emission reductions as an interim approach to estimating only the PM-related benefits of the program.[82,P] However, there are several health benefit categories that EPA was unable to quantify due to limitations associated with using benefits-per-ton estimates, several of which could be substantial. For example, we have not quantified a number of known or suspected health benefits linked to reductions in ozone and other criteria pollutants, as well as health benefits linked to reductions in air toxics. Additionally, we are unable to quantify a number of known welfare effects, including reduced acid and particulate deposition damage to cultural monuments and other materials, and environmental benefits due to reductions of impacts of eutrophication in coastal areas. As a result, the health benefits quantified in this section are likely underestimates of total benefits. If necessary, EPA will quantify and monetize the health and environmental impacts related to both PM and ozone later in the midterm evaluation process, which would entail photochemical air quality modeling.

10.6.1 Economic Value of Reductions in Particulate Matter

As presented in Chapter 12, the standards would reduce emissions of several criteria and toxic pollutants and their precursors. In this analysis, however, EPA only estimates the economic value of the human health benefits associated with the resulting reductions in $PM_{2.5}$ exposure (related to both directly emitted $PM_{2.5}$ and secondarily-formed $PM_{2.5}$). Due to analytical limitations with the benefit per-ton method, this analysis does not estimate benefits resulting

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[P] See also: http://www.epa.gov/airquality/benmap/sabpt.html. The current values available on the webpage have been updated since the publication of the Fann et al., 2012 paper. For more information regarding the updated values, see: http://www.epa.gov/airquality/benmap/models/Source_Apportionment_BPT_TSD_1_31_13.pdf (accessed June 9, 2016).

from reductions in population exposure to other criteria pollutants such as ozone.[Q] Furthermore, the benefits per-ton method, like all air quality impact analyses, does not monetize all of the potential health and welfare effects associated with reduced concentrations of $PM_{2.5}$.

This analysis uses estimates of the benefits from reducing the incidence of the specific $PM_{2.5}$-related health impacts described below. These estimates, which are expressed per ton of $PM_{2.5}$-related emissions eliminated by the standards, represent the total monetized value of human health benefits (including reduction in both premature mortality and premature morbidity) from reducing each ton of directly emitted $PM_{2.5}$, or its precursors (SO_2 and NO_X), from a specified source. Ideally, the human health benefits would be estimated based on changes in ambient $PM_{2.5}$ as determined by full-scale air quality modeling. However, the length of time needed to prepare the necessary emissions inventories, in addition to the processing time associated with the modeling itself, has precluded us from performing air quality modeling for the Draft TAR. If necessary, EPA will conduct this modeling later in the midterm evaluation process.

The PM-related dollar-per-ton benefit estimates used in this analysis are provided in Table 10.12. As the table indicates, these values differ among directly emitted PM and PM precursors (SO_2 and NO_X), and also depend on their original source, because emissions from different sources can result in different degrees of population exposure and resulting health impacts. In the summary of costs and benefits, Chapter 12, EPA presents the monetized value of total PM-related improvements associated with the standards summed across sources (on-road and upstream) sources and across PM-related pollutants (direct $PM_{2.5}$ and PM precursors SO_2 and NO_X).

Table 10.12 PM-Related Benefits-per-ton Values (thousands, 2012$)[a]

Year[c]	On-road Mobile Sources			Upstream Sources[d]		
	Direct $PM_{2.5}$	SO_2	NO_X	Direct $PM_{2.5}$	SO_2	NO_X
Estimated Using a 3 Percent Discount Rate[b]						
2016	$380-$850	$20-$45	$7.7-$18	$330-$750	$69-$160	$6.8-$16
2020	$400-$910	$22-$49	$8.1-$18	$350-$790	$75-$170	$7.4-$17
2025	$440-$1,000	$24-$55	$8.8-$20	$390-$870	$83-$190	$8.1-$18
2030	$480-$1,100	$27-$61	$9.6-$22	$420-$950	$91-$200	$8.7-$20
Estimated Using a 7 Percent Discount Rate[b]						
2016	$340-$770	$18-$41	$6.9-$16	$290-$670	$63-$140	$6.2-$14
2020	$370-$820	$20-$44	$7.4-$17	$320-$720	$67-$150	$6.6-$15
2025	$400-$910	$22-$49	$8.0-$18	$350-$790	$75-$170	$7.3-$17
2030	$430-$980	$24-$55	$8.6-$20	$380-$850	$81-$180	$7.9-$18

Notes:

[a] The benefit-per-ton estimates presented in this table are based on a range of premature mortality estimates derived from the ACS study (Krewski et al., 2009) and the Six-Cities study (Lepeule et al., 2012).

[b] The benefit-per-ton estimates presented in this table assume either a 3 percent or 7 percent discount rate in the valuation of premature mortality to account for a twenty-year segmented cessation lag.

[Q] The air quality modeling that underlies the PM-related benefit per ton values also produced estimates of ozone levels attributable to each sector. However, the complex non-linear chemistry governing ozone formation prevented EPA from developing a complementary array of ozone benefit per ton values. This limitation notwithstanding, we anticipate that the ozone-related benefits associated with reducing emissions of NO_X and VOC could be substantial.

[c] Benefit-per-ton values were estimated for the years 2016, 2020, 2025 and 2030. We hold values constant for intervening years (e.g., the 2016 values are assumed to apply to years 2017-2019; 2020 values for years 2021-2024; 2025 values for years 2026-2029; and 2030 values for years 2031 and beyond).
[d] We assume for the purpose of this analysis that "upstream emissions" are most closely associated with refinery sector benefit per-ton values. The majority of upstream emission reductions associated with the standards are related to domestic onsite refinery emissions and domestic crude production. While upstream emissions also include storage and transport sources, as well as upstream refinery sources, we have chosen to simply apply the refinery values.

The benefit per-ton technique has been used in previous analyses, including EPA's 2017-2025 Light-Duty Vehicle Greenhouse Gas Rule,[83] the Reciprocating Internal Combustion Engine rules,[84,85] and the Residential Wood Heaters NSPS.[86] Table 10.13 shows the quantified $PM_{2.5}$-related co-benefits captured in those benefit per-ton estimates, as well as unquantified effects the benefits per-ton estimates are unable to capture.

Table 10.13 Human Health and Welfare Effects of $PM_{2.5}$

Pollutant	Quantified and Monetized in Primary Estimates	Unquantified Effects Changes in:
$PM_{2.5}$	Adult premature mortality Acute bronchitis Hospital admissions: respiratory and cardiovascular Emergency room visits for asthma Nonfatal heart attacks (myocardial infarction) Lower and upper respiratory illness Minor restricted-activity days Work loss days Asthma exacerbations (asthmatic population) Infant mortality	Chronic and subchronic bronchitis cases Strokes and cerebrovascular disease Low birth weight Pulmonary function Chronic respiratory diseases other than chronic bronchitis Non-asthma respiratory emergency room visits Visibility Household soiling

Readers interested in reviewing the complete methodology for creating the benefit-per-ton estimates used in this analysis can consult EPA's "Technical Support Document: Estimating the Benefit per Ton of Reducing $PM_{2.5}$ Precursors from 17 Sectors."[R] Readers can also refer to Fann et al. (2012) for a detailed description of the benefit-per-ton methodology. As described in the documentation, EPA uses a method that is consistent with the cost-benefit analysis that accompanied the 2012 PM NAAQS revision. The benefit-per-ton estimates utilize the concentration-response functions as reported in the epidemiology literature. [S,87] To calculate the total monetized impacts associated with quantified health impacts, EPA applies values derived from a number of sources. For premature mortality, EPA applies a value of a statistical life (VSL) derived from the mortality valuation literature. For certain health impacts, such as

[R] For more information regarding the updated values, see: http://www.epa.gov/airquality/benmap/models/Source_Apportionment_BPT_TSD_1_31_13.pdf (accessed September 9, 2014).
[S] Although we summarize the main issues in this chapter, we encourage interested readers to see the benefits chapter of the RIA that accompanied the PM NAAQS for a more detailed description of recent changes to the quantification and monetization of PM benefits. Note that the cost-benefit analysis was prepared solely for purposes of fulfilling analysis requirements under Executive Order 12866 and was not considered, or otherwise played any part, in the decision to revise the PM NAAQS.

respiratory-related ailments, EPA applies willingness-to-pay estimates derived from the valuation literature. For the remaining health impacts, EPA applies values derived from current cost-of-illness and/or wage estimates.

The documentation cited above also describes that national per-ton estimates were developed for selected PM-related pollutant/source category combinations. The per-ton values calculated therefore apply only to tons reduced from those specific PM-related pollutant/source combinations (e.g., NO_2 emitted from on-road mobile sources; direct PM emitted from electricity generating units). EPA's estimate of $PM_{2.5}$ benefits is therefore based on the total direct $PM_{2.5}$ and PM-related precursor emissions controlled by sector and multiplied by each per-ton value.

As Table 10.12 indicates, EPA projects that the per-ton values for reducing emissions of non-GHG pollutants from both vehicle use and upstream sources such as fuel refineries will increase over time.[T] These projected increases reflect rising income levels, which increase affected individuals' willingness to pay for reduced exposure to health threats from air pollution.[U] They also reflect future population growth and increased life expectancy, which expands the size of the population exposed to air pollution in both urban and rural areas, especially among older age groups with the highest mortality risk.[V]

The benefit-per-ton estimates are subject to a number of assumptions and uncertainties:

- The benefit-per-ton estimates used in this analysis reflect specific geographic patterns of emissions reductions and specific air quality and benefits modeling assumptions associated with the derivation of those estimates (see the TSD describing the calculation of the national benefit-per-ton estimates).[88,W] Consequently, these estimates may not reflect local variability in population density, meteorology, exposure, baseline health incidence rates, or other local factors associated with the current analysis. Therefore, use of these benefit-per-ton values to estimate non-GHG benefits may lead to higher or lower benefit estimates than if these benefits were calculated based on direct air quality modeling. EPA plans to conduct full-scale air quality modeling later in the midterm evaluation process in an effort to capture this variability.
- This analysis assumes that all fine particles, regardless of their chemical composition, are equally potent in causing premature mortality. This is an important assumption, because $PM_{2.5}$ produced via transported precursors emitted from stationary sources may differ significantly from direct $PM_{2.5}$ released from diesel engines and other

[T] As we present in Chapter 12, the standards would yield emission reductions from upstream refining and fuel distribution due to decreased petroleum consumption.

[U] The issue is discussed in more detail in the 2012 PM NAAQS RIA, Section 5.6.8. See U.S. Environmental Protection Agency. (2012). *Regulatory Impact Analysis for the Final Revisions to the National Ambient Air Quality Standards for Particulate Matter,* Health and Environmental Impacts Division, Office of Air Quality Planning and Standards, EPA-452-R-12-005, December 2012. Available on the internet: http://www.epa.gov/ttnecas1/regdata/RIAs/finalria.pdf.

[V] For more information about EPA's population projections, please refer to the following: http://www.epa.gov/air/benmap/models/BenMAPManualAppendicesAugust2010.pdf (See Appendix K)

[W] See also: http://www.epa.gov/airquality/benmap/sabpt.html. The current values available on the webpage have been updated since the publication of the Fann et al., 2012 paper. For more information regarding the updated values, see: http://www.epa.gov/airquality/benmap/models/Source_Apportionment_BPT_TSD_1_31_13.pdf (accessed September 9, 2014).

industrial sources. The PM ISA, which was twice reviewed by SAB-CASAC, concluded that "many constituents of $PM_{2.5}$ can be linked with multiple health effects, and the evidence is not yet sufficient to allow differentiation of those constituents or sources that are more closely related to specific outcomes."[89] PM composition and the size distribution of those particles vary within and between areas due to source characteristics. Any specific location could have higher or lower contributions of certain PM species and other pollutants than the national average, meaning potential regional differences in health impact of given control strategies. Depending on the toxicity of each PM species reduced by the proposed standards, assuming equal toxicity could over or underestimate benefits.

- When estimating the benefit-per-ton values, EPA assumes that the underlying health impact functions for fine particles are linear within the range of ambient concentrations under consideration. Thus, the estimates include health benefits from reducing fine particles in areas with varied concentrations of $PM_{2.5}$, including regions that are in attainment with the fine particle standard. The direction of bias that assuming a linear-no threshold model (or an alternative model) introduces depends upon the "true" functional from of the relationship and the specific assumptions and data in a particular analysis. For example, if the true function identifies a threshold below which health effects do not occur, benefits may be overestimated if a substantial portion of those benefits were estimated to occur below that threshold. Alternately, if a substantial portion of the benefits occurred above that threshold, the benefits may be underestimated because an assumed linear no-threshold function may not reflect the steeper slope above that threshold to account for all health effects occurring above that threshold.
- There are several health benefit categories that EPA was unable to quantify due to limitations associated with using benefits-per-ton estimates, several of which could be substantial. Because the NO_X and VOC emission reductions associated with the standards are also precursors to ozone, reductions in NO_X and VOC would also reduce ozone formation and the health effects associated with ozone exposure. Unfortunately, ozone-related benefits-per-ton estimates do not exist due to issues associated with the complexity of the atmospheric air chemistry and nonlinearities associated with ozone formation. The PM-related benefits-per-ton estimates also do not include any human welfare or ecological benefits.
- There are many uncertainties associated with the health impact functions that underlie the benefits-per-ton estimates. These include: within-study variability (the precision with which a given study estimates the relationship between air quality changes and health effects); across-study variation (different published studies of the same pollutant/health effect relationship typically do not report identical findings and in some instances the differences are substantial); the application of concentration-response functions nationwide (does not account for any relationship between region and health effect, to the extent that such a relationship exists); extrapolation of impact functions across population (we assumed that certain health impact functions applied to age ranges broader than that considered in the original epidemiological study); and various uncertainties in the concentration-response function, including causality and thresholds. These uncertainties may under- or over-estimate benefits.

- EPA has investigated methods to characterize uncertainty in the relationship between $PM_{2.5}$ exposure and premature mortality. EPA's final $PM_{2.5}$ NAAQS analysis provides a more complete picture about the overall uncertainty in $PM_{2.5}$ benefits estimates. For more information, please consult the $PM_{2.5}$ NAAQS RIA.[90]
- The benefit-per-ton unit values used in this analysis incorporate projections of key variables, including atmospheric conditions, source level emissions, population, health baselines, incomes, and technology. These projections introduce some uncertainties to the benefit per ton estimates.

As mentioned above, emissions changes and benefits-per-ton estimates alone are not a good indication of local or regional air quality and health impacts, as there may be localized impacts associated with the standards. Additionally, the atmospheric chemistry related to ambient concentrations of $PM_{2.5}$, ozone and air toxics is very complex. Full-scale photochemical modeling is therefore necessary to provide the needed spatial and temporal detail to more completely and accurately estimate the changes in ambient levels of these pollutants and their associated health and welfare impacts. As discussed above, timing constraints precluded EPA from conducting a full-scale photochemical air quality modeling analysis in time for the Draft TAR. Later in the midterm evaluation process, EPA plans to quantify and monetize the health and environmental impacts related to both PM and ozone, which entails photochemical air quality modeling.

10.7 Greenhouse Gas Emission Impacts

We estimate the global social benefits of CO_2 emission reductions expected from the 2022-2025 final standards using the SC-CO_2 estimates presented in the *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013, Revised July 2015) ("current TSD").[91] We refer to these estimates, which were developed by the U.S. government, as "SC-CO_2 estimates." The SC-CO_2 is a metric that estimates the monetary value of impacts associated with marginal changes in CO_2 emissions in a given year. It includes a wide range of anticipated climate impacts, such as net changes in agricultural productivity and human health, property damage from increased flood risk, and changes in energy system costs, such as reduced costs for heating and increased costs for air conditioning. It is typically used to assess the avoided damages as a result of regulatory actions (i.e., benefits of rulemakings that lead to an incremental reduction in cumulative global CO_2 emissions).

The SC-CO_2 estimates used in the final 2017-2025 RIA and in this analysis were developed over many years, using the best science available, and with input from the public. Specifically, an interagency working group (IWG) that included the EPA and other executive branch agencies and offices used three integrated assessment models (IAMs) to develop the SC-CO_2 estimates and recommended four global values for use in regulatory analyses. The SC-CO_2 estimates were first released in February 2010 and were used to estimate the value of CO_2 benefits in the final 2017-2025 rulemaking.

These SC-CO_2 estimates were developed using an ensemble of the three most widely cited integrated assessment models in the economics literature with the ability to estimate the SC-CO_2. A key objective of the IWG was to draw from the insights of the three models while respecting the different approaches to linking GHG emissions and monetized damages taken by modelers in the published literature. After conducting an extensive literature review, the interagency group selected three sets of input parameters (climate sensitivity, socioeconomic and emissions trajectories, and discount rates) to use consistently in each model. All other model features were left unchanged, relying on the model developers' best estimates and judgments, as informed by the literature. Specifically, a common probability distribution for the equilibrium climate sensitivity parameter, which informs the strength of climate's response to atmospheric GHG concentrations, was used across all three models. In addition, a common range of scenarios for the socioeconomic parameters and emissions forecasts were used in all three models. Finally, the marginal damage estimates from the three models were estimated using a consistent range of discount rates, 2.5, 3.0, and 5.0 percent. See *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (February 2010) ("2010 TSD") for a complete discussion of the methods used to develop the estimates and the key uncertainties, and the current TSD for the latest estimates.[92]

In 2013, and after the final LD 2017-2025 rulemaking, the IWG updated the SC-CO_2 estimates using new versions of each IAM. The 2013 update did not revisit the 2010 modeling decisions with regards to the discount rate, reference case socioeconomic and emission scenarios, and equilibrium climate sensitivity distribution. Rather, improvements in the way damages are modeled are confined to those that have been incorporated into the latest versions of the models by the developers themselves and published in the peer-reviewed literature. The model updates that are relevant to the SCC estimates include: an explicit representation of sea level rise damages in the Dynamic Integrated Climate and Economy (DICE) and Policy Analysis of the Greenhouse Effect (PAGE) models; updated adaptation assumptions, revisions to ensure damages are constrained by GDP, updated regional scaling of damages, and a revised treatment of potentially abrupt shifts in climate damages in the PAGE model; an updated carbon cycle in the DICE model; and updated damage functions for sea level rise impacts, the agricultural sector, and reduced space heating requirements, as well as changes to the transient response of temperature to the buildup of GHG concentrations and the inclusion of indirect effects of methane emissions in the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) model. The current TSD presents and discusses the 2013 update (including recent minor technical corrections to the estimates).[X]

The updated estimates continue to represent global measures because of the distinctive nature of the climate change, which is highly unusual in at least three respects. First, emissions of most GHGs contribute to damages around the world independent of the country in which they are emitted. The SC-CO_2 must therefore incorporate the full (global) damages caused by GHG emissions to address the global nature of the problem. Second, the U.S. operates in a global and highly interconnected economy, such that impacts on the other side of the world can affect our economy. This means that the true costs of climate change to the U.S. are larger than the direct impacts that simply occur within the U.S. Third, climate change represents a classic public goods problem because each country's reductions benefit everyone else and no country can be excluded from enjoying the benefits of other countries' reductions, even if it provides no reductions itself. In this situation, the only way to achieve an economically efficient level of

[X] Both the 2010 TSD and the current TSD are available at: https://www.whitehouse.gov/omb/oira/social-cost-of-carbon.

emissions reductions is for countries to cooperate in providing mutually beneficial reductions beyond the level that would be justified only by their own domestic benefits. In reference to the public good nature of mitigation and its role in foreign relations, thirteen prominent academics noted that these "are compelling reasons to focus on a global SCC" in a recent article on the SCC (Pizer et al., 2014). In addition, as noted in OMB's Response to Comments on the SC-CO_2, a document discussed further below, there is no bright line between domestic and global damages. Adverse impacts on other countries can have spillover effects on the United States, particularly in the areas of national security, international trade, public health and humanitarian concerns.[93]

The 2010 TSD noted a number of limitations to the SC-CO_2 analysis, including the incomplete way in which the integrated assessment models capture catastrophic and non-catastrophic impacts, their incomplete treatment of adaptation and technological change, uncertainty in the extrapolation of damages to high temperatures, and assumptions regarding risk aversion. Currently integrated assessment models do not assign value to all of the important physical, ecological, and economic impacts of climate change recognized in the climate change literature due to a lack of precise information on the nature of damages and because the science incorporated into these models understandably lags behind the most recent research.[Y] The limited amount of research linking climate impacts to economic damages makes the modeling exercise even more difficult. These individual limitations do not all work in the same direction in terms of their influence on the SC-CO_2 estimates, though taken together they suggest that the SC-CO_2 estimates are likely conservative. In particular, the IPCC Fourth Assessment Report (2007), which was the most current IPCC assessment available at the time of the IWG's 2009-2010 review, concluded that "It is very likely that [SC-CO_2 estimates] underestimate the damage costs because they cannot include many non-quantifiable impacts." Since then, the peer-reviewed literature has continued to support this conclusion. For example, the IPCC Fifth Assessment report observed that SC-CO_2 estimates continue to omit various impacts that would likely increase damages.

The EPA and other agencies have continued to consider feedback on the SC-CO_2 estimates from stakeholders through a range of channels, most recently including public comments on the Clean Power Plan rulemaking[94] and others that use the SC-CO_2 in supporting analyses and through regular interactions with stakeholders and research analysts implementing the SC-CO_2 methodology used by the interagency working group. Commenters have provided constructive recommendations for potential opportunities to improve the SC-CO_2 estimates in future updates. In addition, OMB sought public comment on the approach used to develop the SC-CO_2 estimates through a separate comment period and published a response to those comments in 2015.[Z]

After careful evaluation of the full range of comments submitted to OMB, the IWG continues to recommend the use of the SC-CO_2 estimates in regulatory impact analysis. With the release of the response to comments, the IWG announced plans in July 2015 to obtain expert independent

[Y] Climate change impacts and SCC modeling is an area of active research. For example, see: (1) Howard, Peter, "Omitted Damages: What's Missing from the Social Cost of Carbon." March 13, 2014, http://costofcarbon.org/files/Omitted_Damages_Whats_Missing_From_the_Social_Cost_of_Carbon.pdf; and (2) Electric Power Research Institute, "Understanding the Social Cost of carbon: A Technical Assessment," October 2014, www.epri.com.

[Z] See https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-response-to-comments-final-july-2015.pdf.

advice from the National Academies of Sciences, Engineering and Medicine to ensure that the SC-CO_2 estimates continue to reflect the best available scientific and economic information on climate change.[AA] The Academies then convened a committee, "Assessing Approaches to Updating the Social Cost of Carbon," (Committee) that is reviewing the state of the science on estimating the SC-CO_2 , and will provide expert, independent advice on the merits of different technical approaches for modeling and highlight research priorities going forward. EPA will evaluate its approach based upon any feedback received from the Academies' panel.

To date, the Committee has released an interim report, which recommended against doing a near term update of the SC-CO_2 estimates. For future revisions, the Committee recommended the IWG move efforts towards a broader update of the climate system module consistent with the most recent, best available science, and also offered recommendations for how to enhance the discussion and presentation of uncertainty in the SC-CO_2 estimates. Specifically, the Committee recommended that "the IWG provide guidance in their technical support documents about how [SC-CO_2] uncertainty should be represented and discussed in individual regulatory impact analyses that use the [SC-CO_2]" and that the technical support document for each update of the estimates present a section discussing the uncertainty in the overall approach, in the models used, and uncertainty that may not be included in the estimates.[BB] At the time of this writing, the IWG is reviewing the interim report and considering the recommendations. EPA looks forward to working with the IWG to respond to the recommendations and will continue to follow IWG guidance on SC-CO_2.

The current SC-CO_2 estimates are as follows: \$14, \$47, \$70, and \$140 per ton of CO_2 emissions in the year 2022 (2013\$).[CC] The first three values are based on the average SC-CO_2 from the three IAMs, at discount rates of 5, 3, and 2.5 percent, respectively. SC-CO_2 estimates for several discount rates are included because the literature shows that the SC-CO_2 is quite sensitive to assumptions about the discount rate, and because no consensus exists on the appropriate rate to use in an intergenerational context (where costs and benefits are incurred by different generations). The fourth value is the 95th percentile of the SC-CO_2 from all three models at a 3 percent discount rate. It is included to represent lower probability but higher - impact outcomes from climate change, which are captured further out in the tail of the SC- CO_2 distribution, and while less likely than those reflected by the average SC- CO_2 estimates, would be much more harmful to society and therefore, are relevant to policy makers.

[AA] The Academies' review will be informed by public comments and focus on the technical merits and challenges of potential approaches to improving the SC-CO_2 estimates in future updates. See https://www.whitehouse.gov/blog/2015/07/02/estimating-benefits-carbon-dioxide-emissions-reductions.

[BB] National Academies of Sciences, Engineering, and Medicine. (2016). *Assessment of Approaches to Updating the Social Cost of Carbon: Phase 1 Report on a Near-Term Update*. Committee on Assessing Approaches to Updating the Social Cost of Carbon, Board on Environmental Change and Society. Washington, DC: The National Academies Press. doi: 10.17226/21898. See Executive Summary, page 1, for quoted text.

[CC] The current version of the TSD is available at: https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-tsd-final-july-2015.pdf. The 2010 and 2013 TSDs present SC-CO_2 in 2007\$ per metric ton. The unrounded estimates from the current TSD were adjusted to 2013\$ using GDP Implicit Price Deflator (1.097), http://www.bea.gov/iTable/index_nipa. The estimates presented in this document were rounded to two significant digits.

The current estimates are higher than those used to analyze the CO_2 impacts in the final LD 2017-2025 rulemaking, which preceded the 2013 SC-CO_2 update and were published in the 2010 SC-CO_2 TSD. By way of comparison, the four SC-CO_2 estimates used to analyze the CO_2 impacts for the final LD 2017-2015 rulemaking were $8.1, $30, $48, and $93 per metric ton in 2022 (2013$).[DD] As previously noted, the IWG updated these estimates in 2013 using new versions of each integrated assessment model but did not Table 10.14 presents the current global SC-CO_2 estimates for select years between 2022 and 2050. In order to calculate the dollar value for emission reductions, the SC-CO_2 estimate for each emissions year would be applied to changes in CO_2 emissions for that year, and then discounted back to the analysis year using the same discount rate used to estimate the SC-CO_2. The SC-CO_2 increases over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climate change. Note that the interagency group estimated the growth rate of the SC-CO_2 directly using the three integrated assessment models rather than assuming a constant annual growth rate. This helps to ensure that the estimates are internally consistent with other modeling assumptions. Chapter 12 reports the updated GHG benefits in select model years and calendar years.

Table 10.14 Social Cost of CO_2, 2015-2050 (in 2013$ per metric ton)*

	Discount Rate and Statistic			
Year	5% Average	3% Average	2.5% Average	3% (95th percentile)
2022	$14	$47	$70	$140
2023	$14	$48	$71	$140
2024	$14	$49	$72	$150
2025	$15	$50	$75	$150
2030	$18	$55	$80	$170
2040	$23	$66	$92	$200
2050	$29	$76	$100	$230

Note:
* These SC-CO_2 values are stated in $/metric ton and rounded to two significant figures. The estimates vary depending on the year of CO_2 emissions and are defined in real terms, i.e., adjusted for inflation using the GDP implicit price deflator.

One limitation of the primary benefits analysis in the 2017-2025 final rulemaking is that it did not include the valuation of non-CO_2 GHG impacts (CH_4, N_2O, HFC-134a). Specifically, the IWG did not estimate the social costs of non-CO_2 GHG emissions using an approach analogous to the one used to estimate the SC-CO_2. While there were other estimates of the social cost of non- CO_2 GHGs in the peer review literature, the methodologies underlying those estimates were inconsistent with the methodology the IWG used to estimate the SC-CO_2. As discussed in the

[DD] The 2010 and 2013 TSDs present SC-CO_2 in $2007; see https://www.whitehouse.gov/omb/oira/social-cost-of-carbon for both TSDs. The estimates used in the final 2017-2025 rulemaking were adjusted to $2010 using GDP Implicit Price Deflator. The estimates have been adjusted to 2013$ here for consistency with the Draft TAR. See National Income and Product Accounts Tables, Table 1.1.9 at http://www.bea.gov/iTable/index_nipa.cfm for GDP Implicit Price Deflators.

2017-2025 final rulemaking, there is considerable variation among these published estimates in the models and input assumptions they employ.[EE] These studies differ in the emission perturbation year, employ a wide range of constant and variable discount rate specifications, and consider a range of baseline socioeconomic and emissions scenarios that have been developed over the last 20 years. EPA also determined that the estimates in the literature were most likely underestimates due to changes in the underlying science since their publication.[FF]

However, EPA recognized that non-CO_2 GHG impacts associated with these standards (e.g., net reductions in CH_4, N_2O, and HFC-134a) would provide benefits to society. To understand the potential implication of omitting these benefits, EPA conducted sensitivity analysis using an approximation approach based on global warming potential (GWP) gas comparison metrics that has been used in previous rulemakings. The EPA also sought public comments on the valuation of non-CO_2 GHG impacts in the proposed LD 2017-2025 rulemaking and other previous rulemakings (e.g., U.S. EPA 2012).[95] In general, the commenters strongly encouraged the EPA to incorporate the monetized value of non-CO_2 GHG impacts into the benefit cost analysis, however they noted the challenges associated with the GWP-approach, as discussed further below, and encouraged the use of directly-modeled estimates of the SC-CH_4 to overcome those challenges.

Subsequent to the 2017-2025 final rule, a paper by Marten et al. (2014) provided the first set of published SC-CH_4 and SC-N_2O estimates that are consistent with the modeling assumptions underlying the SC-CO_2.[96] Specifically, the estimation approach of Marten et al. used the same set of three IAMs, five socioeconomic and emissions scenarios, equilibrium climate sensitivity distribution, three constant discount rates, and aggregation approach used by the IWG to develop the SC-CO_2 estimates. The aggregation method involved distilling the 45 distributions of the SC-CH_4 and of the SC-N_2O produced for each emissions year into four estimates: the mean across all models and scenarios using a 2.5 percent, 3 percent, and 5 percent discount rate, and the 95th percentile of the pooled estimates from all models and scenarios using a 3 percent discount rate. Marten et al. also used the same rationale as the IWG to develop global estimates of the SC-CH_4 and SC-N_2O, given that methane and N2O are global pollutants.

The atmospheric lifetime and radiative efficacy of methane and N_2O used by Marten et al. is based on the estimates reported by the IPCC in their Fourth Assessment Report (AR4, 2007), including an adjustment in the radiative efficacy of methane to account for its role as a precursor for tropospheric ozone and stratospheric water. These values represent the same ones used by the IPCC in AR4 for calculating GWPs. At the time Marten et al. developed their estimates of the SC-CH_4, AR4 was the latest assessment report by the IPCC. The IPCC updates GWP estimates with each new assessment, and in the most recent assessment, AR5, the latest estimate of the methane GWP ranged from 28-36, compared to a GWP of 25 in AR4. The updated values reflect a number of changes: changes in the lifetime and radiative efficiency estimates for CO_2, changes in the lifetime estimate for methane, and changes in the correction factor applied to

[EE] The researchers cited in the 2017-2015 RIA include: Fankhauser (1994); Kandlikar (1995); Hammitt et al. (1996); Tol et al. (2003); Tol (2004); and Hope and Newberry (2006).

[FF] See the 2017-2025 RIA, page 7-7, for complete discussion. Literature included studies primarily from the mid-1990s through early 2000s. http://www3.epa.gov/otaq/climate/documents/420r12016.pdf.

methane's GWP to reflect the effect of methane emissions on other climatically important substances such as tropospheric ozone and stratospheric water vapor. In addition, the range presented in the latest IPCC report reflects different choices regarding whether to account for how biogenic and fossil methane have different carbon cycle effects, and for whether to account for climate feedbacks on the carbon cycle for both methane and CO_2 (rather than just for CO_2 as was done in AR4).[97,GG]

Marten et al. (2014) discuss these estimates, (SC-CH_4 and SC-N_2O estimates presented below in Table 10.15), and compare them with other recent estimates in the literature. The authors noted that a direct comparison of their estimates with all of the other published estimates is difficult, given the differences in the models and socioeconomic and emissions scenarios, but results from three relatively recent studies offer a better basis for comparison (see Hope (2006), Marten and Newbold (2012), Waldhoff et al. (2014)). Marten et al. found that, in general, the SC-CH_4 estimates from their 2014 paper are higher than previous estimates and the SC-N_2O estimates from their 2014 paper fall within the range from Waldhoff et al. The higher SC-CH_4 estimates are partially driven by the higher effective radiative forcing due to the inclusion of indirect effects from methane emissions in their modeling. Marten et al., similar to other recent studies, also find that their directly modeled SC-CH_4 and SC-N_2O estimates are higher than the GWP-weighted estimates. More detailed discussion of the SC-CH_4 and SC-N_2O estimation methodology, results and a comparison to other published estimates can be found in Marten et al.

The resulting SC-CH_4 and SC-N_2O estimates are presented in Table 10.15. The tables do not include HFC-134a because EPA is unaware of analogous estimates.

Table 10.15 Social Cost of CH4 and Social Cost of N2O, 2015-2050 (in 2013$ per metric ton)

	Social Cost of CH4				Social Cost of N2O			
Year	5% (Avg)	3% (Avg)	2.5% (Avg)	3% (95th percentile)	5% (Avg)	3% (Avg)	2.5% (Avg)	3% (95th percentile)
2022	$640	$1,400	$1,800	$3,700	$5,500	$17,000	$25,000	$45,000
2023	$660	$1,400	$1,900	$3,800	$5,700	$18,000	$25,000	$46,000
2024	$690	$1,500	$1,900	$3,900	$5,900	$18,000	$26,000	$47,000
2025	$710	$1,500	$2,000	$4,100	$6,000	$19,000	$26,000	$48,000
2030	$830	$1,800	$2,200	$4,600	$6,900	$21,000	$30,000	$54,000
2040	$1,100	$2,200	$2,900	$6,000	$9,200	$25,000	$35,000	$66,000
2050	$1,400	$2,700	$3,400	$7,300	$12,000	$30,000	$41,000	$79,000

Note:
* These SC-CH_4 and SC-N2O values are stated in $/metric ton and rounded to two significant figures. The estimates vary depending on the year of emissions and are defined in real terms, i.e., adjusted for inflation using the GDP implicit price deflator. In addition, the estimates in this table have been adjusted to reflect the minor technical corrections to the SC-CO2 estimates described above. See Corrigendum to Marten et al. (2014) for more details http://www.tandfonline.com/doi/abs/10.1080/14693062.2015.1070550 .

[GG] Note that the Draft TAR uses 100-year GWP values for CO_2 equivalency calculations that are consistent with the GHG emissions inventories and the IPCC Fourth Assessment Report (AR4), i.e., 25 for methane. The IPCC reported the same 100-year GWP for N_2O (298) in AR4 and AR5.

Today's publication updates the analysis of non-CO_2 GHG benefits presented in the 2017-2025 final rule by using Marten et al. (2014) estimates of SC-CH_4 sand SC-N_2O. In particular, the application of directly modeled estimates from Marten et al. (2014) to benefit-cost analysis of a regulatory action is analogous to the use of the SC-CO_2 estimates. Specifically, the SC-CH_4 and SC-N_2O estimates in Table 10.15 are used to monetize the benefits of reductions in methane and N_2O emissions, respectively, expected as a result of the 2022-2025 standards. Forecast changes in methane (or N_2O) emissions in a given year, expected as a result of the standards, are multiplied by the SC-CH_4 (or SC-N_2O) estimate for that year. To obtain a present value estimate, the monetized stream of future non-CO_2 GHG benefits are discounted back to the analysis year using the same discount rate used to estimate the social cost of the non-CO_2 GHG emission changes. In addition, the limitations for the SC-CO_2 estimates discussed above likewise apply to the SC-CH_4 and SC-N_2O estimates, given the consistency in the methodology.

The EPA recently conducted a peer review of the application of the Marten et al. (2014) non-CO_2 social cost estimates in regulatory analysis and received responses that supported this application. Three reviewers considered seven charge questions that covered issues such as the EPA's interpretation of the Marten et al. estimates, the consistency of the estimates with the SC-CO_2 estimates, the EPA's characterization of the limits of the GWP-approach to value non-CO_2 GHG impacts, and the appropriateness of using the Marten et al. estimates in regulatory impact analyses. The reviewers agreed with the EPA's interpretation of Marten et al.'s estimates; generally found the estimates to be consistent with the SC-CO_2 estimates; and concurred with the limitations of the GWP approach, finding directly modeled estimates to be more appropriate. While outside of the scope of the review, the reviewers briefly considered the limitations in the SC-CO_2 methodology (e.g., those discussed earlier in this section) and noted that because the SC-CO_2 and SC-CH_4 (SC-N_2O) methodologies are similar, the limitations also apply to the resulting SC-CH_4 (SC-N_2O) estimates. Two of the reviewers concluded that use in RIAs of the SC-CH_4 (SC-N_2O) estimates developed by Marten et al. and published in the peer-reviewed literature is appropriate, provided that the agency discusses the limitations, similar to the discussion provided for SC-CO_2 and other economic analyses. All three reviewers encouraged continued improvements in the SC-CO_2 estimates and suggested that as those improvements are realized they should also be reflected in the SC-CH_4 (SC-N_2O) estimates, with one reviewer suggesting the SC-CH_4 (SC-N_2O) estimates should lag this process. The EPA supports continued improvement in the SC-CO_2 estimates developed by the U.S. government and agrees that improvements in the SC-CO_2 estimates should also be reflected in the SC-CH_4 (SC-N_2O) estimates. The fact that the reviewers agree that the SC-CH_4 (SC-N_2O) estimates are generally consistent with the SC-CO_2 estimates that are recommended by OMB's guidance on valuing CO_2 emissions reductions, leads the EPA to conclude that use of the SC-CH_4 (SC-N_2O) estimates is an analytical improvement over excluding methane emissions from the monetized portion of the benefit cost analysis.

In light of the favorable peer review and past comments urging the EPA to value non-CO_2 GHG impacts in its rulemakings, the agency has used the Marten et al. (2014) SC-CH_4 and SC-N_2O estimates to value methane and N_2O impacts, respectively, expected from the 2022-2025 standards.

The summary of GHG (CO_2, methane, N_2O) benefits are presented for select model years and calendar years is in Chapter 12.

EPA is unaware of estimates of the social cost of HFC-134a that are analogous to the SC-CO_2, SC-CH_4, and SC-N_2O estimates discussed above. In the 2017-2025 final rulemaking, EPA used the GWP for HFC-134a to convert the emissions of this gas to CO_2 equivalents, which were then valued using the SC-CO_2 estimates. These estimates were presented in a sensitivity analysis due to the limitations associated with using the GWP approach to value changes in non-CO_2 GHG emissions.

The GWP measures the cumulative radiative forcing from a perturbation of a non-CO_2 GHG relative to a perturbation of CO_2 over a fixed time horizon, often 100 years. The GWP mainly reflects differences in the radiative efficiency of gases and differences in their atmospheric lifetimes. While the GWP is a simple, transparent, and well-established metric for assessing the relative impacts of non-CO_2 emissions compared to CO_2 on a purely physical basis, there are several well-documented limitations in using it to value non-CO_2 GHG benefits, as discussed in the 2010 SC-CO_2 TSD and previous rulemakings.[98] In particular, several recent studies found that GWP-weighted benefit estimates for methane are likely to be lower than the estimates derived using directly modeled social cost estimates for these gases. Gas comparison metrics, such as the GWP, are designed to measure the impact of non-CO_2 GHG emissions relative to CO_2 at a specific point along the pathway from emissions to monetized damages (depicted in Figure 10.4), and this point may differ across measures.

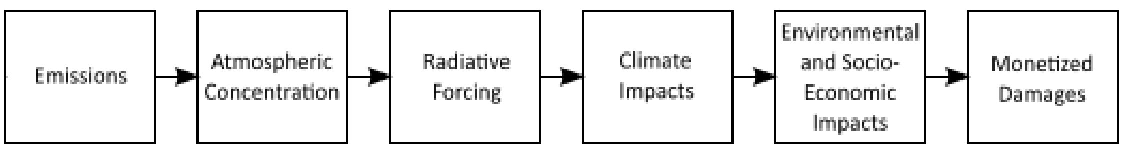

Figure 10.4 Path from GHG Emissions to Monetized Damages (Source: Marten et al., 2014)

The GWP is not ideally suited for use in benefit-cost analyses to approximate the social cost of non-CO_2 GHGs because it ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages. These can become relevant because gases have different lifetimes and the SC-CO_2 takes into account the fact that marginal damages from an increase in temperature are a function of existing temperature levels. Another limitation of gas comparison metrics for this purpose is that some environmental and socioeconomic impacts are not linked to all of the gases under consideration, or radiative forcing for that matter, and will therefore be incorrectly allocated. For example, the economic impacts associated with increased agricultural productivity due to higher atmospheric CO_2 concentrations included in the SC-CO_2 would be incorrectly allocated to methane emissions with the GWP-based valuation approach.

Also of concern is the fact that the assumptions made in estimating the GWP are not consistent with the assumptions underlying SC-CO_2 estimates in general, and the SC-CO_2 estimates developed by the IWG more specifically. For example, the 100-year time horizon usually used in estimating the GWP is less than the approximately 300-year horizon the IWG used in developing the SC-CO_2 estimates. The GWP approach also treats all impacts within the time horizon equally, independent of the time at which they occur. This is inconsistent with the role of discounting in economic analysis, which accounts for a basic preference for earlier over later gains in utility and expectations regarding future levels of economic growth.

The changes in HFC-134a emissions occur through model year 2021, at which point use of HFC-134a in new vehicles is prohibited under the Significant New Alternatives Policy (SNAP). As discussed in Chapter 5.2.9.2, EPA expects that HFC-134a will be entirely replaced by refrigerants with lower GWPs by model year 2021. In other words, there will be no further reductions in HFC-134a emissions after model year 2021. Given that this midterm review considers years after 2021, there are no changes in impacts to report for HFC-134a. See Chapter 5.2.9.2 for complete discussion, including EPA's assessment about the transition to use of low-GWP alternative refrigerants.

10.8 Benefits from Reduced Refueling Time

The total time spent pumping and paying for fuel, and driving to and from fueling stations, represents an economic cost to drivers and other vehicle occupants. Increased driving range provides a benefit to individuals arising from the value of the time saved when refueling events are eliminated. As described in this section, the EPA calculates this benefit by applying DOT-recommended values of travel time savings to estimates of how much time is saved.

The increases in fuel economy resulting from the standards are expected to lead to some increase in vehicle driving range. The extent of this increase depends on manufacturers' decisions to apply reduced fuel consumption requirements towards increasing range, rather than reducing tank size while maintaining range. For the 2012 FRM, EPA conducted a regression analysis to identify the relationship between fuel economy and fuel tank size for different vehicle classes based on historical data. Trends in fuel tank size for a number of redesigned vehicles were also investigated. Based on these analyses, fuel economy improvements were assumed to be entirely realized as improvements in driving range, due to insufficient evidence to indicate that fuel tank size is reduced as vehicle fuel economy is improved. For this Draft TAR analysis, EPA is again using the FRM assumption that fuel tank sizes remain constant; however, we will continue to monitor trends in fuel tank designs and vehicle range.

No direct estimates of the value of extended vehicle range or reduced fuel tank size are readily available. Instead, this analysis calculates the reduction in the annual amount of time a driver would spend filling its fuel tank; this reduced time could result either from fewer refueling events, if new fuel tanks stay the same size, or from less time spent filling the tank during each refueling stop, if new fuel tanks are made proportionately smaller. As discussed in Section 10.4, the average number of miles each type of vehicle is driven annually would likely increase under the regulation, as drivers respond to lower fuel expenditures (the "rebound effect"). The estimates of refueling time in effect allow for this increase in vehicle use. However, the estimate of the rebound effect does not account for any reduction in net operating costs from lower refueling time. Because the rebound effect should measure the change in VMT with respect to the net change in overall operating costs, refueling time costs would ideally factor into this calculation. The effect of this omission is expected to be minor because refueling time savings are generally small relative to the value of reduced fuel expenditures.

The savings in refueling time are calculated as the total amount of time the driver of a typical vehicle would save each year as a consequence of pumping less fuel into the vehicle's tank. The calculation also includes a fixed time per refill event of 3.5 minutes which would not occur as frequently due to the fewer number of refills.

The calculation uses the reduced number of gallons consumed by truck type and divides that value by the tank volume and refill amount to get the number of refills, then multiplies that by the time per refill to determine the number of hours saved in a given year. The calculation then applies DOT-recommended values of travel time savings to convert the resulting time savings to their economic value. The input metrics used in the EPA analysis are included in Table 10.16.

Table 10.16 Metrics Used in Calculating the Value of Refueling Time

Metric	Value
Average tank refill percentage	65%
Average tank volume	15 gallons
Fuel dispense rate	10 gal/min
Fixed time per refill	3.5 minutes
Wage rate for the value of refill time	$25.00
Number of people in vehicle	1.2
Wage growth rate, 2014 baseyear	1.1%

The equation used by EPA to calculate refueling benefits is shown below.

$$Refueling\ Benefit = \left(\frac{Gal_{reference} - Gal_{policy}}{Gal\ per\ refill}\right) \times \left(\frac{Gal\ per\ refill}{Fuel\ dispense\ rate} + time\ per\ refill\right) \times \left(\frac{\$}{hr}\right)_{labor}$$

Table 10.17 Metrics Used in Calculating the Value of Refueling Time by NHTSA

Metric	Value
Average tank refill percentage	65%
Average tank volume	15 gallons
Fuel dispense rate	10 gal/min
Fixed time per refill	3.5 minutes
Wage rate for the value of refill time	$18.07/$18.37
Number of people in vehicle	1.2
Wage growth rate, 2014 base year	1.1%

The economic value of refueling time savings was calculated by applying DOT-recommended valuations for travel time savings to estimates of how much time is saved.[HH] The value of travel time depends on average hourly valuations of personal and business time, which are functions of annual household income and total hourly compensation costs to employers. The nationwide median annual household income, $51,939 in 2013, is divided by 2,080 hours to yield an income of $25.00 per hour. The total hourly compensation cost to employers, inclusive of benefits, in 2013$ is $24.40.[II] Table 10.18 demonstrates the agency's approach to estimating the value of travel time ($/hour) for both urban and rural (intercity) driving. This approach relies on the use of DOT-recommended weights that assign a lesser valuation to personal travel time than to

[HH] https://www.transportation.gov/administrations/office-policy/2015-value-travel-time-guidance.
[II] Ibid.

business travel time, as well as weights that adjust for the distribution between personal and business travel.

Table 10.18 Estimating the Value of Travel Time for Urban and Rural (Intercity) Travel ($/hour)

Urban Travel			
	Personal Travel	**Business Travel**	**Total**
Wage Rate ($/hour)	$25.00	$24.40	-
DOT - Recommended Value of Travel Time Savings, as % of Wage Rate	50%	100%	-
Hourly Valuation (=Wage Rate * DOT-Recommended Value)	$12.50	$24.40	-
% of Total Urban Travel	95.4%	4.6%	100%
Hourly Valuation (Adjusted for % of Total Urban Travel)	$11.93	$1.12	$13.05
Rural (Intercity) Travel			
	Personal Travel	**Business Travel**	**Total**
Wage Rate ($/hour)	$25.00	$24.40	
DOT - Recommended Value of Travel Time Savings, as % of Wage Rate	70%	100%	
Hourly Valuation (=Wage Rate * DOT-Recommended Value)	$17.50	$24.40	
% of Total Rural Travel	78.6%	21.4%	100%
Hourly Valuation (Adjusted for % of Total Rural Travel)	$13.76	$5.22	$18.98

The estimates of the hourly value of urban and rural travel time ($13.05 and $18.98, respectively) shown in Table 10.18 must be adjusted to account for the nationwide ratio of urban to rural driving. By applying this adjustment (as shown in Table 10.19), an overall estimate of the hourly value of travel time – independent of urban or rural status – may be produced. Note that the calculations above assume only one adult occupant per vehicle. To fully estimate the average value of vehicle travel time, the agency must account for the presence of additional adult passengers during refueling trips. NHTSA applies such an adjustment as shown in Table 10.19; this adjustment is performed separately for passenger cars and for light trucks, yielding occupancy-adjusted valuations of vehicle travel time during refueling trips for each fleet. Note that children (persons under age 16) are excluded from average vehicle occupancy counts, as it is assumed that the opportunity cost of children's time is zero.

Table 10.19 Estimating the Value of Travel Time for Light-Duty Vehicles ($/hour)

	Unweighted Value of Travel Time ($/hour)	Weight (% of Total Miles Driven)	Weighted Value of Travel Time ($/hour)
Urban Travel	$13.05	68.2%	$8.90
Rural Travel	$18.98	31.8%	$6.03
Total	-	100.0%	$14.93
	Passenger Cars	2b3 Light Trucks	
Average Vehicle Occupancy During Refueling Trips (persons)	1.21	1.23	
Weighted Value of Travel Time ($/hour)	$14.93	$14.93	
Occupancy-Adjusted Value of Vehicle Travel Time During Refueling Trips ($/hour)	$18.07	$18.37	

10.9 Benefits and Costs from Additional Driving

10.9.1 Travel Benefit

The increase in travel associated with the rebound effect produces additional benefits to vehicle drivers, which reflect the value of the added (or more desirable) social and economic opportunities that become accessible with additional travel. The analysis estimates the economic benefits from increased rebound-effect driving as the sum of fuel expenditures incurred plus the vehicle owner/operator surplus from the additional accessibility it provides. As evidenced by the fact that vehicles make more frequent or longer trips when the cost of driving declines, the benefits from this added travel exceed added expenditures for the fuel consumed. Note that the amount by which the benefits from this increased driving exceed its increased fuel costs measures the net benefits from the additional travel, usually referred to as increased consumer surplus or, in this case, increased driver surplus. The equation for the calculation of the total travel benefit is shown below:

$$Travel\ Benefit = (VMT_{rebound})\left(\frac{\$}{mi}\right)_{policy} + \left(\frac{1}{2}\right)(VMT_{rebound})\left[\left(\frac{\$}{mile}\right)_{reference} - \left(\frac{\$}{mile}\right)_{policy}\right]$$

The agencies' analysis estimates the economic value of the increased owner/operator surplus provided by added driving using the conventional approximation, which is one half of the product of the decline in vehicle operating costs per vehicle-mile and the resulting increase in the annual number of miles driven. Because it depends on the extent of improvement in fuel economy, the value of benefits from increased vehicle use changes by model year and varies among alternative standards. Under even those alternatives that would impose the highest standards, however, the magnitude of the surplus from additional vehicle use represents a small fraction of this benefit.

10.9.2 Costs Associated with Crashes, Congestion and Noise

In contrast to the benefits of additional driving are the costs associated with that driving. If net operating costs of the vehicle decline, then we expect a positive rebound effect. Increased vehicle use associated with a positive rebound effect also contributes to increased traffic congestion, motor vehicle crashes, and highway noise. Depending on how the additional travel is distributed throughout the day and on where it takes place, additional vehicle use can contribute to traffic congestion and delays by increasing traffic volumes on facilities that are already heavily traveled during peak periods. These added delays impose higher costs on drivers and other vehicle occupants in the form of increased travel time and operating expenses. Because drivers do not take these added costs into account in deciding when and where to travel, they must be accounted for separately as a cost of the added driving associated with the rebound effect.

EPA and NHTSA rely on estimates of congestion, crash, and noise costs caused light-duty vehicles developed by the Federal Highway Administration to estimate the increased external costs caused by added driving due to the rebound effect. The FHWA estimates are intended to measure the increases in costs from added congestion, property damages and injuries in traffic crashes, and noise levels caused by various classes of vehicles that are borne by persons other than their drivers (or "marginal" external costs). EPA and NHTSA employed estimates from this source previously in the analysis accompanying the light-duty 2012-2016 vehicle rulemaking. The agencies continue to find them appropriate for this analysis after reviewing the procedures used by FHWA to develop them and considering other available estimates of these values.

FHWA's congestion cost estimates focus on freeways because non-freeway effects are less serious due to lower traffic volumes and opportunities to re-route around the congestion. The agencies, however, applied the congestion cost to the overall VMT increase, though the fraction of VMT on each road type used in MOVES range from X to Y percent of the vehicle miles on freeways for light-duty vehicles. The results of this analysis potentially overestimate the congestions costs associated with increased vehicle use, and thus lead to a conservative estimate of net benefits.

The agencies are using FHWA's "Middle" estimates for marginal congestion, crash, and noise costs caused by increased travel from vehicles. This approach is consistent with the methodology used in both LD and HD GHG rules. These costs are multiplied by the annual increases in vehicle miles travelled from the rebound effect to yield the estimated increases in congestion, crash, and noise externality costs during each future year. The values used are shown in Table 10.20.

Table 10.20 Metrics Used to Calculate the Costs Associated with Congestion, Crashes and Noise Linked to Rebound Miles Traveled

Metric	Value
Congestion	$0.0583 per mile
Crashes	$0.0252 per mile
Noise	$0.0008 per mile

10.10 Discounting Future Benefits and Costs

The benefits and costs are analyzed using 3 percent and 7 percent discount rates, consistent with current OMB guidance.[99,JJ] These rates are intended to represent consumers' preference for current over future consumption (3 percent), and the real rate of return on private investment (7 percent) which indicates the opportunity cost of capital. However, neither of these rates necessarily represents the discount rate that individual decision-makers use, nor do they reflect the rates in OMB Circular A-94 Appendix C, which are revised annually.[100] The 2015 Appendix lists real (i.e., inflation-adjusted) discount rates between 0.3 percent (for a 3-year period) and 1.5 percent (for a 30-year time horizon). All costs and benefits are discounted to 2015 except for those considered in payback analyses where costs and benefits are discounted to the first year of a vehicle's life.

[JJ] Discounting involving the Social Cost of Carbon (SC-CO_2) values uses several discount rates because the literature shows that the SC-CO_2 is quite sensitive to assumptions about the discount rate, and because no consensus exists on the appropriate rate to use in an intergenerational context (where costs and benefits are incurred by different generations). Refer to Section 10.7 for more information.

10.11 Additional Costs of Vehicle Ownership

10.11.1 Maintenance & Repair Costs

We continue to believe that the maintenance estimates used in the FRM are still reasonable and have therefore used them again in this analysis. We distinguish maintenance from repair costs as follows: maintenance costs are those costs that are required to keep a vehicle properly maintained and, as such, are usually recommended by auto makers to be conducted on a regular, periodic schedule. Examples of maintenance costs are oil and air filter changes, tire replacements, etc. Repair costs are those costs that are unexpected and, as such, occur randomly and uniquely for every driver, if at all. Examples of repair costs would be parts replacement following a crash or a mechanical failure, etc.

In Chapter 3.6 of the final joint TSD supporting the 2012 FRM, the agencies presented a lengthy discussion of maintenance costs and the impacts projected as part of that rule.[101] Table 10.21 shows the results of that analysis, the maintenance impacts used in the 2012 FRM and again in this analysis, although the costs here have been updated to 2013$. Note that the technologies shown in Table 10.21 are those for which we believe that maintenance costs would change; it is clearly not a complete list of technologies expected to meet the MY2025 standards.

Table 10.21 Maintenance Event Costs & Intervals (2013$)

New Technology	Reference Technology	Cost per Maintenance Event	Maintenance Interval (miles)
Low rolling resistance tires level 1	Standard tires	$6.71	40,000
Low rolling resistance tires level 2	Standard tires	$51.55	40,000
Diesel fuel filter replacement	Gasoline vehicle	$51.93	20,000
EV oil change	Gasoline vehicle	-$40.78	7,500
EV air filter replacement	Gasoline vehicle	-$30.16	30,000
EV engine coolant replacement	Gasoline vehicle	-$62.21	100,000
EV spark plug replacement	Gasoline vehicle	-$87.52	105,000
EV/PHEV battery coolant replacement	Gasoline vehicle	$123.37	150,000
EV/PHEV battery health check	Gasoline vehicle	$40.78	15,000

Note that many of the maintenance event costs for EVs are negative. The negative values represent savings since EVs do not incur these costs while their gasoline counterparts do. Note also that the 2010 FRM is expected to result in widespread use of low rolling resistance tires level 1 (LRRT1) on the order of 85 percent penetration. Therefore, as 2012 FRM results in increasing use of low rolling resistance tire level 2 (LRRT2), there is a corresponding decrease in the use of LRRT1. As such, as LRRT2 maintenance costs increase with increasing market penetration, LRRT1 maintenance costs decrease. The technology penetrations of these technologies are those shown in Section 12.2. The resultant maintenance costs are as shown in Section 12.4.

10.11.2 Sales Taxes

When consumers consider their total cost of ownership of a vehicle, or its potential payback, they may consider the sales taxes they have to pay at the time of purchasing the vehicle. As these costs are transfer payments, they are not included in the societal costs of the program, but they are included as one of the increased costs to the consumer for these standards when we calculate costs that the consumer pays out for vehicle ownership as part of our payback analysis. In the 2012 FRM, the agencies took the most recent auto sales taxes by state and weighted them by population by state to determine a national weighted-average sales tax of 5.46 percent.[KK] The agencies sought to weight sales taxes by new vehicle sales by state; however, such data were, and continue to be, unavailable. It is recognized that for this purpose, new vehicle sales by state is a superior weighting mechanism to Census population; in an effort to approximate new vehicle sales by state, during the 2012 FRM, a study of the change in new vehicle registrations (using R.L. Polk data) by state across recent years was conducted, resulting in a corresponding set of weights. Use of the weights derived from the study of vehicle registration data resulted in a national weighted-average sales tax rate almost identical to that resulting from the use of Census population estimates as weights, just slightly above 5.5 percent. The agencies opted to utilize Census population rather than the registration-based proxy of new vehicle sales as the basis for computing this weighted average, as the end results were negligibly different and the analytical approach involving new vehicle registrations had not been as thoroughly reviewed. We have used the same value in this Draft TAR as was used in the 2012 FRM.

10.11.3 Insurance Costs

The agencies considered the standards' impact to consumers' auto insurance expenses over vehicle lifetimes. More expensive vehicles will require more expensive collision and comprehensive (e.g., theft) car insurance. The scope of this analysis is to estimate the increased cost to the consumer for these standards, not the increase in societal costs due to collision and property damage. The increase in insurance costs was estimated from the average value of collision plus comprehensive insurance as a proportion of average new vehicle price. Collision plus comprehensive insurance represent the portion of insurance costs that depend on vehicle value. In the 2012 FRM, a study by Quality Planning provided the average value of collision plus comprehensive insurance for new vehicles, in 2010$, as $521 ($396 of which was collision and $125 of which was comprehensive).[102] The average consumer expenditure for a new passenger car in 2011, according to the Bureau of Economic Analysis was $24,572 and the average price of a new light truck was $31,721 in $2010.[103] Using sales volumes from the Bureau, we determined an average passenger car and an average light truck price was $27,953 in $2010 dollars.[104]

Dividing the cost to insure a new vehicle by the average price of a new vehicle gives the proportion of comprehensive plus collision insurance as 1.86 percent of the price of a vehicle. As vehicles' values decline with vehicle age, comprehensive and collision insurance premiums likewise decline. Data on the change in insurance premiums as a function of vehicle age are scarce; however, the agencies utilized data from the aforementioned Quality Planning study that

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[KK] See http://www.factorywarrantylist.com/car-tax-by-state.html (last accessed April 5, 2012). Note that county, city, and other municipality-specific taxes were excluded from the weighted averages, as the variation in locality taxes within states, lack of accessible documentation of locality rates, and lack of availability of weights to apply to locality taxes complicate the ability to reliably analyze the subject at this level of detail. Localities with relatively high automobile sales taxes may have relatively fewer auto dealerships, as consumers would endeavor to purchase vehicles in areas with lower locality taxes, therefore reducing the impact of the exclusion of municipality-specific taxes from this analysis.

cite the cost to insure the average vehicle on the road today (average age 10.8 years) to enable a linear interpolation of the change in insurance premiums during the first 11 years of a typical vehicle's life.[LL] To illustrate, as a percentage of the base vehicle price of $27,953, the cost of collision and comprehensive insurance in each of the first five years of a vehicle's life is 1.86 percent, 1.82 percent, 1.75 percent, 1.64 percent, and 1.50 percent, respectively, or 8.57 percent in aggregate. The agencies additionally utilized data from the same Quality Planning study that cite average insurance costs for vehicles greater than 10 years of age (for which the agencies estimated age to be 18, as this is the age at which half of vehicles in service at age 10 remain in service) to extrapolate insurance costs to age 18. Discounting is applied to future insurance payments in the model's calculations, and all calculations are adjusted by projected vehicle survival rates.

The agencies considered whether to estimate incremental comprehensive and collision insurance premiums only to year 18. As vehicles age, it becomes increasingly impractical to purchase these forms of insurance, and the Quality Planning study indicates that many owners drop these forms of insurance much earlier – in some cases upon repayment of the initial auto loan. The agencies nevertheless use the 30-year lifetime of the vehicle because we use survival-weighted values, which take into account the probability that some vehicles are no longer incurring costs because they no longer exist. This approach may tend to overstate insurance costs, because many owners are not paying insurance collision/comprehensive premiums even on vehicles that continue to exist. Therefore, the insurance premiums were age-adjusted to year 30 using the assumption that by end-of-life, no vehicle would remain on comprehensive or collision insurance. This approach provides the agencies with our estimates of the impact of insurance costs on vehicle owners based on the expected increase in MSRP resulting from the standards.

As discussed earlier, the scope of this analysis is to estimate the increased cost to the consumer in the context of our payback analysis, not the increase in societal costs or benefits.

[LL] Insurance data did not differentiate between passenger cars and light trucks. Therefore, a 30-year lifetime was assumed in this analysis. Due to several factors, among them discounting, decreased vehicle value with age, and limited vehicle survival in later years of vehicles' lifetimes, this assumption is of minimal impact on the results.

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Chapter 11:Credits, Incentives and Flexibilities

11.1 Overview

The National Program was designed with a wide range of optional flexibilities to allow manufacturers to maintain consumer choice, spur technology development, and minimize compliance costs, while achieving significant GHG and oil reductions. The National Program also includes several EPA temporary incentives that encourage the use of advanced technologies such as electric, hybrid, and fuel cell vehicles and these vehicles are also included in the performance calculations for CAFE. This section provides an overview of all of these compliance flexibilities.

Averaging, banking, and trading (ABT) provisions, including credit carry-forward and carry-back provisions, define how credits may be used and are integral to the program. ABT provisions are described in Chapter 11.2. Credits for improvements to air conditioning systems that increase efficiency and reduce refrigerant leakage, and credits for using technologies that reduce emissions and improve fuel consumption that aren't captured on EPA tests ("off-cycle" technologies) are discussed in Chapter 11.3 and 11.4, respectively. These credit opportunities currently do not sunset, remaining a part of the program through MY2025 and beyond unless the program is changed as part of a future regulatory action.

As noted above, the GHG program includes temporary incentives for advanced technology vehicles including incentives for large pickups using advanced technologies. The CAFE program also includes credits for large pickups using advanced technologies. These provisions are described below in Chapter 11.4 and 11.5. In the final rule, the agencies recognized that temporary regulatory incentives will reduce the short-term benefits of the program, but believed that it is worthwhile to have a limited short-term loss of benefits to increase the potential for far-greater game changing benefits in the longer run. The agencies also believed that the temporary regulatory incentives may help bring some technologies to market more quickly than in the absence of incentives.[1]

The use of the optional credit and incentive provisions varies from manufacturer to manufacturer (some manufacturers have not availed themselves of the extra credit options, while others have used some combination of, or all, options available under the regulations).[2] Although a manufacturer's use of the credit and incentive provisions is optional, EPA projected that the standards would be met on a fleet-wide basis by using a combination of reductions in tailpipe CO_2 and some use of the additional optional credit and incentive provisions in the regulations.[3] NHTSA is limited by its statutory authority to not include credits flexibilities in the setting of CAFE standards.

The discussion in this chapter is focused on compliance flexibilities which are integral to the National Program. There are numerous other programs at the national, state, and local level which provide incentives to consumers and manufacturers to develop, produce, and buy vehicles with advanced technologies for reducing emissions and oil use. For example, tax incentives and

HOV lane access to incentive the purchase of electrified vehicles, and loan programs to encourage investment in the development and manufacturing of advanced technologies.[A]

11.2 Averaging, Banking, and Trading Provisions

Both the CAFE and GHG programs include provisions for how credits may be used within the programs. These averaging, banking, and trading (ABT) provisions include credit carry-forward, credit carry-back (also called deficit carry-forward), credit transfers (within a manufacturer), and credit trading (across manufacturers). Credit carry-forward refers to banking (saving) credits for future use, after satisfying any needs to offset pre-existing debits within a vehicle category (car fleet or truck fleet). Credit carry-back refers to using credits to offset any deficit in meeting the fleet average standards that had accrued in a prior model year. A manufacturer may have a deficit at the end of a model year (after averaging across its fleet using credit transfers between cars and trucks)—that is, a manufacturer's fleet average level may fail to meet the required fleet average standard. The EPCA/EISA statutory framework for the CAFE program limits credit carry-forward to 5 years and credit carry-back to 3 years. Although the Clean Air Act does not include such limitations on the duration of credit provisions, in the MYs 2012–2016 and 2017-2025 programs, EPA chose to adopt 5-year credit carry-forward (generally, with an exception noted below) and 3-year credit carry-back provisions as a reasonable approach that maintained consistency between the agencies' provisions.

Although the credit carry-forward and carry-back provisions generally remain in place for MY2017 and later, EPA finalized provisions allowing all unused (banked) credits generated in MY2010–2016 (but not MY2009 early credits) to be carried forward through MY2021. See § 86.1865–12(k)(6)(ii) and 77 FR 62788. This amounts to the normal 5 year carry-forward for MY2016 and later credits, but provides additional carry-forward years for credits generated in MYs 2010–2015. Extending the life for MY2010–2015 credits provides greater flexibility for manufacturers in using the credits they have generated. This provision helps facilitate the transition to increasingly more stringent standards through MY2021 by helping manufacturers resolve lead-time issues they might face in the early model years of the program. The one-time extension of credit carry-forward also provides additional incentive for manufacturers to generate credits earlier, for example in MYs 2014 and 2015, thereby encouraging the earlier use of additional CO_2 reducing technologies. It does not change the overall CO_2 benefits of the National Program, as EPA would not expect that any of the credits at issue would otherwise have

[A] The Advanced Technology Vehicles Manufacturing (ATVM) Loan Program provides long-term, low-interest rate loans to support the domestic manufacturing of advanced technology vehicles and automotive components. The ATVM Loan Program is administered by the U.S. Department of Energy's (DOE) Loan Programs Office (LPO). It was authorized concurrently with the first Congressionally-mandated increase in CAFE standards in thirty years and was designed to ensure that rising fuel economy standards did not disadvantage domestic manufacturing.
ATVM can finance a wide range of project costs, including the construction of new manufacturing facilities; retooling, reequipping, modernizing, or expanding an existing facility in the U.S; and the engineering integration costs necessary to manufacture eligible vehicles and components.
With more than $16 billion in remaining loan authority, the ATVM program can provide the financing needed to support the manufacturing of fuel-efficient technologies and components. By comparison, commercial lenders may be unwilling to lend at rates that allow automakers and suppliers to fully build out manufacturing capacity or ensure that new facilities are located in the U.S.

been allowed to expire. Rather, the credits would be used or traded for use by other manufacturers.

Transferring credits in the EPA program refers to exchanging credits between the two averaging sets, passenger cars and light trucks, within a manufacturer. For CAFE, credit transfers can occur between compliance fleets (i.e., domestic and import passenger cars and light trucks). For example, credits accrued by over-compliance with a manufacturer’s car fleet average standard could be used to offset debits accrued due to that manufacturer not meeting the truck fleet average standard in a given year. (Put another way, a manufacturer's car and truck fleets are, in essence, a single averaging set in the EPA program). For NHTSA, transferring credits between compliance fleets is possible but must to done using an adjustment which ensures “total oil savings" are preserved because of differences in CAFE performance and standards for compliance fleets and the amount of credits which can be transferred are capped by statutory requirements.

Finally, accumulated credits may be traded to another manufacturer. Credit trading is now occurring on a regular basis for the first time in an EPA vehicle program and has existed for NHTSA since 2011. As of the end of MY2014, four manufacturers have sold credits and three manufacturers have purchased credits under the EPA program.[4] For NHTSA, since 2011, six manufacturers have traded 151 million (unadjusted) CAFE credits. Manufacturers are acquiring credits to offset immediate credit shortfalls and to bank for future compliance use. As standards become more stringent and total credit shortfalls increase, NHTSA projects an increase in credit trades and carry-forwards and a reduction in civil penalty payments as a result of these changes in flexibility usage.

The EPA ABT provisions are generally consistent with those included in the CAFE program, with a few notable exceptions. As with EPA’s approach (except for the provision just discussed above for a one-time extended carry-forward of MY2010–2016 credits), under EISA, credits generated in the CAFE program can be carried forward for 5 model years or back for 3 years, and can also be transferred between a manufacturer’s fleets or traded to another manufacturer. Transfers of credits across a manufacturer’s car and truck compliance fleets are also allowed under CAFE, but with limits established by EISA on the use of transferred credits. The amount of transferred credits that can be used in a year is limited under CAFE, and transferred credits may not be used to meet the CAFE minimum domestic passenger car standard, also per statute. CAFE allows credit trading, but again, traded credits cannot be used to meet the minimum domestic passenger car standard.[5]

The ABT provisions are an integral part of the GHG and CAFE programs and the agencies expect that manufacturers will continue to fully utilize these provisions into the future. EPA’s annual GHG Manufacturers Performance Report provides details on the use of these provisions in the GHG program thus far.[6] Details on final compliance for model year 2014 for the NHTSA and EPA programs are also summarized in Chapter 3.

11.3 Air Conditioning System Credits

There are two mechanisms by which air conditioning (A/C) systems contribute to the emissions of greenhouse gases: through leakage of hydrofluorocarbon refrigerants into the atmosphere (sometimes called “direct emissions”) and through the consumption of fuel to provide mechanical power to the A/C system (sometimes called “indirect emissions”).[7] The high global warming potential of the current automotive refrigerant, HFC-134a, means that leakage of a small amount of refrigerant will have a far greater impact on global warming than emissions of a similar amount of CO_2. The impacts of refrigerant leakage can be reduced significantly by systems that incorporate leak-tight components, or, ultimately, by using a refrigerant with a lower global warming potential. The A/C system also contributes to increased tailpipe CO_2 emissions through the additional work required to operate the compressor, fans, and blowers. This additional power demand is ultimately met by using additional fuel, which is converted into CO_2 by the engine during combustion and exhausted through the tailpipe. These emissions can be reduced by increasing the overall efficiency of an A/C system, thus reducing the additional load on the engine from A/C operation, which in turn means a reduction in fuel consumption and a commensurate reduction in GHG emissions.

Manufacturers may generate credits for improved A/C systems in complying with the CO_2 fleet average standards in the MY2012 and later model years. Manufacturers may generate fuel consumption improvement credits for A/C efficiency improvement under the CAFE program equivalent to the CO_2 credits beginning in MY2017. EPA expected manufacturers to generate A/C credits and accounted for those credits in developing the final CO_2 standards by adjusting the standards to make them more stringent. EPA's A/C credits program is also related to EPA action under the Significant New Alternatives Policy (SNAP) program which on July, 20, 2015 changed the listing status of HFC-134a to unacceptable for newly manufactured light-duty vehicles beginning with MY2021 due to the refrigerant's high global warming potential (GWP).[8] This action effectively requires auto manufacturer's to choose an alternative refrigerant with a lower GWP beginning with MY2021. Prior to MY2021, the use of low GWP refrigerants in light-duty vehicles is encouraged by EPA's credit program. A detailed discussion of A/C credits and technologies is provided in Chapter 5.2.

11.4 Off-cycle Technology Credits

“Off-cycle” emission reductions can be achieved by employing technologies that result in real-world benefits, but where that benefit is not adequately captured on the test procedures used by manufacturers to demonstrate compliance with emission standards. EPA’s light-duty vehicle greenhouse gas program acknowledges these benefits by giving automobile manufacturers several options for generating “off-cycle” technology CO_2 credits. Starting in MY2017, manufacturers may also generate equivalent fuel consumption improvement credits in the CAFE program.

There are three pathways by which a manufacturer may accrue off-cycle technology credits. The first is a predetermined list or “menu” of credit values for specific off-cycle technologies that may be used beginning for model year 2014.[9] This pathway allows manufacturers to use conservative credit values established by EPA for a wide range of off-cycle technologies, with minimal data submittal or testing requirements. In cases where additional laboratory testing can demonstrate emission benefits, a second pathway allows manufacturers to use a broader array of emission tests (known as “5-cycle” testing because the methodology uses five different testing procedures) to demonstrate and justify off-cycle CO_2 credits.[10] The additional emission tests allow emission benefits to be demonstrated over some elements of real-world driving not captured by the GHG compliance tests, including high speeds, rapid accelerations, and cold temperatures. Credits determined according to this methodology do not undergo additional public review. The third and last pathway allows manufacturers to seek EPA approval to use an alternative methodology for determining the off-cycle technology CO_2 credits.[11] This option is only available if the benefit of the technology cannot be adequately demonstrated using the 5-cycle methodology. Manufacturers may also use this option for model years prior to 2014 to demonstrate off-cycle CO_2 reductions for off-cycle technologies that are on the menu, or to demonstrate reductions that exceed those available via use of the menu. As with other emissions controls, off-cycle technologies are subject to full useful life requirements.

Chapter 5.2 provides a detailed description of the off-cycle technology program including what off-cycle technologies manufacturers have used to date to generate credits and the magnitude of those credits. Chapter 5.2 also discusses how the agencies have considered off-cycle credits in the Draft TAR analysis.

11.5 Incentives for Advanced Technology Vehicles

EPA included incentives for advanced technologies to promote the commercialization of technologies that have the potential to transform the light-duty vehicle sector by achieving zero or near-zero GHG emissions and oil consumption in the longer term, but which face major near-term market barriers. Providing temporary regulatory incentives for certain advanced technologies will decrease the overall GHG emissions reductions associated with the program in the near term. However, in setting the 2017-2025 standards, EPA believed it is worthwhile to forego modest additional emissions reductions in the near term in order to lay the foundation for the potential for much larger ‘‘game-changing’’ GHG emissions and oil reductions in the longer term. EPA also believed that temporary regulatory incentives may help bring some technologies to market more quickly than in the absence of incentives. See 77 FR 62811 et seq. EPA accounts for the higher real world GHG emissions and lower GHG emissions reductions associated with these temporary regulatory incentives in all of our regulatory analyses, as well as in this Draft TAR.

A multiplier incentive is available for MY2017-2021 electric vehicles (EVs), plug-in hybrid electric vehicles (PHEVs), fuel cell vehicles (FCVs) and compressed natural gas (CNG) vehicles.[12] The multiplier allows a vehicle to “count” as more than one vehicle in the manufacturer’s compliance calculation. Table 11.1 provides the multipliers for the various vehicle technologies included in the 2012 final rule for MY2017-2021 vehicles.[13] Since the GHG performance for these vehicle types is significantly better than that of conventional vehicles, the multiplier provides a significant benefit to the manufacturer. The specific multiplier levels were picked to be large enough to provide a meaningful incentive, but not be so large as to promote vehicles being produced only to take advantage of the incentive. The multipliers for EVs and FCVs are larger because they face greater market barriers.

Table 11.1 Incentive Multipliers for EV, FCV, PHEVs, and CNG Vehicles

Model Years	EVs and FCVs	PHEVs and CNG
2017-2019	2.0	1.6
2020	1.75	1.45
2021	1.5	1.3

Although EPA does not view CNG as a game changing technology from a GHG tailpipe emissions perspective, EPA included a multiplier incentive for dedicated and dual-fueled CNG vehicles because EPA considered investments in CNG technology and refueling infrastructure to be a valuable, indirect step towards hydrogen FCVs, which can be a game-changer in terms of GHG emissions.[14] In this way, EPA believed that CNG could be a critical facilitator of a next-generation technology.

EPA included a second incentive for EVs, PHEVs, and FCVs by allowing temporary and limited 0 g/mile treatment of the electric operation of those vehicles.[15] The tailpipe GHG emissions from EVs, from PHEVs operated on grid electricity, and from hydrogen-fueled FCVs are zero, and traditionally the emissions of the vehicle itself are all that EPA takes into account for purposes of compliance with standards set under Clean Air Act section 202(a). Focusing on vehicle tailpipe emissions has not raised any issues for criteria pollutants, as upstream criteria emissions associated with production and distribution of the fuel are addressed by comprehensive regulatory programs focused on the upstream sources of those emissions. At the time of the final rule, however, there was no such comprehensive program addressing upstream emissions of GHGs,[16] and the upstream GHG emissions associated with production and distribution of electricity are higher, on a national average basis, than the corresponding upstream GHG emissions of gasoline or other petroleum based fuels.

Therefore, EPA placed limits on the use of 0 g/mile for MY2022-2025 vehicles and the use of 0 g/mile is currently not allowed after MY2025. EPA included per-company vehicle production caps for use of 0 g/mile in MYs 2022–2025, and 0 g/mile cannot be used for production that exceeds these caps. The cumulative per-company caps for MYs 2022–2025 are 600,000 EV/PHEV/FCVs for those manufacturers that produce a total of 300,000 or more EV/PHEV/FCVs in MYs 2019–2021, and 200,000 EV/ PHEV/FCVs for all other manufacturers. The structure of these per-company caps was based on a balancing of promoting game-changing technologies, while minimizing the short-term loss in overall GHG savings. Once the production cap is met, the manufacturer must include net upstream emissions associated with electricity generation on a g/mile basis in their compliance calculations. Currently, U.S. annual sales of advanced technology vehicles are well below the per manufacturer thresholds. Tesla's 2015 annual sales are estimated to be just under 26,000 vehicles and GM, Ford, and Nissan 2015 sales were in the 17,000-19,000 vehicles per year range.[17]

The final rule provides a methodology for determining the net upstream GHG emissions value to be assigned to a vehicle for purposes of vehicle certification and compliance calculations.[18] EPA concluded in the MY2017-2025 final rule that the "compliance treatment finalized for EV/PHEV/FCVs strikes a reasonable balance between promoting the commercialization of EV/PHEV/FCVs, which have the potential to achieve game-changing GHG emissions reductions in the future, and accounting for upstream emissions once such vehicles reach a reasonable threshold in the market." [19]

EPA recognized that the mid-term evaluation would provide an opportunity to review the status of advanced vehicle technology commercialization, the status of upstream GHG emissions control programs, and other relevant factors.[20] At the time of the MY2017-2025 final rule, part of the rationale for including upstream emissions associated with electricity production, for production volumes in excess of the per-company production volume caps, was because these upstream GHG emissions values are generally higher than the upstream GHG emissions values associated with gasoline vehicles, and because there was then no federal program in place to reduce GHG emissions from electric power plants. EPA also stated that in the future, if there were a program to comprehensively address upstream GHG emissions, then the zero tailpipe levels from these vehicles have the potential to contribute to very large GHG reductions, and to transform the transportation sector's contribution to nationwide GHG emissions (as well as oil consumption).

Since the MY2017-2025 final rule, EPA has adopted GHG controls for electricity generation. On August 3, 2015, EPA issued final GHG emissions regulations addressing both existing (referred to as the Clean Power Plan[21]) and new electricity generating units. These rules are expected to markedly decrease GHG emissions associated with future electricity generation. In the MY2017-2025 final rule, EPA used the Office of Atmospheric Programs' Integrated Planning Model, along with assumptions for the 2030 timeframe about total light-duty vehicle demand for electricity, geographical distribution of EVs and PHEVs, and on-peak versus off-peak charging, to project that the average power plant electricity GHG emissions factor in 2030 for vehicle electricity use would be 0.445 grams/watt-hour.[22] The overall vehicle electricity GHG emissions factor was projected to be 0.534 grams/watt-hour when using a multiplicative value of 1.20 to account for feedstock-related GHG emissions upstream of the power plant. EPA is currently exploring whether there are appropriate updates to these projected emissions factors for the incremental electricity that would be necessary for electric vehicle operation in the 2030 timeframe, which we plan to assess in more detail further during the midterm evaluation process. EPA also plans to develop a similar methodology for net upstream GHG emissions associated with hydrogen fuel production and distribution.

11.6 Advanced Technology Incentives for Large Pickups

The agencies recognized that the MY2017–2025 standards will be challenging for large vehicles, including full-size pickup trucks that are often used for commercial purposes. In the MY2017-2025 final rule, EPA and NHTSA included a per-vehicle credit provision for manufacturers that hybridize a significant number of their full-size pickup trucks, or use other technologies that comparably reduce CO_2 emissions and fuel consumption. The agencies' goal was to incentivize the penetration into the marketplace of ''game changing'' technologies for these pickups. The incentives provide an opportunity in the program's early years to begin penetration of advanced technologies into this category of vehicles, and in turn creates more opportunities for achieving the more stringent later year standards. Full-size pickup trucks using mild hybrid technology will be eligible for a per-truck 10 g/mi CO_2 credit (equivalent to 0.0011 gal/mi for a gasoline-fueled truck) during MYs 2017–2021. Full-size pickup trucks using strong hybrid technology will be eligible for a per-truck 20 g/mi CO_2 credit (0.0023 gal/mi) during MYs 2017–2025.[23] Eligibility for both the mild and strong hybrid credit is dependent on the manufacturer reaching the minimum technology penetration thresholds discussed below. The agencies established definitions for full-size pickup and mild and strong hybrid for the program.[24]

Alternatively, manufacturers may generate performance-based credits for full-size pickups. This performance-based credit is 10 g/mi CO_2 (equivalent to 0.0011 gal/mi for the CAFE program) or 20 g/mi CO_2 (0.0023 gal/mi) for full-size pickups achieving 15 percent or 20 percent, respectively, better CO_2 than their footprint-based targets in a given model year.[25,26] This second option incentivizes other, non-hybrid, advanced technologies that can reduce pickup truck GHG emissions and fuel consumption at rates comparable to strong and mild hybrid technology. These performance-based credits have no specific technology or design requirements; automakers can use any technology or set of technologies as long as the vehicle's

CO_2 performance is at least 15 or 20 percent below the vehicle's footprint-based target. However, a vehicle cannot receive both hybrid and performance-based credits, since that would be double-counting.

The 10 g/mi performance-based credit is available for MYs 2017 to 2021. In recognition of the nature of automotive redesign cycles, a vehicle model meeting the requirements in a model year will receive the credit in subsequent model years through 2021 unless its CO_2 level increases or its production level drops below the penetration threshold described below, even if the year-by-year reduction in standards levels causes the vehicle to fall below the 15 percent over-compliance threshold. Not doing so would reduce substantially the incentive to introduce advanced technology in earlier model years if the incentive wasn't available for the design cycle period. The 10 g/mi credit is not available after MY2021 because the stringency of the post-MY2021 standards quickly overtake designs that were originally 15 percent over-compliant, making the awarding of credits to them inappropriate. See also 80 FR at 40253 (advanced technology credits from phase 1 heavy duty GHG rules inappropriate for phase 2, since these technologies are now part of the compliance basis for the proposed phase 2 standards). The 20 g/mi CO_2 performance-based credit will be available for a maximum of 5 consecutive model years (the typical redesign cycle period) within the 2017 to 2025 model year period, provided the vehicle model's CO_2 level does not increase from the level determined in its first qualifying model year, and subject to the technology penetration requirement described below. A qualifying vehicle model that subsequently undergoes a major redesign can requalify for the credit for an additional period starting in the redesign model year, not to exceed 5 model years and not to extend beyond MY2025.[27]

Access to any of these large pickup credits requires that the technology be used on a minimum percentage of a manufacturer's full-size pickups.[28] These minimum percentages, established in the 2012 final rule, are set to encourage significant penetration of these technologies, leading to long-term market acceptance. Meeting the penetration threshold in one model year does not ensure credits in subsequent years; if the production level in a model year drops below the required threshold, the credit is not earned for that model year. The required penetration levels are shown in the table below.[29]

Table 11.2 Penetration Rate Requirements by Model Year for Full-size Pickup Credits (% of Production)

	2017	2018	2019	2020	2021	2022	2023	2024	2025
Strong hybrid	10	10	10	10	10	10	10	10	10
Mild Hybrid	20	30	55	70	80	N/A	N/A	N/A	N/A
20% better performance	10	10	10	10	10	10	10	10	10
15% better performance	15	20	28	35	40	N/A	N/A	N/A	N/A

11.7 Harmonized CAFE Incentives and Flexibilities

Since issuing standards in the October 2012 final rule (see 77 FR 62624) for model year 2017 to 2025 light duty vehicles, the Alliance of Automobile Manufacturers and some individual automobile manufacturers have reached out to NHTSA to discuss several programmatic differences between NHTSA's CAFE and EPA's GHG programs. Many of the incentives and flexibilities available under the EPA program are not statutorily available to the CAFE program because of prescribed limitations establish by Congress in EISA and EPCA. The issues identified by the Alliance are contained in a presentation shared with NHTSA, available in NHTSA's docket.

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[4] Greenhouse Gas Emission Standards for Light-duty Vehicles, Manufacturer Performance Report for the 2014 Model Year, EPA-420-R-15-026, December 2015.
[5] See generally 49 U.S.C. § 32903.
[6] Greenhouse Gas Emission Standards for Light-duty Vehicles, Manufacturer Performance Report for the 2014 Model Year, EPA-420-R-15-026, December 2015.
[7] 40 CFR 1867-12 and 40 CFR 86.1868-12.
[8] 80 FR 42870, July 20, 2015.
[9] See 40 CFR 86.1869-12(b).
[10] See 40 CFR 86.1869-12(c).
[11] See 40 CFR 86.1869-12(d).
[12] 77 FR 62810, October 15, 2012.
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[16] EPA had proposed but had not yet adopted a New Source Performance Standard for greenhouse gas emissions from new electricity generating units, see 77 FR 22392.
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[27] 77 FR 62826, October 15, 2012.
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[29] 40 CFR 86.1870-12.

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Chapter 12:EPA's Analysis of the MY2022-2025 GHG Standards

This chapter documents EPA's initial analysis of the impacts of the MY2022 through 2025 GHG emission standards for light duty vehicles. While the Draft TAR is not a policy or decision document, EPA believes it is important to present our updated assessment of the potential effects of the changes that have been observed since the 2012 FRM to the light-duty automobile market on the MY2022 to 2025 greenhouse gas program. In Section 12.1, EPA presents the inputs and the outputs of our OMEGA analysis. This includes the CO_2 targets and achieved levels in meeting the MY2022-2025 standards, along with the associated costs per vehicle and technology penetrations for a central set of input values and several sensitivity cases. This section also includes payback metrics associated with increased vehicle purchase costs countered by increased fuel savings to illustrate how long it takes for those fuel savings to "pay back" the higher upfront costs. In Section 12.2, EPA presents our estimates of emission inventory impacts, including CO_2 and other GHGs and criteria pollutants, and impacts on fuel consumption. In Section 12.3, EPA presents our draft benefit cost analysis (BCA) for both our model year lifetime analysis (BCA considering the full lifetimes of MY2021-2025 vehicles) and our calendar year analysis (BCA considering the calendar years 2021 through 2050).

The MY2022 through 2025 GHG standards will significantly reduce harmful GHG emissions. CO_2 emissions from automobiles are the product of fuel combustion and, consequently, reducing CO_2 emissions will also achieve a significant reduction in projected fuel consumption. EPA's projections of these impacts are also shown in this chapter. Because of anticipated changes to driving behavior and fuel production, co-pollutant emissions would also be affected by the standards. This analysis quantifies the impacts on GHGs, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and hydrofluorocarbons (HFC-134a); impacts on "criteria" air pollutants, including carbon monoxide (CO), fine particulate matter ($PM_{2.5}$), sulfur dioxide (SO_2), and the ozone precursors hydrocarbons (VOC) and oxides of nitrogen (NO_x); and impacts on several air toxics, including benzene, 1,3-butadiene, formaldehyde, acetaldehyde, and acrolein.

This chapter describes the methods used by EPA in its analysis. Detailed discussion of the inputs to this analysis are found elsewhere in this Draft TAR (e.g., baseline fleet development is in Chapter 4, technology costs and effectiveness are in Chapter 5, VMT, rebound effect, and other economic inputs are in Chapter 10). Chapter 4 also includes a discussion of how the ZEV program is characterized in our analysis fleet which includes over 400,000 ZEV program vehicles by MY2025. Note that if the GHG assessment did not consider the California ZEV program and the adoption of that program by several states across the country, then our assessment of the technology pathways for meeting the 2022-2025 standards would likely show higher penetrations of other more advanced technologies, such as mild and strong hybrids.

All OMEGA input and output files for runs presented in this Chapter, and all input and output files supporting the inventories, benefits and costs presented here are in the EPA docket and are available on EPA's website at https://www3.epa.gov/otaq/climate/models.htm.[1]

12.1 EPA's Estimates of Costs per Vehicle & Technology Penetrations Based on OMEGA

As in the analysis of the MYs 2017-2025 rulemaking (the 2012 FRM), our evaluation here includes identifying potentially available technologies and assessing their effectiveness, cost, and impacts. The wide number of technologies that are available, and likely to be used in combination, requires a method to account for their combined cost and effectiveness, as well as estimates of their availability to be applied to vehicles. The methodologies and tools applied in this Draft TAR are largely unchanged since the 2012 FRM. The inputs to the process have changed significantly to reflect all of the research and analysis that EPA has performed as part of the development of this Draft TAR.

As done in establishing the GHG standards for MY2012-2016 and 2017-2025, EPA is using a computerized program called the Optimization Model for reducing Emissions of Greenhouse gases from Automobiles (OMEGA). Broadly, OMEGA starts with a description of the future vehicle fleet, including manufacturer, sales, base CO_2 emissions, vehicle footprint, and an assessment of which GHG emissions-reducing technologies are already employed on the vehicles. For the purpose of this analysis, EPA uses OMEGA to analyze roughly 200 vehicle platforms which encompass approximately 1,300 vehicle models to capture the important differences in vehicle and engine design and utility of future vehicle sales of roughly 15-17 million units annually in the 2021-2025 timeframe.[A] The model is then provided with a list of technologies applicable to various types of vehicles, along with the technologies' cost and effectiveness and the percentage of vehicle sales that we estimate can be applied to each technology during the redesign period. The model combines this information with economic parameters, such as fuel prices and discount rates, to project how various manufacturers could apply the available technology in order to meet increasing levels of GHG emissions control. The result is a description of which technologies could be added to each vehicle and vehicle platform, along with the resulting costs and achieved CO_2 levels. The model can also be set to account for some types of compliance flexibilities.[B]

EPA has described OMEGA's specific methodologies and algorithms previously in the model documentation.[2] The model is publicly available on the EPA website,[3] and it has been peer reviewed.[4] Emission control technology can be applied individually or in groups, often called technology "packages." The OMEGA user specifies the cost and effectiveness of each technology or package for a specific "vehicle type," such as midsize cars with V6 engines or large trucks with V8 engines. The user can limit the application of a specific technology to a

[A] The MY2014 baseline fleet used in this analysis actually consists of over 2000 vehicle models, but many of those are only minor variations of others (generally a minor footprint--a vehicle's footprint is the product of its track width and wheelbase, usually specified in terms of square feet--variation of 0.1 square feet due to, for example, different wheel and/or tire applications). For simplicity here, we do not focus on those minor variations although our modeling does indeed make use of those variations since a different footprint results in a different target for any given vehicle.

[B] While OMEGA can apply technologies which reduce CO_2 efficiency related emissions and refrigerant leakage emissions associated with air conditioner use, this task is currently handled outside of the OMEGA core model. A/C improvements are highly cost-effective, and would always be added to vehicles by the model, thus they are simply added into the OMEGA results at the projected penetration levels (see Table 12-6) for each manufacturer.

specified percentage of each vehicle's sales (i.e., a "maximum penetration cap"). The effectiveness, cost, and any application limits of each technology package can also vary over time.[C] A list of technologies or packages is provided to OMEGA for each vehicle type, providing the connection to the specific vehicles being modeled. Appendix C includes more details on the OMEGA model and approaches used in OMEGA, such as the building of technology packages, a detailed description of the technology packages, and the mapping of the fleet into vehicle types and classes, etc.

For each manufacturer, OMEGA applies technology (subject to any appropriate penetration caps, as discussed in Appendix C) to vehicles until the sales and VMT-weighted emission average complies with a given standard or until all the available technologies have been applied. OMEGA allows the input of a standard which can be in the form of a flat standard applicable to all vehicles within a vehicle class (e.g., cars, trucks or both cars and trucks). Alternatively, the GHG standard can be in the form of a linear or constrained logistic function, which sets each vehicle's CO_2 target as a function of a vehicle attribute, such as footprint (vehicle track width times wheelbase). When the linear form of footprint-based standard is used, the "line" can be converted to a flat standard for footprints either above or below specified levels. This is referred to as a piece-wise linear standard, and was used in modeling the footprint-based standards in this analysis.

The OMEGA model is designed to estimate the cost of complying with a standard (or target) in a given future year. While the OMEGA design assumes that a manufacturer's entire fleet of vehicles can be redesigned within one redesign cycle, it is unlikely that a manufacturer will redesign the exact same percentage of its vehicle sales in each and every model year. The base emissions and emission reductions of the vehicles being redesigned will vary. Thus, OMEGA inherently assumes the averaging and banking of credits--such credits differ from off-cycle credits--to enable compliance with standards in the intermediate years of a redesign cycle using the technology projected for the final year of the cycle, assuming that the intermediate standards require gradual improvement each year.[D,E] This assumption has been confirmed by compliance data from the 2012-2016 MY light duty vehicle standards, which reflect robust use of averaging by the manufacturers. We also allow for transfer of credits between cars and trucks within each

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[C] "Learning," as discussed in Chapter 5.3, is the process whereby the cost of manufacturing a certain item tends to decrease with increased production volumes. While OMEGA does not explicitly incorporate "learning" into the technology cost estimation procedure, the user can currently simulate learning by inputting lower technology costs in each subsequent redesign cycle.

[D] ABT credits have to do with averaging under- and over-compliance with the standards. Over-compliance somewhere allows for under-compliance somewhere else provided "on-average" a fleet complies. If over-compliance exceeds under-compliance in any given year, those over-compliance credits can be banked for future use within the framework and restrictions of the given program. Trading allows for trading of credits between entities, presumably at a cost to the recipient and a financial gain to the provider. Off-cycle credits are real CO2 reductions that would occur in-use, or the real world, but that are not measured on the 2-cycle test upon which fuel economy regulations have long been based.

[E] EPA considered modeling credit banking as part of this analysis, but decided that the central analysis would not analyze the program using this approach for two reasons. First, since the GHG standards continue indefinitely, rather than expiring in 2025, EPA wants to represent the cost of bringing vehicles into compliance with the standards in MY2025. Second, consistent with the design of the OMEGA model, EPA is not using the OMEGA model to project changes on a year-by-year basis, which could be an important element of explicitly modeling credit banking.

manufacturer's fleet allowing the more cost effective of the car/truck fleets to "assist" the other in compliance.

EPA has typically used a 5 year redesign cycle in OMEGA. As such, in the control case for this analysis, some portion of the fleet is estimated for redesign to the MY2025 standards in MY2021. This in turn results in the achieved CO_2 level in the control case in MY2021 being lower than the target level for that model year. We explain in section 12.1.1.1.2 the process used to generate the control case standards in MY2021.

Once technology has been added so that every manufacturer meets the specified targets (or exhausts all of the available technologies), the model produces a variety of output files. The files include information about the specific technology added to each vehicle and the resulting costs and emissions levels. Average costs and emissions per vehicle by manufacturer and industry-wide are also determined for each vehicle fleet (car and truck).

Throughout the discussion of EPA's analysis results is mention of a "reference case" and a "control case." Since the purpose of this Draft TAR is to assess issues relevant to the MY2022-2025 standards, the reference case refers to a situation where the future fleet continues to comply with the MY2021 standards indefinitely. Note that EPA's "baseline fleet" (as described in Chapter 4.1) is based on the MY2014 fleet with sales projections going forward through the year 2030. That fleet, by definition, complies with the 2014 standards in MY2014 but not necessarily in MY2025.[F] That "baseline fleet" is contrasted by the "reference case fleet" which adds additional technology to bring the "baseline fleet" into compliance with the reference case, or 2021 standards. That "reference case fleet" would then continue meeting the reference case standards (i.e., the MY 2021 standards) indefinitely. The "control case" refers to any situation where the future fleet complies with the MY2022 through MY2025 standards, and then with the MY2025 standards indefinitely thereafter. The difference between these two cases is the incremental effect of the standards (or "delta"). We use "central analysis" control case to specifically refer to the MY2022-2025 standards established in the 2012 FRM and as analyzed using what EPA considers to be the central set of input values (e.g., AEO 2015 reference case fuel prices are considered to be part of the central analysis).[G] The general term "control case" can be used for any control case whether it be the central case or a sensitivity case (e.g., AEO 2015 high or low fuel prices are used in sensitivities). As such, while there are several control cases, one control case is actually considered to be the central control case. Sensitivity analyses use different inputs that can vary the analytical outcomes.

Finally, EPA decided to complete three analysis scenarios built around the AEO 2015 estimates for future fuel prices (see Chapter 10.2). These future fuel price scenarios include a low, reference and high fuel price forecast. EPA is treating the reference fuel price forecast as its central analysis case. These fuel price scenarios are also reflected in the development of the baseline fleet as described in Chapter 4.

[F] Given the fleet changes projected by the year 2025, that fleet in fact does not comply with the MY2014 standards in MY2025.

[G] Throughout the discussion presented here in Chapter 12, any reference to "AEO" is meant to refer to "AEO2015."

12.1.1 Central Analysis Results

The central analysis uses the AEO 2015 reference fuel price case and, thus, the AEO 2015 reference fuel price based fleet. The central case also uses both indirect cost multipliers (ICMs) and retail price equivalents (RPEs) as a means of estimating the indirect costs of technologies. The central analysis consists of a reference case representing a future fleet complying with the MY2021 standards indefinitely, and a control case representing a future fleet complying with the MY2022 to 2025 standards in those respective model years, and then with the MY2025 standard indefinitely.

12.1.1.1 CO_2 Targets and Achieved Values

The central analysis uses two approaches for reflecting indirect costs, both ICMs and RPEs as discussed in Chapter 5. Because there are differences in the technology costs for the ICM and RPE cases, which result in slightly different technology penetrations and car/truck credit transfers, these differences lead to differences in the CO_2 Achieved levels in the ICM compared to RPE cases, as shown below. Technology costs are presented in Section 12.1.1.2, and technology penetration rates are presented in Section 12.1.1.3.

Note that the GHG standards (i.e., the standard curves) apply to individual vehicles. Depending on the footprint and model year of that individual vehicle, its target value can be determined by selecting the appropriate standard curve. A fleet of vehicles—whether a car/truck fleet, a given manufacturer's fleet, or the entire fleet—complying with its individual targets (determined by the standard curves) while giving consideration to the sales, or sales weighting, of each would result in a target value for that given fleet. We present here the fleetwide target values for each manufacturer's car fleet, the entire car fleet, each manufacturer's truck fleet, and the entire truck fleet. These target values are not the standards but rather the sales-weighted CO_2 emissions of each particular fleet assuming that individual vehicles comply with their respective footprint targets.

12.1.1.1.1 <u>Reference Case</u>

The reference case represents the fleet meeting the MY2021 standards in MYs 2021 and thereafter. We present the reference case CO_2 targets and projected achieved levels in MY2021 in Table 12.1. We present the reference case CO_2 targets and projected achieved levels in MY2025 in Table 12.2. While both tables represent the same set of reference case standards, the target and achieved CO_2 levels reflect differences, which are attributed to fleet changes between MYs 2021 and 2025.

Table 12.1 Reference Case Targets and Achieved CO_2 in MY2021 in the Central Analysis (g/mi CO_2)

Manufacturer	Car Target	Truck Target	Fleet Target	Car Achieved, ICM	Truck Achieved, ICM	Fleet Achieved, ICM	Car Achieved, RPE	Truck Achieved, RPE	Fleet Achieved, RPE
BMW	178.6	237.5	194.4	182.7	227.7	194.8	183.3	226.5	194.9
FCA	182.4	246.0	227.1	194.1	241.5	227.5	196.4	240.9	227.7
Ford	179.8	280.3	239.3	198.3	268.7	240.0	203.2	266.5	240.7
GM	178.7	277.2	230.1	197.8	262.2	231.4	197.2	262.7	231.4
Honda	172.5	231.0	201.0	176.5	226.5	200.8	176.7	226.5	200.9
Hyundai/Kia	177.0	227.2	183.3	178.9	215.4	183.5	179.8	210.7	183.7
JLR	189.7	235.4	226.8	169.7	239.4	226.2	172.8	238.8	226.3
Mazda	175.5	223.1	189.9	181.3	211.6	190.5	177.1	219.1	189.8
Mercedes-Benz	180.3	237.5	204.0	179.6	237.8	203.7	177.9	240.3	203.7
Mitsubishi	164.7	208.4	181.5	180.1	185.2	182.0	178.8	189.1	182.7
Nissan	173.6	241.9	202.4	179.1	235.1	202.7	179.8	234.1	202.7
Subaru	170.0	210.6	201.6	206.5	201.8	202.8	215.2	198.9	202.5
Tesla	205.7	0.0	205.7	0.0	0.0	0.0	0.0	0.0	0.0
Toyota	174.4	247.3	209.1	173.1	248.3	208.9	173.0	247.7	208.5
Volkswagen	174.0	231.1	196.6	170.4	235.7	196.2	169.1	237.1	196.0
Volvo	182.0	227.7	206.4	193.4	219.2	207.1	191.6	220.5	207.0
Fleet	177.0	251.5	213.8	182.2	244.5	213.0	183.0	243.8	213.1

Note: Fleet values are sales weighted but not VMT weighted.

Table 12.2 Reference Case Targets and Achieved CO_2 in MY2025 in the Central Analysis (g/mi CO_2)

Manufacturer	Car Target	Truck Target	Fleet Target	Car Achieved, ICM	Truck Achieved, ICM	Fleet Achieved, ICM	Car Achieved, RPE	Truck Achieved, RPE	Fleet Achieved, RPE
BMW	177.5	237.0	191.7	180.3	229.2	192.0	180.1	229.8	191.9
FCA	182.3	247.2	227.9	189.6	244.6	228.2	192.0	243.7	228.3
Ford	179.6	280.0	237.9	196.4	269.5	238.9	198.5	268.4	239.1
GM	178.8	277.3	227.9	197.1	261.6	229.3	197.5	260.8	229.1
Honda	172.8	232.9	200.8	175.9	229.9	201.1	178.6	227.2	201.3
Hyundai/Kia	177.1	227.9	183.1	179.0	214.5	183.2	178.3	213.5	182.5
JLR	189.7	235.0	225.5	170.8	239.0	224.7	167.4	239.0	224.1
Mazda	175.2	223.4	190.0	177.6	218.1	190.0	177.9	218.1	190.2
Mercedes-Benz	180.0	237.0	201.7	180.4	236.4	201.7	178.3	239.3	201.5
Mitsubishi	164.8	208.4	180.4	179.2	186.4	181.8	178.4	187.6	181.7
Nissan	173.3	243.0	200.9	177.2	237.0	200.9	177.8	237.1	201.2
Subaru	170.0	210.5	201.4	210.6	200.3	202.6	213.0	199.5	202.6
Tesla	205.7	0.0	205.7	0.0	0.0	0.0	0.0	0.0	0.0
Toyota	174.5	246.3	207.0	174.6	246.2	207.0	170.2	250.5	206.6
Volkswagen	174.6	230.4	195.7	170.1	236.3	195.1	168.9	237.6	194.9
Volvo	182.0	227.7	205.8	188.3	222.7	206.2	187.5	222.6	205.8
Fleet	176.9	251.3	212.4	181.0	244.8	211.4	180.9	244.7	211.3

Note: Fleet values are sales weighted but not VMT weighted.

12.1.1.1.2 Control Case

The central analysis control case represents the fleet meeting the MY2022 through MY2025 standards in their respective model years, and the fleet meeting the MY2025 standards indefinitely thereafter. We continue to estimate a 5 year redesign cycle. This cycle is consistent with our understanding of industry practice (although there are indications that cycles are becoming shorter due to competitive pressures, especially on cars). This is how EPA's modeling has always been done. We know that industry plans ahead for compliance with future standards and carefully considers their redesign cycles when developing their compliance plans. To accommodate a 5 year redesign cycle, we have estimated that 20 percent of the MY2021 fleet will be redesigned to meet the MY2025 standards, and so on through MY2024. As noted above, this effectively results in the MY2021 through MY2024 control case targets and achieved CO_2 levels being below (i.e., better than) the reference case target (i.e., the MY2021 target) since 20 percent of each fleet will be redesigned to meet the MY2025 standards. The actual standards and the control case targets used in this analysis are shown graphically in Figure 12.1 for cars and Figure 12.2 for trucks.

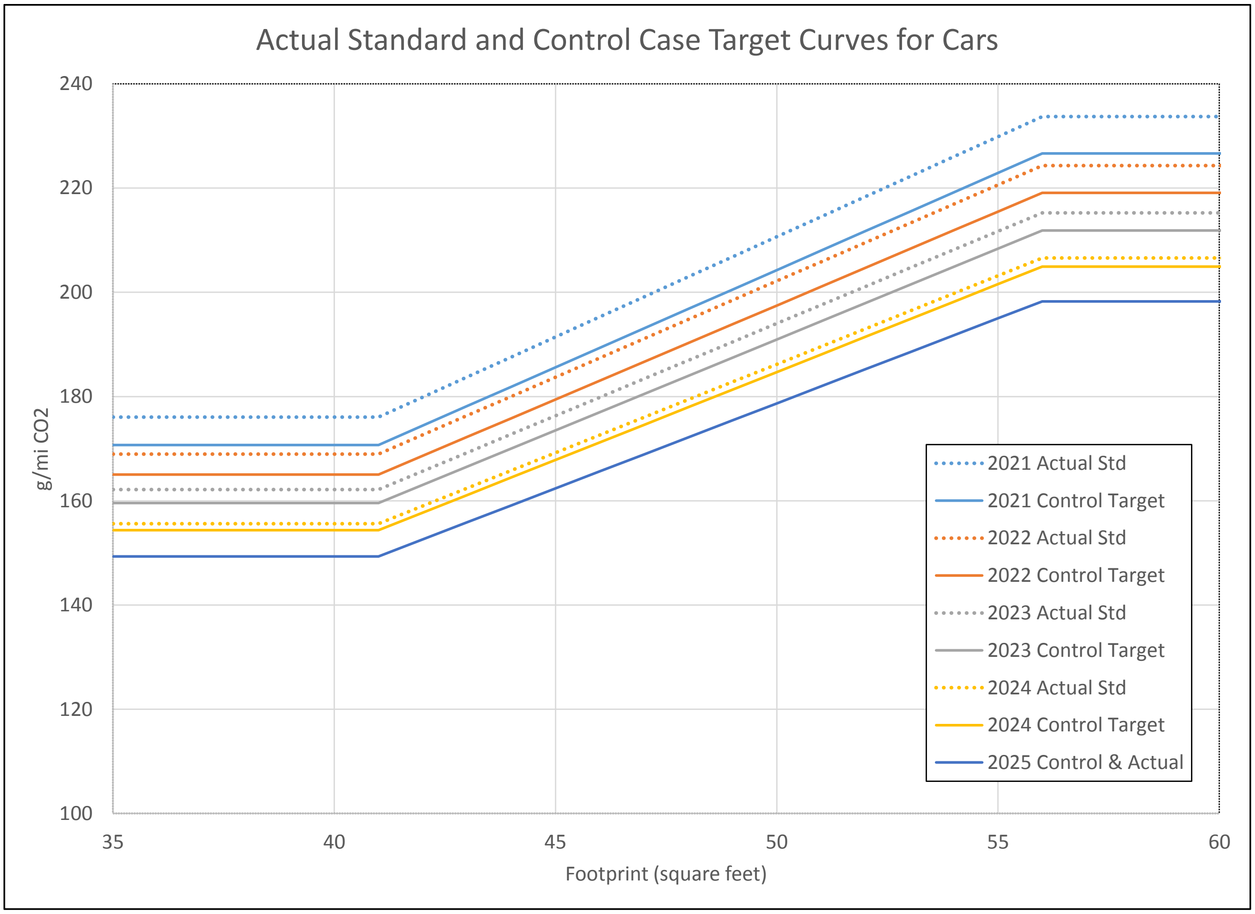

Figure 12.1 Actual Standard Curves and the Control Case Target Curves Used for Cars in this Draft TAR Analysis to Reflect a 5-Year Redesign Cycle

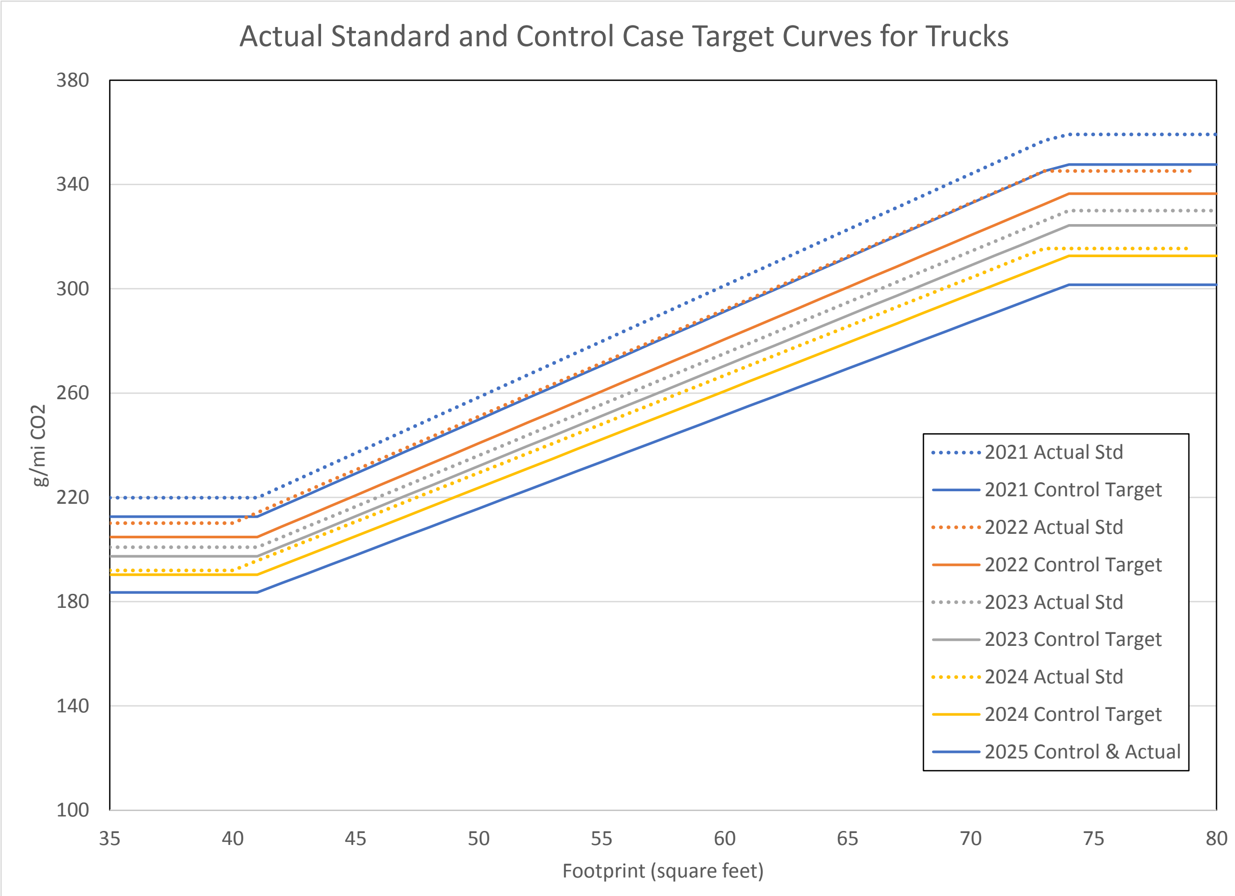

Figure 12.2 Actual Standard Curves and the Control Case Target Curves Used for Trucks in this Draft TAR Analysis to Reflect a 5-Year Redesign Cycle

Shown in these figures are the "actual," or promulgated greenhouse gas standard curves for the years 2021 through 2024 (dashed lines) and the control case target curves used in this analysis (solid lines). The control case target curves reflect greater stringency (lower CO_2) to reflect the 5 year redesign cycle discussed above. In effect, the target curves represent over-compliance with the actual standard curves in each year leading up to 2025. Just one curve is shown for 2025 since the actual standard and control case target curves are the same by then.

Importantly, the control case "standards" being used here are not new standard curves. Instead, they are an OMEGA modeling artifact used to simulate over-compliance with the actual standards. This over-compliance is being projected by EPA only to accommodate the 5-year redesign cycle stance, reflecting industry practice, and which we have used in the analyses for both of the LDV GHG rules.

Nonetheless, these standard curves, whether actual or the control case curves are being used, are used for determining the OMEGA target values for individual vehicles depending on the MY and their unique footprints. By determining those target values for each vehicle in the fleet and sales-weighting those, a fleet target can be determined for each manufacturer and for the entire fleet. Running that fleet through OMEGA and determining the most cost-effective path toward compliance (while also considering any appropriate technology penetration caps (see Appendix C) and other limitations on the application of technology), and considering credits and transfers as allowed under the program, we can estimate the achieved CO_2 level for each manufacturer and for the entire fleet.

We present the CO_2 targets and projected achieved levels in MY2021 in Table 12.3 and in MY2025 in Table 12.4. Note that the targets and achieved values shown in Table 12.3 include over-compliance with the actual standards, as explained above. For the 2012 FRM, EPA predicted an overall fleet average CO_2 performance of 163 g/mi. As shown in Table 12.4, the overall fleet performance is predicted to achieve 174.1 g/mi. This increase in CO_2 emissions can be largely attributed to the increase in sales of trucks.

Table 12.3 Control Case Targets and Achieved CO_2 in MY2021 in the Central Analysis (g/mi CO_2)

Manufacturer	Car Target	Truck Target	Fleet Target	Car Achieved, ICM	Truck Achieved, ICM	Fleet Achieved, ICM	Car Achieved, RPE	Truck Achieved, RPE	Fleet Achieved, RPE
BMW	172.6	228.9	187.8	173.4	225.7	187.5	173.7	226.2	187.8
FCA	176.3	237.2	219.1	192.1	230.3	219.0	192.7	231.1	219.7
Ford	173.8	270.4	231.0	191.1	260.2	232.1	191.2	260.2	232.1
GM	172.7	267.4	222.2	187.9	255.4	223.1	190.5	253.5	223.4
Honda	166.7	222.7	193.9	171.0	217.9	193.8	171.2	217.1	193.5
Hyundai/Kia	171.1	218.9	177.1	173.7	201.3	177.2	174.5	197.9	177.5
JLR	183.3	226.9	218.7	157.3	231.3	217.3	155.2	231.8	217.3
Mazda	169.6	215.0	183.3	171.0	211.6	183.2	171.1	211.9	183.5
Mercedes-Benz	174.2	229.0	196.9	170.3	233.2	196.3	170.7	233.3	196.6
Mitsubishi	159.2	200.7	175.1	175.6	176.9	176.1	176.3	177.3	176.7
Nissan	167.7	233.2	195.3	174.9	224.7	195.9	174.7	224.9	195.9
Subaru	164.3	202.9	194.3	202.8	193.5	195.6	209.0	191.0	195.0
Tesla	198.9	0.0	198.9	-18.8	0.0	-18.8	0.0	0.0	0.0
Toyota	168.6	238.4	201.8	169.1	237.8	201.8	170.2	235.9	201.5
Volkswagen	168.1	222.8	189.7	161.8	229.4	188.6	160.8	231.3	188.7
Volvo	175.9	219.5	199.1	179.2	217.0	199.4	181.8	214.2	199.1
Fleet	171.0	242.5	206.4	176.0	235.7	205.5	176.8	235.0	205.6

Note: Fleet values are sales weighted but not VMT weighted; targets include 20% over-compliance to the MY2025 standards.

Table 12.4 Control Case Targets and Achieved CO_2 in MY2025 in the Central Analysis (g/mi CO_2)

Manufacturer	Car Target	Truck Target	Fleet Target	Car Achieved, ICM	Truck Achieved, ICM	Fleet Achieved, ICM	Car Achieved, RPE	Truck Achieved, RPE	Fleet Achieved, RPE
BMW	147.7	193.8	158.7	146.0	197.5	158.3	146.3	197.6	158.5
FCA	151.8	202.3	187.3	159.9	199.4	187.6	159.4	199.5	187.6
Ford	149.5	229.7	196.1	165.7	219.0	196.7	168.5	218.0	197.2
GM	148.8	227.4	188.0	168.6	209.3	188.9	168.9	210.1	189.5
Honda	143.7	190.4	165.5	142.2	191.9	165.4	147.5	186.3	165.6
Hyundai/Kia	147.3	186.2	152.0	149.5	171.0	152.0	148.3	173.1	151.3
JLR	158.1	192.1	185.0	102.4	204.6	183.2	104.4	204.2	183.3
Mazda	145.8	182.4	157.0	148.6	174.9	156.6	149.0	176.2	157.3
Mercedes-Benz	149.8	193.8	166.6	141.8	203.2	165.2	142.5	203.9	165.9
Mitsubishi	137.0	169.9	148.8	148.2	150.5	149.0	149.5	150.5	149.8
Nissan	144.1	198.8	165.8	145.6	196.9	165.9	150.9	188.9	165.9
Subaru	141.3	171.7	164.9	173.6	163.7	165.9	179.8	162.2	166.1
Tesla	171.6	0.0	171.6	-18.8	0.0	-18.8	0.0	0.0	0.0
Toyota	145.2	201.5	170.7	143.4	203.5	170.5	144.8	201.3	170.4
Volkswagen	145.2	188.3	161.5	133.7	204.5	160.5	131.3	205.9	159.5
Volvo	151.5	186.1	169.5	154.3	183.3	169.4	147.2	189.5	169.2
Fleet	147.2	205.7	175.1	149.8	200.7	174.1	151.2	199.4	174.2

Note: Fleet values are sales weighted but not VMT weighted; targets include 20% over-compliance to the MY2025 standards.

12.1.1.1.3 Off-Cycle, Pickup Incentive and A/C Credits in OMEGA

In achieving the targets as shown in the tables above, manufacturers have available to them off-cycle credits for technologies, such as active aero and stop-start, that achieve real world CO_2 reductions although their impact is not adequately captured on the 2-cycle test (see II.F.2 of the 2012 FRM, 77 FR 62726). There are also incentive credits available for certain advanced technologies, such as strong hybrids on pickup trucks (see II.F.3 of the 2012 FRM, 77 FR 62738). Lastly, there are A/C credits which EPA assumes that all manufacturers will use in meeting the targets shown above (see II.F.1 of the 2012 FRM, 77 FR 62721). While manufacturers have available to them broader options for utilizing off-cycle technologies, including a fuller list of pre-approved off-cycle credits (see 40 CFR 86.1869-12), EPA is making a very conservative assumption for purposes of this Draft TAR analysis and is only making available within the OMEGA model two of those off-cycle technologies, active aero and stop-start, as shown in the table below. EPA will consider expanding the off-cycle technology included in our modeling assessment for future steps in the MTE process. The credits shown below are available within the model in both the reference and control cases.

Table 12.5 Off-cycle & Pickup Incentive Credits Available for Achieving the CO_2 Targets (g/mi CO_2)

MY	Vehicle	Active Aero	Stop-start	Mild HEV Incentive	Strong HEV Incentive
2021	Car	0.6	2.5	0.0	0.0
2022	Car	0.6	2.5	0.0	0.0
2023	Car	0.6	2.5	0.0	0.0
2024	Car	0.6	2.5	0.0	0.0
2025	Car	0.6	2.5	0.0	0.0
2021	Truck, non-pickup	1.0	4.4	0.0	0.0
2022	Truck, non-pickup	1.0	4.4	0.0	0.0
2023	Truck, non-pickup	1.0	4.4	0.0	0.0
2024	Truck, non-pickup	1.0	4.4	0.0	0.0
2025	Truck, non-pickup	1.0	4.4	0.0	0.0
2021	Pickup	1.0	4.4	10.0	20.0
2022	Pickup	1.0	4.4	0.0	20.0
2023	Pickup	1.0	4.4	0.0	20.0
2024	Pickup	1.0	4.4	0.0	20.0
2025	Pickup	1.0	4.4	0.0	20.0

The magnitude of the credits used within OMEGA, and reflected in the achieved CO_2 values presented in the "Target and Achieved CO_2" tables above are shown in the table below. The A/C credits used within OMEGA and reflected in both the targets and the achieved CO_2 values presented in the "Target and Achieved CO_2" tables above are also shown in the tables below.

Table 12.6 Off-cycle, Pickup Incentive and A/C Credits Used to Achieve the CO_2 Targets (g/mi CO_2)

			Off-cycle Credits			Incentive Credits	A/C Credits		
Case	Standard	MY	Car	Truck	Combined	Pickups	Car	Truck	Combined
AEO Ref, ICM	Reference	2021	0.499	1.367	0.960	0	18.8	24.4	21.6
	Control	2021	0.612	2.256	1.485	0	18.8	24.4	21.6
	Reference	2025	0.458	1.083	0.779	0	18.8	24.4	21.5
	Control	2025	1.089	3.481	2.317	0	18.8	24.4	21.5
AEO High, ICM	Reference	2021	0.533	1.664	1.030	0	18.8	24.4	21.6
	Control	2021	0.630	2.624	1.506	0	18.8	24.4	21.6
	Reference	2025	0.376	1.199	0.721	0	18.8	24.4	21.5
	Control	2025	1.190	3.482	2.151	0	18.8	24.4	21.5
AEO Low, ICM	Reference	2021	0.470	1.364	0.979	0	18.8	24.4	21.6
	Control	2021	0.597	2.065	1.434	0	18.8	24.4	21.6
	Reference	2025	0.330	1.057	0.733	0	18.8	24.4	21.5
	Control	2025	1.105	3.356	2.354	0	18.8	24.4	21.5
AEO Ref, RPE	Reference	2021	0.515	1.350	0.959	0	18.8	24.4	21.6
	Control	2021	0.629	2.329	1.531	0	18.8	24.4	21.6
	Reference	2025	0.480	1.225	0.863	0	18.8	24.4	21.5
	Control	2025	1.233	3.858	2.579	0	18.8	24.4	21.5

Note: The car A/C credit is composed of an indirect (or efficiency) credit of 5.0 g/mi CO_2 and a direct (or leakage) credit of 13.8 g/mi CO_2eq; the truck credit is composed of an indirect credit of 7.2 g/mi CO_2 and a direct credit (leakage credit) of 17.2 g/mi CO_2eq.

12.1.1.1.4 *Projected 2-Cycle CO_2*

The compliance targets presented above include use of A/C and the specified off-cycle credits. The actual tailpipe CO_2 as tested over the 2-cycle test procedure are higher than the actual targets since the A/C portion of the standards are not included as part of the test results. The tables below show the projected 2-cycle tailpipe CO_2 values for cars, trucks and the fleet using AEO 2015 reference fuel price case and ICMs.

Table 12.7 EPA Projections for Car Tailpipe Emissions Compliance with CO_2 Standards Using ICMs and the AEO Reference Fuel Price Case (CO_2 g/mi)

MY	Compliance Target, (CO2 Standard)	Compliance Target as MPG	Incentive Credits	Off-cycle Credits	Leakage A/C Credits	Efficiency A/C Credits	Projected 2-cycle Tailpipe CO2
2021	171	51.9	0	0.612	13.8	5.0	190
2022	165	53.9	0	0.731	13.8	5.0	184
2023	159	56.0	0	0.851	13.8	5.0	178
2024	153	58.2	0	0.970	13.8	5.0	173
2025	147	60.3	0	1.089	13.8	5.0	167

Table 12.8 EPA Projections for Truck Tailpipe Emissions Compliance with CO_2 Standards Using ICMs and the AEO Reference Fuel Price Case (CO_2 g/mi)

MY	Compliance Target, (CO2 Standard)	Compliance Target as MPG	Incentive Credits	Off-cycle Credits	Leakage A/C Credits	Efficiency A/C Credits	Projected 2-cycle Tailpipe CO2
2021	242	36.7	0	2.256	17.2	7.2	269
2022	232	38.3	0	2.562	17.2	7.2	259
2023	223	39.9	0	2.869	17.2	7.2	250
2024	214	41.6	0	3.175	17.2	7.2	241
2025	206	43.2	0	3.481	17.2	7.2	233

Table 12.9 EPA Projections for Combined Fleet Tailpipe Emissions Compliance with CO_2 Standards Using ICMs and the AEO Reference Fuel Price Case (CO_2 g/mi)

MY	Compliance Target, (CO2 Standard)	Compliance Target as MPG	Incentive Credits	Off-cycle Credits	Leakage A/C Credits	Efficiency A/C Credits	Projected 2-cycle Tailpipe CO2
2021	206	43.1	0	1.485	15.5	6.1	229
2022	198	44.9	0	1.693	15.5	6.1	221
2023	190	46.8	0	1.901	15.5	6.1	213
2024	182	48.8	0	2.109	15.4	6.1	206
2025	175	50.8	0	2.317	15.4	6.0	199

The tables below show the projected 2-cycle tailpipe CO_2 values for cars, trucks and the fleet using AEO 2015 high fuel price case and ICMs.

Table 12.10 EPA Projections for Car Tailpipe Emissions Compliance with CO_2 Standards Using ICMs and the AEO High Fuel Price Case (CO_2 g/mi)

MY	Compliance Target, (CO2 Standard)	Compliance Target as MPG	Incentive Credits	Off-cycle Credits	Leakage A/C Credits	Efficiency A/C Credits	Projected 2-cycle Tailpipe CO2
2021	171	52.0	0	0.630	13.8	5.0	190
2022	165	54.0	0	0.770	13.8	5.0	184
2023	158	56.1	0	0.910	13.8	5.0	178
2024	153	58.2	0	1.050	13.8	5.0	173
2025	147	60.4	0	1.190	13.8	5.0	167

Table 12.11 EPA Projections for Truck Tailpipe Emissions Compliance with CO_2 Standards Using ICMs and the AEO High Fuel Price Case (CO_2 g/mi)

MY	Compliance Target, (CO2 Standard)	Compliance Target as MPG	Incentive Credits	Off-cycle Credits	Leakage A/C Credits	Efficiency A/C Credits	Projected 2-cycle Tailpipe CO2
2021	240	36.7	0	2.624	17.2	7.2	268
2022	231	38.3	0	2.838	17.2	7.2	258
2023	222	39.9	0	3.053	17.2	7.2	249
2024	213	41.6	0	3.267	17.2	7.2	240
2025	204	43.2	0	3.482	17.2	7.2	232

Table 12.12 EPA Projections for Combined Fleet Tailpipe Emissions Compliance with CO_2 Standards Using ICMs and the AEO High Fuel Price Case (CO_2 g/mi)

MY	Compliance Target, (CO2 Standard)	Compliance Target as MPG	Incentive Credits	Off-cycle Credits	Leakage A/C Credits	Efficiency A/C Credits	Projected 2-cycle Tailpipe CO2
2021	199	43.1	0	1.506	15.2	5.9	222
2022	191	44.9	0	1.667	15.2	5.9	214
2023	183	46.8	0	1.829	15.1	5.9	206
2024	176	48.8	0	1.990	15.1	5.9	199
2025	169	50.8	0	2.151	15.1	5.8	192

The tables below show the projected 2-cycle tailpipe CO_2 values for cars, trucks and the fleet using AEO 2015 low fuel price case and ICMs.

Table 12.13 EPA Projections for Car Tailpipe Emissions Compliance with CO_2 Standards Using ICMs and the AEO Low Fuel Price Case (CO_2 g/mi)

MY	Compliance Target, (CO2 Standard)	Compliance Target as MPG	Incentive Credits	Off-cycle Credits	Leakage A/C Credits	Efficiency A/C Credits	Projected 2-cycle Tailpipe CO2
2021	171	51.9	0	0.597	13.8	5.0	191
2022	165	53.9	0	0.724	13.8	5.0	184
2023	159	56.0	0	0.851	13.8	5.0	178
2024	153	58.1	0	0.978	13.8	5.0	173
2025	147	60.3	0	1.105	13.8	5.0	167

Table 12.14 EPA Projections for Truck Tailpipe Emissions Compliance with CO_2 Standards Using ICMs and the AEO Low Fuel Price Case (CO_2 g/mi)

MY	Compliance Target, (CO2 Standard)	Compliance Target as MPG	Incentive Credits	Off-cycle Credits	Leakage A/C Credits	Efficiency A/C Credits	Projected 2-cycle Tailpipe CO2
2021	242	36.7	0	2.065	17.2	7.2	269
2022	233	38.2	0	2.388	17.2	7.2	259
2023	223	39.8	0	2.711	17.2	7.2	250
2024	214	41.5	0	3.034	17.2	7.2	242
2025	206	43.2	0	3.356	17.2	7.2	234

Table 12.15 EPA Projections for Combined Fleet Tailpipe Emissions Compliance with CO_2 Standards Using ICMs and the AEO Low Fuel Price Case (CO_2 g/mi)

MY	Compliance Target, (CO2 Standard)	Compliance Target as MPG	Incentive Credits	Off-cycle Credits	Leakage A/C Credits	Efficiency A/C Credits	Projected 2-cycle Tailpipe CO2
2021	209	42.5	0	1.434	15.6	6.2	232
2022	201	44.2	0	1.664	15.6	6.2	224
2023	193	46.2	0	1.894	15.6	6.2	216
2024	185	48.1	0	2.124	15.6	6.1	209
2025	178	50.0	0	2.354	15.6	6.1	202

12.1.1.2 Cost per Vehicle

12.1.1.2.1 Reference & Control Case

EPA presents the incremental costs of meeting the control case standards in MY2021 in Table 12.16 and in MY2025 in Table 12.17. We present the estimated progression of these incremental, control case costs relative to the reference case costs for cars in Table 12.18, and for trucks in Table 12.19.

As shown in Table 12.17, the average per vehicle costs to meet the MY2025 standards in MY2025 (compared to meeting the MY2021 standards in MY2025) is between $894 and $1,017. These costs are less than those estimated in the 2012 FRM, as discussed below in section 12.1.1.2.2.

EPA presents absolute costs for MY2025 vehicles meeting the 2021 standards (i.e., the reference case) and for MY2025 vehicles meeting the 2025 standards (i.e., the central analysis control case), for cars, trucks, and the fleet in section 12.4. The costs presented there are the costs used as inputs to the OMEGA Inventory, Cost and Benefit Tool discussed in more detail in Chapter 12.2

Table 12.16 MY2021 Control Case Cost/Vehicle Incremental to the Reference Case Cost/Vehicle in the Central Analysis Using AEO Reference Case Fuel Prices and Fleet Projections and Using both ICMs and RPEs (2013$)

Manufacturer	Car	Truck	Combined
BMW	$402-$423	$21-$123	$299-$342
FCA	$64-$126	$382-$394	$296-$306
Ford	$105-$188	$128-$159	$137-$153
GM	$185-$215	$137-$163	$173-$174
Honda	$68-$75	$150-$169	$108-$120
Hyundai/Kia	$144-$155	$491-$526	$187-$202
JLR	$941-$1264	$578-$677	$708-$727
Mazda	$80-$126	$0-$115	$88-$90
Mercedes-Benz	$351-$453	$332-$501	$403-$413
Mitsubishi	$60-$98	$177-$273	$128-$142
Nissan	$90-$92	$191-$196	$134-$135
Subaru	$33-$66	$84-$85	$73-$81
Tesla	$0-$0	$0-$0	$0-$0
Toyota	$45-$50	$189-$238	$113-$140
Volkswagen	$432-$433	$437-$468	$434-$447
Volvo	$445-$624	$194-$455	$395-$450
Fleet	$154-$162	$225-$234	$189-$197

Table 12.17 MY2025 Control Case Cost/Vehicle Incremental to the Reference Case Cost/Vehicle in the Central Analysis Using AEO Reference Case Fuel Prices and Fleet Projections and Using both ICMs and RPEs (2013$)

Manufacturer	Car	Truck	Combined
BMW	$1080-$1181	$1070-$1188	$1078-$1183
FCA	$879-$1063	$1400-$1501	$1245-$1371
Ford	$535-$606	$1147-$1273	$890-$993
GM	$593-$710	$1520-$1633	$1055-$1170
Honda	$544-$569	$493-$771	$520-$663
Hyundai/Kia	$731-$901	$1279-$1284	$797-$946
JLR	$3363-$3366	$1391-$1592	$1804-$1963
Mazda	$469-$539	$652-$748	$525-$603
Mercedes-Benz	$1383-$1401	$1253-$1528	$1334-$1449
Mitsubishi	$673-$724	$719-$866	$689-$775
Nissan	$635-$680	$816-$1218	$734-$866
Subaru	$451-$461	$531-$647	$515-$603
Tesla	$0-$0	$0-$0	$0-$0
Toyota	$548-$555	$871-$1140	$694-$820
Volkswagen	$1333-$1544	$1202-$1316	$1284-$1458
Volvo	$1247-$1575	$1257-$1575	$1410-$1417
Fleet	$707-$789	$1099-$1267	$894-$1017

Table 12.18 MY2021-2025 Control Case Cost/Vehicle Incremental to the Reference Case Cost/Vehicle Year-by-Year Costs per Car in the Central Analysis Using AEO Reference Case Fuel Prices and Fleet Projections (2013$)

Manufacturer	MY2021	MY2022	MY2023	MY2024	MY2025
BMW	$402-$423	$588-$597	$752-$791	$916-$986	$1080-$1181
FCA	$64-$126	$268-$360	$472-$594	$675-$829	$879-$1063
Ford	$105-$188	$213-$293	$320-$397	$427-$501	$535-$606
GM	$185-$215	$310-$316	$404-$448	$499-$579	$593-$710
Honda	$68-$75	$187-$198	$306-$322	$425-$445	$544-$569
Hyundai/Kia	$144-$155	$291-$342	$437-$528	$584-$715	$731-$901
JLR	$941-$1264	$1546-$1790	$2152-$2315	$2757-$2840	$3363-$3366
Mazda	$80-$126	$195-$212	$298-$310	$384-$424	$469-$539
Mercedes-Benz	$351-$453	$614-$685	$876-$918	$1138-$1151	$1383-$1401
Mitsubishi	$60-$98	$226-$242	$386-$392	$529-$558	$673-$724
Nissan	$90-$92	$228-$237	$364-$385	$500-$533	$635-$680
Subaru	$33-$66	$140-$162	$247-$258	$354-$355	$451-$461
Tesla	$0-$0	$0-$0	$0-$0	$0-$0	$0-$0
Toyota	$45-$50	$170-$177	$296-$303	$422-$429	$548-$555
Volkswagen	$432-$433	$658-$710	$883-$988	$1108-$1266	$1333-$1544
Volvo	$445-$624	$727-$780	$935-$1010	$1091-$1292	$1247-$1575
Fleet	$154-$162	$292-$319	$430-$475	$569-$632	$707-$789

Table 12.19 MY2021-2025 Control Case Cost/Vehicle Incremental to the Reference Case Cost/Vehicle Year-by-Year Costs per Truck in the Central Analysis Using AEO Reference Case Fuel Prices and Fleet Projections (2013$)

Manufacturer	MY2021	MY2022	MY2023	MY2024	MY2025
BMW	$21-$123	$313-$360	$597-$605	$834-$897	$1070-$1188
FCA	$382-$394	$645-$662	$897-$942	$1148-$1221	$1400-$1501
Ford	$128-$159	$406-$414	$653-$700	$900-$987	$1147-$1273
GM	$137-$163	$483-$530	$829-$898	$1174-$1266	$1520-$1633
Honda	$150-$169	$235-$319	$321-$470	$407-$621	$493-$771
Hyundai/Kia	$491-$526	$689-$714	$887-$903	$1085-$1091	$1279-$1284
JLR	$578-$677	$831-$855	$1034-$1085	$1213-$1339	$1391-$1592
Mazda	$0-$115	$163-$273	$326-$432	$489-$590	$652-$748
Mercedes-Benz	$332-$501	$563-$758	$793-$1014	$1023-$1271	$1253-$1528
Mitsubishi	$177-$273	$312-$422	$448-$570	$583-$718	$719-$866
Nissan	$191-$196	$351-$448	$506-$705	$661-$961	$816-$1218
Subaru	$84-$85	$196-$225	$308-$366	$419-$506	$531-$647
Tesla	$0-$0	$0-$0	$0-$0	$0-$0	$0-$0
Toyota	$189-$238	$359-$464	$530-$689	$700-$915	$871-$1140
Volkswagen	$437-$468	$651-$656	$835-$876	$1018-$1096	$1202-$1316
Volvo	$194-$455	$539-$656	$856-$884	$1057-$1230	$1257-$1575
Fleet	$225-$234	$444-$492	$662-$750	$881-$1008	$1099-$1267

Note that the costs shown in Table 12.18 and Table 12.19 are based on interpolations between the incremental costs of the control case standards in MY2021 and the control case standards in MY2025 (both based on actual OMEGA output), using the control case CO_2 targets for each fleet (car and truck) for each individual OEM.

12.1.1.3 Technology Penetration

12.1.1.3.1 Reference Case

EPA presents technology penetration rates in the MY2025 reference case (that is, the case where MY2021 standards remain in place in MY2025), in absolute terms, for cars and trucks and the fleet, using both ICMs and RPEs, in the tables below. First we present a table with the technology codes and their definitions as used in the following technology penetration tables. For detailed descriptions of each technology, refer to Chapter 5. In the interests of space, we do not present the technology penetrations for all technologies considered in this analysis. We present here only those technologies that we believe to be of most interest to the reader. Therefore, technologies like the accommodation of low friction lubes and lower rolling resistance tires are not presented here largely because those technologies are very cost effective and, therefore, have very high penetrations and, while important in achieving the standards, are not the primary drivers behind the feasibility of the standards. Note that the OMEGA output files include technology penetrations for all technologies considered; those output files are contained in the docket and on EPA's website at https://www3.epa.gov/otaq/climate/models.htm.

All technology penetration rate tables use the AEO 2015 reference fuel price case. One note of interest regarding the weight reduction technologies shown in the following tables: The "WRtech" is the weight reduction technology applied to the vehicle. This is the technology used to determine the costs associated with weight reduction. If 10 percent WRtech is applied, then the costs associated with that are those costs for a 10 percent weight reduction. The "WRnet" is the net weight reduction, or the WRtech less the added weight of any added batteries for electrification (i.e., HEVs, EVs, and PHEVs). The WRnet value determines effectiveness values and is used in the safety analysis (Chapter 8). As shown in the technology penetration tables that follow, there is not much difference between "WRtech" and "WRnet" because our modeling does projects very little increased electrification of the fleet to meet either the reference or control case standards. Nonetheless, the distinction between these two technologies is important and is tracked for that reason.

Note that the electrified vehicle technology penetrations--EV and PHEV, in particular--include the penetration of ZEV program vehicles as discussed in detail in Chapter 4 of this Draft TAR. Importantly, the ZEV program vehicles were "built" into the fleet with the projection that they would apply 20 percent mass reduction technology (WRtech) and 20 percent net mass reduction (WRnet). The result being that the mass reduction technology penetrations include a 20 percent mass reduction on roughly 2.5 percent of the fleet due to the way we have assessed the ZEV program vehicles.

Table 12.20 Technology Code Definitions used in Technology Penetration Tables

Code	Definition
WR Tech	Weight reduction technology applied
WR Net	Weight reduction net (includes added weight from batteries on electrified vehicles)
TDS18	Turbocharged and downsized engine - 18 bar BMEP
TDS24	Turbocharged and downsized engine- 24 bar BMEP
TRX11	Transmission level 1 (i.e., 6 speed auto, 6 speed DCT or CVT today)
TRX12	Transmission level 1 (i.e., TRX11 with efficiency improvements)
TRX21	Transmission level 2 (i.e., TRX11 with a wider gear ratio spread)
TRX22	Transmission level 2 (i.e., TRX21 with efficiency improvements)
Deac	Cylinder deactivation
VVLT	Variable valve lift
VVT	Variable valve timing
CEGR	Cooled Exhaust Gas Recirculation
Strong HEV	Strong hybrid
EV	Full battery electric vehicle
PHEV	Plug-in hybrid electric vehicle)
ATK1	Atkinson cycle engine used in Full Hybrid & REEV
ATK2	Atkinson cycle engine used in naturally aspirated, non-hybrid engines
Miller	Miller cycle, or turbocharged ATK2
Stop-Start	Stop-start, but without also being hybridized
Mild Hybrid	Mild hybrid 48 Volt
DSL	Diesel

The tables that follow for reference case technology penetrations are:

- Table 12.21 Absolute Technology Penetrations for Cars in the MY2025 Reference Case Using ICMs
- Table 12.22 Absolute Technology Penetrations for Cars in the MY2025 Reference Case Using RPEs
- Table 12.23 Absolute Technology Penetrations for Trucks in the MY2025 Reference Case Using ICMs
- Table 12.24 Absolute Technology Penetrations for Trucks in the MY2025 Reference Case Using RPEs
- Table 12.25 Absolute Technology Penetrations for the Fleet in the MY2025 Reference Case Using ICMs
- Table 12.26 Absolute Technology Penetrations for the Fleet in the MY2025 Reference Case Using RPEs
- Table 12.27 Summary of Absolute Technology Penetrations in the MY2025 Reference Case

Table 12.21 Absolute Technology Penetrations for Cars in the MY2025 Reference Case Using ICMs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	7.3%	5.2%	47.6%	10.9%	1.2%	0.0%	62.1%	23.0%	29.2%	49.0%	89.9%	29.2%	0.1%	3.4%	4.6%	0.0%	16.9%	0.0%	67.6%	12.3%	3.3%
FCA	7.3%	7.3%	35.9%	0.0%	0.4%	0.0%	71.4%	17.4%	51.3%	10.9%	94.4%	13.1%	0.0%	2.8%	2.9%	0.0%	13.1%	0.0%	1.6%	0.1%	0.0%
FORD	4.5%	4.2%	39.0%	0.0%	23.7%	0.0%	66.8%	0.0%	0.0%	0.0%	95.6%	0.0%	3.7%	2.3%	2.9%	3.7%	0.0%	0.0%	0.0%	0.0%	0.0%
GM	5.2%	4.5%	48.7%	0.0%	9.4%	0.0%	73.6%	9.6%	6.6%	12.6%	97.0%	0.5%	0.0%	1.6%	2.7%	1.1%	0.0%	0.0%	11.2%	0.6%	0.5%
HONDA	3.1%	3.1%	0.0%	0.0%	75.4%	0.0%	5.8%	0.0%	9.2%	94.5%	94.5%	1.1%	12.0%	2.6%	3.0%	6.5%	0.0%	0.0%	0.0%	0.0%	0.0%
HYUNDAI/KIA	3.8%	3.7%	13.6%	0.0%	3.6%	0.0%	73.7%	17.0%	45.1%	0.0%	97.1%	10.2%	2.2%	1.3%	1.6%	1.2%	10.2%	0.0%	1.5%	0.0%	0.0%
JLR	16.0%	15.0%	51.4%	3.6%	0.0%	0.0%	51.4%	24.2%	20.6%	51.4%	75.6%	24.2%	0.0%	14.5%	10.5%	0.0%	20.6%	0.0%	35.3%	40.3%	0.0%
MAZDA	6.8%	6.8%	0.0%	0.0%	75.2%	0.0%	0.0%	0.0%	0.0%	0.0%	96.1%	0.0%	0.0%	1.8%	2.1%	0.0%	96.1%	0.0%	0.0%	0.0%	0.0%
MERCEDES-BENZ	10.5%	10.1%	62.1%	15.7%	0.0%	0.0%	64.3%	27.3%	12.9%	61.7%	90.9%	28.1%	0.0%	4.1%	4.3%	0.0%	12.2%	0.0%	76.7%	12.8%	0.7%
MITSUBISHI	4.2%	4.2%	9.6%	0.0%	10.4%	0.0%	43.8%	0.6%	20.0%	0.0%	95.5%	0.0%	0.0%	3.1%	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
NISSAN	6.0%	6.0%	19.0%	0.0%	26.2%	0.0%	64.3%	0.0%	0.0%	5.1%	95.0%	0.0%	0.6%	2.7%	2.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SUBARU	2.9%	2.9%	9.0%	0.0%	77.8%	0.0%	0.0%	0.0%	0.0%	0.0%	96.1%	35.8%	0.0%	1.8%	2.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TESLA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TOYOTA	3.4%	3.0%	0.0%	0.0%	68.5%	0.0%	25.2%	0.0%	0.0%	1.4%	95.5%	18.8%	17.9%	2.4%	3.0%	18.7%	0.0%	0.0%	0.0%	0.0%	0.0%
VOLKSWAGEN	9.1%	8.3%	51.4%	12.0%	0.0%	0.0%	60.8%	25.8%	17.6%	44.2%	80.7%	34.9%	0.4%	4.2%	3.2%	0.0%	17.3%	1.4%	62.6%	29.1%	11.9%
VOLVO	9.5%	9.5%	84.5%	4.3%	0.0%	0.0%	73.4%	18.3%	2.9%	0.0%	91.7%	7.2%	0.0%	3.8%	4.5%	0.0%	2.9%	0.0%	5.4%	0.0%	0.0%
Fleet	5.2%	4.8%	25.2%	1.6%	27.7%	0.0%	52.3%	8.3%	14.4%	19.0%	93.3%	9.8%	4.5%	3.6%	2.7%	4.0%	7.3%	0.1%	10.6%	2.8%	0.9%

Table 12.22 Absolute Technology Penetrations for Cars in the MY2025 Reference Case Using RPEs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	5.0%	4.6%	48.7%	0.0%	1.2%	0.0%	61.4%	23.7%	38.6%	50.9%	89.9%	29.2%	0.1%	3.4%	4.6%	0.0%	27.8%	0.0%	73.8%	12.3%	3.3%
FCA	5.6%	5.6%	35.9%	0.0%	0.0%	0.0%	71.4%	17.8%	46.3%	15.6%	94.4%	13.1%	0.0%	2.8%	2.9%	0.0%	13.1%	0.0%	1.7%	0.1%	0.0%
FORD	3.1%	2.9%	31.9%	0.0%	18.7%	0.0%	68.9%	2.9%	0.0%	0.0%	95.6%	0.0%	3.7%	2.3%	2.9%	3.7%	0.0%	0.0%	0.0%	0.0%	0.0%
GM	4.1%	3.9%	48.5%	0.0%	1.8%	0.0%	73.6%	17.3%	8.1%	12.6%	97.0%	0.5%	0.0%	1.6%	2.7%	1.1%	0.0%	0.0%	11.2%	0.6%	0.5%
HONDA	2.2%	2.2%	0.0%	0.0%	59.7%	0.0%	18.7%	0.0%	9.2%	94.5%	94.5%	1.1%	12.0%	2.6%	3.0%	6.5%	0.0%	0.0%	0.0%	0.0%	0.0%
HYUNDAI/KIA	3.3%	3.3%	13.6%	0.0%	2.2%	0.0%	73.7%	18.4%	73.2%	0.0%	97.1%	10.0%	2.2%	1.3%	1.6%	1.2%	10.0%	0.0%	1.5%	0.0%	0.0%
JLR	12.8%	11.8%	48.6%	0.0%	0.0%	0.0%	48.6%	24.2%	24.2%	46.3%	72.8%	24.2%	0.0%	17.7%	10.5%	0.0%	24.2%	0.0%	34.5%	38.3%	0.0%
MAZDA	6.7%	6.7%	0.0%	0.0%	52.9%	0.0%	22.3%	0.0%	0.0%	0.0%	96.1%	0.0%	0.0%	1.8%	2.1%	0.0%	96.1%	0.0%	0.0%	0.0%	0.0%
MERCEDES-BENZ	7.2%	6.0%	61.6%	0.0%	0.0%	0.0%	63.5%	27.3%	28.1%	56.2%	90.5%	27.7%	0.0%	4.9%	4.3%	0.0%	28.0%	0.0%	43.9%	44.8%	0.4%
MITSUBISHI	3.5%	3.5%	9.6%	0.0%	3.5%	0.0%	43.8%	7.4%	27.2%	0.0%	95.5%	0.0%	0.0%	3.1%	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
NISSAN	5.7%	5.7%	9.2%	0.0%	14.3%	0.0%	72.5%	3.7%	0.0%	9.7%	95.0%	0.0%	0.6%	2.7%	2.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SUBARU	0.8%	0.8%	9.0%	0.0%	76.9%	0.0%	0.9%	0.0%	0.0%	0.0%	96.1%	35.8%	0.0%	1.8%	2.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TESLA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TOYOTA	2.9%	2.7%	0.0%	0.0%	36.3%	0.0%	57.1%	0.2%	0.0%	1.4%	95.5%	18.8%	17.9%	2.4%	3.0%	18.7%	0.0%	0.0%	0.0%	0.0%	0.0%
VOLKSWAGEN	7.4%	6.7%	45.8%	0.0%	0.0%	0.0%	59.2%	25.8%	33.8%	33.4%	79.3%	34.7%	0.4%	6.0%	3.2%	0.0%	29.4%	0.9%	61.1%	29.4%	11.6%
VOLVO	8.9%	8.9%	83.4%	0.0%	0.0%	0.0%	73.4%	18.3%	8.3%	0.0%	91.7%	8.3%	0.0%	3.8%	4.5%	0.0%	8.3%	0.0%	17.2%	0.0%	0.0%
Fleet	4.1%	4.0%	23.1%	0.0%	17.9%	0.0%	59.6%	10.5%	19.9%	19.1%	93.2%	9.8%	4.5%	3.7%	2.7%	4.0%	8.9%	0.1%	9.9%	3.7%	0.9%

Table 12.23 Absolute Technology Penetrations for Trucks in the MY2025 Reference Case Using ICMs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	5.6%	4.4%	69.4%	9.8%	0.0%	0.0%	71.0%	29.0%	18.1%	75.5%	97.2%	30.6%	0.0%	0.0%	0.0%	0.0%	18.1%	2.6%	54.8%	45.2%	2.8%
FCA	5.6%	5.6%	49.6%	12.4%	0.0%	0.0%	78.4%	19.6%	34.0%	2.2%	97.2%	19.6%	0.0%	0.3%	0.4%	0.0%	12.5%	0.0%	29.6%	0.0%	2.1%
FORD	5.0%	5.0%	66.9%	0.0%	8.5%	0.0%	79.8%	11.5%	0.0%	0.0%	99.8%	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GM	5.3%	5.3%	28.9%	0.0%	0.0%	0.0%	79.8%	20.0%	64.9%	0.0%	99.8%	1.9%	0.0%	0.1%	0.1%	0.0%	1.9%	0.0%	0.0%	0.0%	0.0%
HONDA	5.7%	5.7%	0.0%	0.0%	35.6%	0.0%	62.3%	0.0%	55.7%	97.9%	97.9%	0.0%	0.0%	1.0%	1.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HYUNDAI/KIA	7.1%	7.1%	49.9%	0.0%	0.0%	0.0%	78.8%	19.7%	48.5%	0.0%	98.5%	12.1%	0.0%	0.7%	0.8%	0.0%	12.1%	0.0%	12.5%	0.0%	0.0%
JLR	12.5%	11.3%	70.0%	0.0%	0.0%	0.0%	70.0%	30.0%	30.0%	70.0%	100.0%	30.0%	11.5%	0.0%	0.0%	0.0%	30.0%	30.0%	38.5%	50.0%	0.0%
MAZDA	5.4%	5.4%	0.0%	0.0%	19.4%	0.0%	77.8%	0.0%	0.0%	0.0%	97.2%	0.0%	0.0%	1.3%	1.5%	0.0%	68.9%	0.0%	0.0%	0.0%	0.0%
MERCEDES-BENZ	6.9%	5.7%	66.3%	12.2%	0.0%	0.0%	70.0%	30.0%	13.9%	78.5%	92.4%	33.7%	0.0%	0.0%	0.0%	0.0%	13.9%	13.9%	50.0%	50.0%	7.6%
MITSUBISHI	7.9%	7.9%	0.0%	0.0%	0.0%	0.0%	78.5%	19.6%	0.0%	53.0%	88.4%	0.0%	0.0%	0.6%	1.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
NISSAN	6.7%	6.7%	57.3%	0.0%	17.3%	0.0%	76.6%	3.2%	0.0%	1.9%	98.8%	0.0%	1.4%	0.5%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SUBARU	5.6%	5.5%	2.9%	0.0%	92.4%	0.0%	0.2%	0.0%	0.0%	0.0%	96.3%	3.9%	2.1%	1.7%	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TESLA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TOYOTA	5.2%	5.2%	51.6%	0.0%	16.2%	0.0%	77.1%	3.7%	0.0%	0.0%	98.7%	6.1%	0.7%	0.7%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
VOLKSWAGEN	8.7%	7.4%	66.1%	8.1%	0.0%	0.0%	70.3%	29.7%	15.4%	74.1%	89.6%	33.9%	0.9%	0.0%	0.0%	0.0%	15.4%	15.4%	49.5%	49.5%	10.4%
VOLVO	5.0%	4.5%	73.1%	11.7%	0.0%	0.0%	76.1%	23.9%	15.3%	15.6%	100.0%	26.9%	0.0%	0.0%	0.0%	0.0%	15.3%	0.0%	43.3%	19.5%	0.0%
Fleet	5.8%	5.6%	42.9%	3.1%	14.2%	0.0%	71.4%	12.6%	24.8%	16.4%	98.0%	8.2%	0.5%	0.4%	0.5%	0.0%	5.5%	1.3%	10.2%	4.2%	1.0%

Table 12.24 Absolute Technology Penetrations for Trucks in the MY2025 Reference Case Using RPEs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	5.7%	4.8%	66.1%	0.0%	0.0%	0.0%	76.7%	23.3%	28.3%	61.1%	94.5%	33.9%	0.0%	0.0%	0.0%	0.0%	28.3%	12.4%	82.4%	16.3%	5.5%
FCA	5.6%	5.6%	46.5%	0.0%	0.0%	0.0%	77.3%	20.7%	46.3%	4.4%	97.2%	24.4%	0.0%	0.3%	0.4%	0.0%	22.3%	0.0%	30.7%	1.1%	2.1%
FORD	5.0%	5.0%	59.1%	0.0%	3.2%	0.0%	79.8%	16.7%	0.0%	0.0%	99.8%	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GM	5.2%	5.2%	28.9%	0.0%	0.0%	0.0%	79.8%	20.0%	65.2%	0.0%	99.8%	1.9%	0.0%	0.1%	0.1%	0.0%	1.9%	0.0%	6.5%	0.0%	0.0%
HONDA	5.7%	5.7%	0.0%	0.0%	19.6%	0.0%	78.3%	0.0%	55.7%	97.9%	97.9%	0.0%	0.0%	1.0%	1.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HYUNDAI/KIA	7.1%	7.1%	37.4%	0.0%	0.0%	0.0%	78.8%	19.7%	61.0%	0.0%	98.5%	24.6%	0.0%	0.7%	0.8%	0.0%	24.6%	0.0%	0.0%	0.0%	0.0%
JLR	12.3%	11.0%	70.0%	0.0%	0.0%	0.0%	70.0%	30.0%	30.0%	70.0%	100.0%	30.0%	12.1%	0.0%	0.0%	0.0%	30.0%	30.0%	38.5%	49.4%	0.0%
MAZDA	5.4%	5.4%	0.0%	0.0%	19.4%	0.0%	77.8%	0.0%	0.0%	0.0%	97.2%	0.0%	0.0%	1.3%	1.5%	0.0%	68.9%	0.0%	0.0%	0.0%	0.0%
MERCEDES-BENZ	5.8%	4.6%	67.0%	0.0%	0.0%	0.0%	70.0%	30.0%	25.4%	67.0%	92.4%	33.0%	0.0%	0.0%	0.0%	0.0%	25.4%	7.4%	50.0%	50.0%	7.6%
MITSUBISHI	7.9%	7.9%	0.0%	0.0%	0.0%	0.0%	78.5%	19.6%	2.4%	50.5%	90.8%	0.0%	0.0%	0.6%	1.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
NISSAN	6.7%	6.7%	26.1%	0.0%	5.2%	0.0%	76.5%	15.3%	0.7%	2.0%	98.8%	0.7%	1.4%	0.5%	0.7%	0.0%	0.7%	0.0%	0.0%	0.0%	0.0%
SUBARU	5.6%	5.5%	2.9%	0.0%	87.9%	0.0%	4.7%	0.0%	0.0%	0.0%	96.3%	3.9%	2.1%	1.7%	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TESLA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TOYOTA	5.2%	5.2%	5.9%	0.0%	5.9%	0.0%	77.0%	14.0%	0.0%	0.0%	98.7%	6.1%	0.7%	0.7%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
VOLKSWAGEN	8.0%	6.7%	66.1%	0.0%	0.0%	0.0%	70.3%	29.7%	23.5%	66.0%	89.6%	33.9%	0.9%	0.0%	0.0%	0.0%	23.5%	11.7%	49.5%	49.5%	10.4%
VOLVO	5.2%	4.7%	71.9%	0.0%	0.0%	0.0%	80.0%	20.0%	28.1%	23.8%	100.0%	28.1%	0.0%	0.0%	0.0%	0.0%	28.1%	0.0%	45.9%	19.5%	0.0%
Fleet	5.7%	5.6%	32.8%	0.0%	9.4%	0.0%	73.1%	15.8%	28.2%	16.1%	98.0%	9.4%	0.5%	0.4%	0.5%	0.0%	8.4%	1.1%	11.6%	4.1%	1.0%

Table 12.25 Absolute Technology Penetrations for the Fleet in the MY2025 Reference Case Using ICMs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	6.9%	5.0%	52.8%	10.6%	0.9%	0.0%	64.2%	24.4%	26.5%	55.3%	91.6%	29.5%	0.1%	2.6%	3.5%	0.0%	17.2%	0.6%	64.5%	20.1%	3.2%
FCA	6.1%	6.1%	45.6%	8.7%	0.1%	0.0%	76.3%	19.0%	39.1%	4.8%	96.4%	17.7%	0.0%	1.0%	1.2%	0.0%	12.7%	0.0%	21.2%	0.0%	1.5%
FORD	4.8%	4.7%	55.2%	0.0%	14.9%	0.0%	74.4%	6.7%	0.0%	0.0%	98.0%	0.0%	1.5%	1.0%	1.3%	1.5%	0.0%	0.0%	0.0%	0.0%	0.0%
GM	5.2%	4.9%	38.8%	0.0%	4.7%	0.0%	76.7%	14.8%	35.7%	6.3%	98.4%	1.2%	0.0%	0.9%	1.4%	0.5%	1.0%	0.0%	5.6%	0.3%	0.3%
HONDA	4.4%	4.3%	0.0%	0.0%	56.8%	0.0%	32.1%	0.0%	30.9%	96.1%	96.1%	0.6%	6.4%	1.8%	2.1%	3.4%	0.0%	0.0%	0.0%	0.0%	0.0%
HYUNDAI/KIA	4.2%	4.1%	18.0%	0.0%	3.2%	0.0%	74.3%	17.3%	45.5%	0.0%	97.3%	10.4%	2.0%	1.3%	1.5%	1.1%	10.4%	0.0%	2.8%	0.0%	0.0%
JLR	13.3%	12.1%	66.1%	0.7%	0.0%	0.0%	66.1%	28.8%	28.0%	66.1%	94.9%	28.8%	9.1%	3.0%	2.2%	0.0%	28.0%	23.7%	37.8%	48.0%	0.0%
MAZDA	6.4%	6.4%	0.0%	0.0%	58.1%	0.0%	23.8%	0.0%	0.0%	0.0%	96.5%	0.0%	0.0%	1.6%	1.9%	0.0%	87.8%	0.0%	0.0%	0.0%	0.0%
MERCEDES-BENZ	9.1%	8.4%	63.7%	14.4%	0.0%	0.0%	66.5%	28.3%	13.3%	68.1%	91.5%	30.2%	0.0%	2.5%	2.7%	0.0%	12.8%	5.3%	66.5%	27.0%	3.4%
MITSUBISHI	5.5%	5.5%	6.1%	0.0%	6.6%	0.0%	56.2%	7.4%	12.8%	19.0%	93.0%	0.0%	0.0%	2.2%	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
NISSAN	6.3%	6.3%	34.2%	0.0%	22.7%	0.0%	69.1%	1.3%	0.0%	3.8%	96.5%	0.0%	0.9%	1.8%	1.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SUBARU	5.0%	4.9%	4.2%	0.0%	89.1%	0.0%	0.2%	0.0%	0.0%	0.0%	96.2%	11.0%	1.6%	1.7%	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TESLA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TOYOTA	4.2%	4.0%	23.3%	0.0%	44.8%	0.0%	48.7%	1.7%	0.0%	0.8%	96.9%	13.0%	10.1%	1.6%	1.9%	10.2%	0.0%	0.0%	0.0%	0.0%	0.0%
VOLKSWAGEN	8.9%	8.0%	56.9%	10.5%	0.0%	0.0%	64.4%	27.3%	16.7%	55.5%	84.1%	34.5%	0.6%	2.6%	2.0%	0.0%	16.6%	6.7%	57.6%	36.8%	11.3%
VOLVO	7.1%	6.9%	78.5%	8.1%	0.0%	0.0%	74.8%	21.2%	9.3%	8.1%	96.0%	17.5%	0.0%	1.8%	2.1%	0.0%	9.3%	0.0%	25.1%	10.1%	0.0%
Fleet	5.5%	5.2%	33.6%	2.3%	21.3%	0.0%	61.4%	10.4%	19.4%	17.8%	95.5%	9.0%	2.6%	2.1%	1.7%	2.1%	6.4%	0.7%	10.4%	3.5%	1.0%

Table 12.26 Absolute Technology Penetrations for the Fleet in the MY2025 Reference Case Using RPEs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	5.2%	4.7%	52.9%	0.0%	0.9%	0.0%	65.0%	23.6%	36.1%	53.3%	91.0%	30.3%	0.1%	2.6%	3.5%	0.0%	27.9%	3.0%	75.9%	13.2%	3.9%
FCA	5.6%	5.6%	43.4%	0.0%	0.0%	0.0%	75.6%	19.8%	46.3%	7.7%	96.4%	21.0%	0.0%	1.0%	1.2%	0.0%	19.5%	0.0%	22.1%	0.8%	1.5%
FORD	4.2%	4.1%	47.7%	0.0%	9.7%	0.0%	75.2%	10.9%	0.0%	0.0%	98.0%	0.0%	1.5%	1.0%	1.3%	1.5%	0.0%	0.0%	0.0%	0.0%	0.0%
GM	4.6%	4.5%	38.7%	0.0%	0.9%	0.0%	76.7%	18.6%	36.6%	6.3%	98.4%	1.2%	0.0%	0.9%	1.4%	0.5%	1.0%	0.0%	8.8%	0.3%	0.3%
HONDA	3.9%	3.9%	0.0%	0.0%	41.0%	0.0%	46.5%	0.0%	30.9%	96.1%	96.1%	0.6%	6.4%	1.8%	2.1%	3.4%	0.0%	0.0%	0.0%	0.0%	0.0%
HYUNDAI/KIA	3.8%	3.8%	16.5%	0.0%	2.0%	0.0%	74.3%	18.6%	71.7%	0.0%	97.3%	11.7%	2.0%	1.3%	1.5%	1.1%	11.7%	0.0%	1.3%	0.0%	0.0%
JLR	12.4%	11.2%	65.5%	0.0%	0.0%	0.0%	65.5%	28.8%	28.8%	65.0%	94.3%	28.8%	9.5%	3.7%	2.2%	0.0%	28.8%	23.7%	37.7%	47.1%	0.0%
MAZDA	6.3%	6.3%	0.0%	0.0%	42.6%	0.0%	39.3%	0.0%	0.0%	0.0%	96.5%	0.0%	0.0%	1.6%	1.9%	0.0%	87.8%	0.0%	0.0%	0.0%	0.0%
MERCEDES-BENZ	6.7%	5.5%	63.6%	0.0%	0.0%	0.0%	66.0%	28.3%	27.1%	60.3%	91.2%	29.7%	0.0%	3.0%	2.7%	0.0%	27.0%	2.8%	46.2%	46.8%	3.1%
MITSUBISHI	5.1%	5.1%	6.1%	0.0%	2.3%	0.0%	56.2%	11.8%	18.3%	18.1%	93.8%	0.0%	0.0%	2.2%	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
NISSAN	6.1%	6.1%	15.9%	0.0%	10.7%	0.0%	74.1%	8.3%	0.3%	6.6%	96.5%	0.3%	0.9%	1.8%	1.7%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%
SUBARU	4.5%	4.4%	4.2%	0.0%	85.4%	0.0%	3.9%	0.0%	0.0%	0.0%	96.2%	11.0%	1.6%	1.7%	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TESLA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TOYOTA	3.9%	3.8%	2.7%	0.0%	22.6%	0.0%	66.1%	6.5%	0.0%	0.8%	96.9%	13.0%	10.1%	1.6%	1.9%	10.2%	0.0%	0.0%	0.0%	0.0%	0.0%
VOLKSWAGEN	7.7%	6.7%	53.5%	0.0%	0.0%	0.0%	63.4%	27.3%	29.9%	45.7%	83.2%	34.4%	0.6%	3.7%	2.0%	0.0%	27.1%	5.0%	56.8%	37.0%	11.2%
VOLVO	7.0%	6.7%	77.4%	0.0%	0.0%	0.0%	76.8%	19.2%	18.6%	12.4%	96.0%	18.6%	0.0%	1.8%	2.1%	0.0%	18.6%	0.0%	32.1%	10.1%	0.0%
Fleet	4.9%	4.7%	27.7%	0.0%	13.8%	0.0%	66.0%	13.0%	23.9%	17.7%	95.5%	9.6%	2.6%	2.2%	1.7%	2.1%	8.7%	0.6%	10.7%	3.9%	1.0%

Table 12.27 Summary of Absolute Technology Penetrations in the MY2025 Reference Case

Indirect Cost Approach	C/T/Fleet	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
ICM	C	5.2%	4.8%	25.2%	1.6%	27.7%	0.0%	52.3%	8.3%	14.4%	19.0%	93.3%	9.8%	4.5%	3.6%	2.7%	4.0%	7.3%	0.1%	10.6%	2.8%	0.9%
ICM	T	5.8%	5.6%	42.9%	3.1%	14.2%	0.0%	71.4%	12.6%	24.8%	16.4%	98.0%	8.2%	0.5%	0.4%	0.5%	0.0%	5.5%	1.3%	10.2%	4.2%	1.0%
ICM	Fleet	5.5%	5.2%	33.6%	2.3%	21.3%	0.0%	61.4%	10.4%	19.4%	17.8%	95.5%	9.0%	2.6%	2.1%	1.7%	2.1%	6.4%	0.7%	10.4%	3.5%	1.0%
RPE	C	4.1%	4.0%	23.1%	0.0%	17.9%	0.0%	59.6%	10.5%	19.9%	19.1%	93.2%	9.8%	4.5%	3.7%	2.7%	4.0%	8.9%	0.1%	9.9%	3.7%	0.9%
RPE	T	5.7%	5.6%	32.8%	0.0%	9.4%	0.0%	73.1%	15.8%	28.2%	16.1%	98.0%	9.4%	0.5%	0.4%	0.5%	0.0%	8.4%	1.1%	11.6%	4.1%	1.0%
RPE	Fleet	4.9%	4.7%	27.7%	0.0%	13.8%	0.0%	66.0%	13.0%	23.9%	17.7%	95.5%	9.6%	2.6%	2.2%	1.7%	2.1%	8.7%	0.6%	10.7%	3.9%	1.0%

Mass reduction technology is applied along a continuum of possible levels, and values shown in the tables above represent the average percentage mass reduction applied (WRtech) and average percentage net mass reduction (WRnet). The values above do not indicate the proportion of the fleet with the technology applied, as is the case with the other technologies shown. Not readily apparent in the tables above is the number, or percentage, of vehicles that receive specific levels of mass reduction. The table below provides more detail on mass reduction technology in our projections by showing the percentage of vehicles that receive the level of mass reduction within the given mass reduction ranges. Note that we account for the additional mass associated with batteries and electrical components of EVs and PHEVs, which explains the difference between "WRtech" and "WRnet." "Baseline" represents the amount of mass reduction relative to EPA's "null" or "floor" (i.e., in the case of weight reduction, EPA's "null" is the 2008 baseline fleet used in the 2012 FRM) present in MY2014 vehicles with MY2025 projected volumes. In the table, we show results excluding the ZEV program vehicles because, as noted above, roughly 2.5 percent of the fleet (the fleet reflecting the ZEV program) was "built" with 20 percent mass reduction technology applied (WRtech) and 20 percent mass reduction on net (WRnet).

Table 12.28 Percentage of Vehicles Receiving the Mass Reduction Levels within the Indicated Ranges in the MY2025 Reference Case Using ICMs and AEO Reference Case Fuel Prices

Fleet	%MR Range	Baseline	WRtech	WRnet
Including ZEV Program Vehicles	<=5%	87.0%	57.4%	61.0%
	5% to <=10%	9.1%	30.7%	28.0%
	10% to <=15%	0.9%	7.3%	8.3%
	15% to <=20%	3.0%	4.6%	2.7%
Excluding ZEV Program Vehicles (as explained above)	<=5%	89.3%	58.9%	62.6%
	5% to <=10%	9.3%	31.5%	28.8%
	10% to <=15%	0.9%	7.5%	8.5%
	15% to <=20%	0.5%	2.1%	0.2%

12.1.1.3.2 Control Case

The technology penetration rates in the MY2025 control case (that is, the case where the MY2025 standards are in effect in MY2025), again in absolute terms, are presented for cars, trucks and the fleet, using both ICMs and RPEs, in the tables below. We also present the technology penetration changes, i.e., the technology added to move from compliance with the reference case standards to the control case standards, for cars, trucks and the fleet using both ICMs and RPEs in the tables below. All technology penetration rate tables use the AEO 2015 reference fuel price case.

Much like both the 2012 FRM and the 2015 NAS report, the results from the control case show that the MY 2025 standards can be met largely through the application of advanced gasoline engines and transmissions and moderate hybridization. The technology penetrations for the previously identified technologies are shown in the last row of Table 12.33 for the entire light-duty fleet. (This table presents fleet level technology penetrations using ICMs).

For advanced gasoline engines EPA has projected that the fleet would be 33 percent 18-bar and 24-bar turbo-charged engines and 44 percent Atkinson 2 engines. This similar penetration of two competing engine technologies demonstrates that there are multiple cost effective advanced gasoline technologies available to manufacturers. In order to acknowledge that manufacturers may choose to focus on turbo-downsized technology over Atkinson, EPA conducted a sensitivity analysis restricting Atkinson 2 technology application as described in the Sensitivity Analysis Results below. In addition to turbo-charging and Atkinson cycle, EPA has also projected cylinder deactivation (DEAC), variable valve timing (VVT) and cooled EGR will be prominent engine technologies, with respective penetration rates of 54 percent, 96 percent, and 53 percent. With respect to transmissions, EPA has projected that over 90 percent of the transmissions will be high ratio spread (TRX21+TRX22) and 39 percent (TRX22) of these transmissions will also implement further improvements in transmission efficiency beyond current transmissions.[H]

Stop-start and Mild HEV technologies, such as 48-volt systems, are anticipated to be applied with increasing frequency. 48-volt mild hybrids help improve the overall efficiency of conventional powertrains at less expense compared to strong hybridization. Stop-start is projected to penetrate the market in 20 percent of the fleet, and Mild HEV's at an 18 percent penetration.

Mass reduction is also expected to be applied at moderate levels across the majority of the fleet. For MY 2025 EPA has projected an average mass reduction technology penetration rate for the entire fleet of 7 percent (WR Tech) which, when taking into consideration the additional mass of electrification, yields a net mass reduction of 6 percent (WR Net). The highest average amount of mass reduction for an individual manufacturer is projected to be 13 percent for Jaguar-Land Rover and the lowest mass reduction is projected to be 5 percent for Toyota.

For some manufacturers, strong electrification is expected to be utilized, however, for the overall fleet EPA has projected a minimal amount of strong electrification technology penetration. For strong HEV's, battery electric vehicles (EV), and plug-in hybrid electric vehicles (PHEV), EPA has projected fleet technology penetration rates of 3 percent, 2 percent, and 2 percent respectively. The highest penetration rates for strong HEVs was projected at 11 percent for JLR, for EVs, Volkswagen has been projected to utilize 9 percent, and for PHEVs, BMW is projected to utilize 4 percent. EPA notes that our analysis included consideration for compliance with other related regulations including CARB's ZEV regulation that has also been adopted by nine other states under section 177 of the Federal Clean Air Act. Therefore, some of the EV and PHEV penetration in the following tables is ZEV program-related (2.6 percent of the combined fleet), some is in EPA's purchased fleet projections (1.2 percent of the combined fleet), and some is generated by OMEGA to reach compliance (an additional 0.5 percent of the combined fleet for a total of 4.3 percent in the AEO 2015 reference fuel price and ICM case). See Table 12.33 where the final EV (2.6 percent) and PHEV (1.7 percent) penetrations can be added to 4.3 percent; see Table 12.39 where the incremental EV penetration is shown as 1 percent, rounded from 0.5 percent. EPA's analysis also reflects considerable penetration of certain advanced engine technologies such as the Atkinson-2 technology introduced since the

[H] EPA has used transmission designations TRX11, TRX12, TRX21 and TRX22 to represent levels of improvement to the transmission in the baseline fleet. As such, these transmission designations could include automatic transmissions, dual clutch transmissions or CVTs. The point is, TRX21 and TRX22 transmissions have wider ratio spreads, regardless of the type of transmission, than do TRX11 and TRX12 transmissions. Similarly, TRX12 and TRX22 transmissions have additional efficiency improvements beyond those found in TRX11 and TRX21 transmissions.

2012 FRM. Had the analysis not taken these factors into account, it is likely that estimates of strong hybridization and electrification penetration rates would be higher.[I]

The tables that follow for control case technology penetrations are:

- Table 12.29 Absolute Technology Penetrations for Cars in the MY2025 Control Case Using ICMs
- Table 12.30 Absolute Technology Penetrations for Cars in the MY2025 Control Case Using RPEs
- Table 12.31 Absolute Technology Penetrations for Trucks in the MY2025 Control Case Using ICMs
- Table 12.32 Absolute Technology Penetrations for Trucks in the MY2025 Control Case Using RPEs
- Table 12.33 Absolute Technology Penetrations for the Fleet in the MY2025 Control Case Using ICMs
- Table 12.34 Absolute Technology Penetrations for the Fleet in the MY2025 Control Case Using RPEs

The tables that follow for control case incremental technology penetrations are:

- Table 12.35 Incremental Technology Penetrations for Cars in the MY2025 Central Analysis Using ICMs
- Table 12.36 Incremental Technology Penetrations for Cars in the MY2025 Central Analysis Using RPEs
- Table 12.37 Incremental Technology Penetrations for Trucks in the MY2025 Central Analysis Using ICMs
- Table 12.38 Incremental Technology Penetrations for Trucks in the MY2025 Central Analysis Using RPEs
- Table 12.39 Incremental Technology Penetrations for the Fleet in the MY2025 Central Analysis Using ICMs
- Table 12.40 Incremental Technology Penetrations for the Fleet in the MY2025 Central Analysis Using RPEs

The final two tables show summaries of the above control case tables.

- Table 12.41 Summary of Absolute Technology Penetrations in the MY2025 Control Case
- Table 12.42 Summary of Incremental Technology Penetrations in the MY2025 Control Case

[I] This section is focused on describing the results of the OMEGA model for this Draft TAR. As noted in the Executive Summary and elsewhere, there are differences between the EPA and DOT approaches that derive different penetration rates for hybrid as well as other technologies. These derive from a range of factors, including but not limited to different penetration rates of EVs and PHEVs in the two agencies' reference fleets, and differences in technology effectiveness assumptions, and others.

Table 12.29 Absolute Technology Penetrations for Cars in the MY2025 Control Case Using ICMs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	9.1%	7.8%	18.1%	17.7%	1.2%	0.0%	6.5%	76.0%	52.6%	18.1%	88.4%	68.9%	0.1%	7.8%	4.6%	0.0%	51.4%	0.0%	36.5%	49.2%	0.5%
FCA	8.7%	8.4%	9.8%	22.1%	0.0%	0.0%	22.1%	68.3%	62.4%	2.0%	94.3%	66.0%	0.0%	2.8%	2.9%	0.0%	56.5%	0.0%	37.4%	12.4%	0.0%
FORD	6.1%	5.7%	50.4%	0.0%	4.4%	0.0%	85.7%	0.4%	40.7%	0.0%	95.6%	30.7%	3.7%	2.3%	2.9%	3.7%	30.7%	0.0%	0.0%	0.0%	0.0%
GM	6.8%	5.8%	39.5%	0.0%	0.6%	0.0%	69.5%	22.5%	51.9%	6.1%	97.0%	41.5%	0.0%	1.6%	2.7%	1.1%	44.3%	0.0%	20.2%	3.7%	0.5%
HONDA	4.2%	4.1%	11.5%	0.0%	11.8%	0.0%	69.4%	0.0%	57.9%	25.1%	94.5%	39.7%	12.0%	2.6%	3.0%	6.5%	38.6%	0.0%	0.0%	0.0%	0.0%
HYUNDAI/KIA	4.3%	4.0%	3.4%	8.5%	2.2%	0.0%	55.1%	37.1%	83.0%	1.6%	97.1%	71.2%	2.2%	1.3%	1.6%	1.2%	82.8%	0.0%	25.3%	5.0%	0.0%
JLR	19.9%	17.4%	0.3%	0.0%	0.0%	0.0%	0.0%	62.2%	60.4%	1.7%	62.2%	60.4%	0.0%	29.9%	11.8%	1.4%	60.4%	60.4%	0.0%	60.7%	0.0%
MAZDA	7.1%	7.1%	0.0%	0.0%	0.0%	0.0%	75.2%	0.0%	20.6%	0.0%	96.1%	20.6%	0.0%	1.8%	2.1%	0.0%	96.1%	0.0%	0.0%	0.0%	0.0%
MERCEDES-BENZ	11.5%	9.5%	15.4%	45.6%	0.0%	0.0%	2.1%	82.7%	23.6%	20.9%	84.7%	68.8%	0.0%	11.3%	4.3%	0.0%	23.6%	8.3%	10.9%	71.8%	0.1%
MITSUBISHI	5.6%	5.6%	9.6%	0.0%	0.0%	0.0%	51.8%	3.0%	64.1%	0.0%	95.5%	48.1%	0.0%	3.1%	1.4%	0.0%	48.1%	0.0%	0.0%	0.0%	0.0%
NISSAN	7.3%	7.3%	27.6%	0.1%	0.0%	0.0%	90.0%	0.4%	63.3%	0.0%	95.0%	39.0%	0.6%	2.7%	2.3%	0.0%	38.9%	0.0%	0.0%	0.0%	0.0%
SUBARU	3.1%	3.1%	10.1%	0.0%	0.0%	0.0%	77.8%	0.0%	48.1%	0.0%	96.1%	40.3%	0.0%	1.8%	2.1%	0.0%	4.5%	0.0%	0.0%	0.0%	0.0%
TESLA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TOYOTA	4.6%	4.1%	14.1%	0.0%	18.9%	0.0%	74.4%	0.3%	58.1%	0.0%	95.5%	42.5%	17.9%	2.4%	3.0%	18.7%	23.7%	0.0%	0.0%	0.0%	0.0%
VOLKSWAGEN	10.0%	8.2%	11.4%	46.5%	0.0%	0.0%	0.4%	81.6%	24.3%	18.0%	82.2%	70.2%	0.4%	13.6%	3.2%	0.0%	24.3%	17.1%	16.4%	66.7%	1.3%
VOLVO	10.9%	9.9%	20.5%	11.9%	0.0%	0.0%	0.0%	91.7%	59.4%	20.5%	91.7%	68.8%	0.0%	3.8%	4.5%	0.0%	56.9%	0.0%	51.6%	40.1%	0.0%
Fleet	6.3%	5.8%	20.5%	7.6%	4.7%	0.0%	58.9%	24.2%	54.3%	6.2%	93.1%	48.4%	4.5%	4.6%	2.7%	4.0%	43.9%	1.4%	12.1%	10.4%	0.2%

Table 12.30 Absolute Technology Penetrations for Cars in the MY2025 Control Case Using RPEs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	5.3%	4.6%	16.2%	0.0%	1.2%	0.0%	6.5%	74.0%	68.6%	16.2%	84.8%	68.9%	0.1%	9.7%	4.6%	0.0%	67.4%	1.2%	53.7%	30.2%	2.2%
FCA	6.1%	5.8%	9.5%	0.0%	0.0%	0.0%	11.7%	78.7%	84.8%	7.6%	94.3%	66.0%	0.0%	2.8%	2.9%	0.0%	78.5%	0.0%	56.7%	14.8%	0.0%
FORD	3.5%	3.3%	50.4%	0.0%	4.4%	0.0%	85.7%	0.4%	40.7%	0.0%	95.6%	30.7%	3.7%	2.3%	2.9%	3.7%	30.7%	0.0%	0.0%	0.0%	0.0%
GM	5.0%	4.7%	39.3%	0.0%	0.6%	0.0%	60.5%	32.5%	52.1%	6.1%	97.2%	41.5%	0.0%	1.6%	2.7%	1.1%	44.3%	0.0%	20.3%	6.6%	0.5%
HONDA	2.3%	2.3%	3.6%	0.0%	11.8%	0.0%	69.4%	0.0%	66.2%	30.2%	94.5%	29.3%	12.0%	2.6%	3.0%	6.5%	28.2%	0.0%	0.0%	0.0%	0.0%
HYUNDAI/KIA	3.6%	3.5%	3.4%	0.0%	2.2%	0.0%	47.2%	45.0%	91.5%	3.0%	97.1%	71.2%	2.2%	1.3%	1.6%	1.2%	83.0%	0.0%	57.6%	3.6%	0.0%
JLR	15.3%	12.6%	0.0%	0.0%	0.0%	0.0%	0.0%	62.4%	58.9%	3.6%	62.4%	58.9%	0.0%	29.9%	13.6%	3.6%	58.9%	58.9%	0.0%	58.9%	0.0%
MAZDA	6.7%	6.7%	0.0%	0.0%	0.0%	0.0%	75.2%	0.0%	20.6%	0.0%	96.1%	20.6%	0.0%	1.8%	2.1%	0.0%	96.1%	0.0%	0.0%	0.0%	0.0%
MERCEDES-BENZ	6.8%	5.6%	13.0%	0.0%	0.0%	0.0%	2.1%	80.2%	69.3%	13.0%	82.3%	68.8%	0.0%	13.9%	4.3%	0.0%	69.3%	11.4%	38.8%	41.4%	0.0%
MITSUBISHI	3.9%	3.9%	2.4%	0.0%	0.0%	0.0%	51.8%	3.0%	71.3%	0.0%	95.5%	55.3%	0.0%	3.1%	1.4%	0.0%	55.3%	0.0%	0.0%	0.0%	0.0%
NISSAN	5.9%	5.9%	27.6%	0.0%	0.0%	0.0%	90.0%	0.4%	52.9%	0.0%	95.0%	24.6%	0.6%	2.7%	2.3%	0.0%	24.6%	0.0%	0.1%	0.0%	0.0%
SUBARU	0.8%	0.8%	10.1%	0.0%	0.0%	0.0%	77.8%	0.0%	48.7%	0.0%	96.1%	40.3%	0.0%	1.8%	2.1%	0.0%	4.5%	0.0%	0.0%	0.0%	0.0%
TESLA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TOYOTA	3.1%	2.9%	14.1%	0.0%	18.9%	0.0%	74.4%	0.3%	58.1%	0.0%	95.5%	42.5%	17.9%	2.4%	3.0%	18.7%	23.7%	0.0%	0.0%	0.0%	0.0%
VOLKSWAGEN	7.9%	6.4%	9.7%	0.0%	0.0%	0.0%	0.4%	78.0%	66.2%	9.4%	75.8%	70.2%	0.4%	15.4%	3.2%	0.0%	66.2%	16.9%	27.4%	54.0%	6.0%
VOLVO	9.1%	8.2%	15.9%	0.0%	0.0%	0.0%	0.0%	87.1%	71.2%	15.9%	87.1%	68.8%	0.0%	8.7%	4.5%	0.0%	68.8%	0.0%	51.6%	35.5%	0.0%
Fleet	4.5%	4.2%	19.3%	0.0%	4.7%	0.0%	55.7%	27.1%	61.4%	6.5%	92.5%	46.1%	4.5%	4.8%	2.7%	4.0%	47.6%	1.5%	19.9%	8.4%	0.5%

Table 12.31 Absolute Technology Penetrations for Trucks in the MY2025 Control Case Using ICMs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	5.5%	3.5%	25.0%	17.9%	0.0%	0.0%	0.0%	100.0%	56.0%	42.9%	98.9%	75.0%	0.0%	0.0%	0.0%	0.0%	56.0%	47.6%	20.0%	80.0%	1.1%
FCA	6.5%	4.8%	16.0%	34.1%	0.0%	0.0%	0.0%	99.0%	47.6%	28.2%	97.7%	74.5%	0.0%	0.3%	0.4%	0.0%	42.2%	0.0%	18.3%	70.9%	1.6%
FORD	5.2%	5.0%	28.9%	7.9%	0.0%	0.0%	38.4%	61.3%	63.0%	7.3%	99.8%	62.7%	0.0%	0.1%	0.1%	0.0%	55.7%	0.0%	63.8%	7.8%	0.0%
GM	5.4%	4.8%	9.5%	14.2%	0.0%	0.0%	38.4%	61.4%	76.1%	6.5%	99.8%	72.5%	0.0%	0.1%	0.1%	0.0%	60.3%	0.0%	65.0%	24.1%	0.0%
HONDA	7.4%	7.4%	55.7%	0.0%	0.0%	0.0%	89.9%	8.0%	42.2%	0.0%	97.9%	25.7%	0.0%	1.0%	1.1%	0.0%	25.7%	0.0%	0.0%	0.0%	0.0%
HYUNDAI/KIA	10.1%	8.8%	12.5%	27.5%	0.0%	0.0%	0.0%	98.5%	58.5%	12.5%	98.5%	73.9%	0.0%	0.7%	0.8%	0.0%	58.5%	0.0%	10.0%	52.1%	0.0%
JLR	14.0%	12.1%	25.0%	0.0%	0.0%	0.0%	0.0%	100.0%	75.0%	25.0%	100.0%	75.0%	14.4%	0.0%	0.0%	0.0%	75.0%	75.0%	8.5%	77.1%	0.0%
MAZDA	8.9%	8.9%	28.4%	0.0%	0.0%	0.0%	97.2%	0.0%	51.6%	0.0%	97.2%	51.6%	0.0%	1.3%	1.5%	0.0%	68.9%	0.0%	0.0%	0.0%	0.0%
MERCEDES-BENZ	6.8%	4.8%	25.0%	0.0%	0.0%	0.0%	0.0%	100.0%	72.0%	25.0%	97.0%	75.0%	0.0%	0.0%	0.0%	0.0%	72.0%	72.0%	20.0%	80.0%	3.0%
MITSUBISHI	10.2%	10.2%	9.8%	0.0%	0.0%	0.0%	98.2%	0.0%	88.4%	0.0%	98.2%	66.3%	0.0%	0.6%	1.3%	0.0%	66.3%	0.0%	0.0%	0.0%	0.0%
NISSAN	8.2%	8.1%	40.8%	15.9%	1.4%	0.0%	70.1%	26.6%	41.5%	1.2%	98.8%	47.5%	1.4%	0.5%	0.7%	0.0%	34.9%	0.0%	12.6%	2.2%	0.0%
SUBARU	10.1%	9.9%	5.9%	0.0%	2.1%	0.0%	90.5%	0.0%	0.0%	0.0%	96.3%	3.9%	2.1%	1.7%	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TESLA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TOYOTA	6.6%	6.6%	29.6%	21.9%	0.7%	0.0%	77.3%	19.0%	45.0%	0.0%	98.7%	58.8%	0.7%	0.7%	0.6%	0.0%	36.4%	0.0%	17.5%	0.0%	0.0%
VOLKSWAGEN	9.6%	7.5%	25.7%	0.0%	0.0%	0.0%	0.9%	99.1%	70.1%	25.6%	95.8%	74.3%	0.9%	0.0%	0.0%	0.0%	70.1%	70.1%	19.8%	79.3%	4.2%
VOLVO	5.2%	3.2%	25.0%	21.4%	0.0%	0.0%	0.0%	100.0%	53.6%	46.4%	100.0%	75.0%	0.0%	0.0%	0.0%	0.0%	53.6%	33.6%	20.0%	80.0%	0.0%
Fleet	6.9%	6.2%	24.5%	14.8%	0.3%	0.0%	43.4%	54.7%	52.8%	10.5%	98.5%	58.9%	0.5%	0.4%	0.5%	0.0%	45.0%	5.9%	29.5%	26.9%	0.5%

Table 12.32 Absolute Technology Penetrations for Trucks in the MY2025 Control Case Using RPEs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	5.5%	3.5%	25.0%	0.0%	0.0%	0.0%	0.0%	100.0%	73.9%	25.0%	98.9%	75.0%	0.0%	0.0%	0.0%	0.0%	73.9%	47.6%	20.0%	80.0%	1.1%
FCA	5.8%	4.1%	16.0%	0.0%	0.0%	0.0%	0.0%	99.0%	81.7%	16.0%	97.7%	74.5%	0.0%	0.3%	0.4%	0.0%	76.3%	0.0%	21.2%	70.9%	1.6%
FORD	5.2%	5.2%	26.0%	0.0%	0.0%	0.0%	38.1%	61.7%	73.8%	2.1%	99.8%	65.5%	0.0%	0.1%	0.1%	0.0%	66.4%	0.0%	80.2%	2.6%	0.0%
GM	5.4%	5.2%	7.2%	0.0%	0.0%	0.0%	2.3%	97.5%	92.6%	6.5%	99.8%	69.9%	0.0%	0.1%	0.1%	0.0%	71.8%	0.0%	82.3%	9.9%	0.0%
HONDA	6.2%	6.2%	33.2%	0.0%	0.0%	0.0%	89.9%	8.0%	64.7%	0.0%	97.9%	48.1%	0.0%	1.0%	1.1%	0.0%	48.1%	0.0%	8.0%	0.0%	0.0%
HYUNDAI/KIA	7.7%	6.4%	12.5%	0.0%	0.0%	0.0%	0.0%	98.5%	86.0%	12.5%	98.5%	73.9%	0.0%	0.7%	0.8%	0.0%	86.0%	0.0%	10.0%	52.1%	0.0%
JLR	13.9%	12.0%	25.0%	0.0%	0.0%	0.0%	0.0%	100.0%	75.0%	25.0%	100.0%	75.0%	16.8%	0.0%	0.0%	0.0%	75.0%	75.0%	8.5%	74.7%	0.0%
MAZDA	6.3%	6.3%	24.8%	0.0%	0.0%	0.0%	97.2%	0.0%	55.3%	0.0%	97.2%	55.3%	0.0%	1.3%	1.5%	0.0%	72.5%	0.0%	3.6%	0.0%	0.0%
MERCEDES-BENZ	6.3%	4.3%	25.0%	0.0%	0.0%	0.0%	0.0%	100.0%	72.0%	25.0%	97.0%	75.0%	0.0%	0.0%	0.0%	0.0%	72.0%	72.0%	20.0%	80.0%	3.0%
MITSUBISHI	10.2%	10.2%	9.8%	0.0%	0.0%	0.0%	98.2%	0.0%	88.4%	0.0%	98.2%	66.3%	0.0%	0.6%	1.3%	0.0%	66.3%	0.0%	0.0%	0.0%	0.0%
NISSAN	7.6%	7.5%	15.4%	0.0%	1.4%	0.0%	77.5%	18.5%	82.9%	1.2%	98.8%	73.0%	1.4%	0.5%	0.7%	0.0%	73.7%	0.0%	54.0%	0.7%	0.0%
SUBARU	5.6%	5.5%	5.9%	0.0%	2.1%	0.0%	90.5%	0.0%	25.9%	0.0%	96.3%	29.5%	2.1%	1.7%	2.0%	0.0%	25.9%	0.0%	0.0%	0.0%	0.0%
TESLA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TOYOTA	6.6%	6.6%	32.1%	0.0%	0.7%	0.0%	77.3%	19.0%	64.5%	0.0%	98.7%	56.3%	0.7%	0.7%	0.6%	0.0%	54.6%	0.0%	36.9%	0.0%	0.0%
VOLKSWAGEN	8.3%	6.3%	25.7%	0.0%	0.0%	0.0%	0.9%	99.1%	70.1%	25.6%	95.8%	74.3%	0.9%	0.0%	0.0%	0.0%	70.1%	70.1%	19.8%	79.3%	4.2%
VOLVO	5.0%	3.8%	25.0%	0.0%	0.0%	0.0%	0.0%	100.0%	75.0%	25.0%	100.0%	75.0%	0.0%	0.0%	0.0%	0.0%	75.0%	14.0%	51.3%	48.7%	0.0%
Fleet	6.1%	5.6%	20.1%	0.0%	0.3%	0.0%	38.0%	60.1%	73.8%	7.0%	98.5%	64.2%	0.6%	0.4%	0.5%	0.0%	64.8%	5.8%	41.9%	23.4%	0.5%

Table 12.33 Absolute Technology Penetrations for the Fleet in the MY2025 Control Case Using ICMs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	8.2%	6.8%	19.7%	17.8%	0.9%	0.0%	5.0%	81.7%	53.4%	24.0%	90.9%	70.4%	0.1%	6.0%	3.5%	0.0%	52.5%	11.3%	32.6%	56.5%	0.6%
FCA	7.1%	5.9%	14.2%	30.5%	0.0%	0.0%	6.6%	89.8%	52.0%	20.4%	96.7%	71.9%	0.0%	1.0%	1.2%	0.0%	46.4%	0.0%	24.0%	53.5%	1.1%
FORD	5.6%	5.3%	37.9%	4.6%	1.9%	0.0%	58.2%	35.8%	53.7%	4.3%	98.0%	49.3%	1.5%	1.0%	1.3%	1.5%	45.2%	0.0%	37.1%	4.5%	0.0%
GM	6.1%	5.3%	24.6%	7.1%	0.3%	0.0%	54.0%	41.9%	63.9%	6.3%	98.4%	57.0%	0.0%	0.9%	1.4%	0.5%	52.2%	0.0%	42.5%	13.9%	0.3%
HONDA	5.7%	5.7%	32.1%	0.0%	6.3%	0.0%	79.0%	3.7%	50.6%	13.4%	96.1%	33.1%	6.4%	1.8%	2.1%	3.4%	32.6%	0.0%	0.0%	0.0%	0.0%
HYUNDAI/KIA	5.0%	4.6%	4.5%	10.8%	2.0%	0.0%	48.5%	44.4%	80.0%	2.9%	97.3%	71.5%	2.0%	1.3%	1.5%	1.1%	79.9%	0.0%	23.5%	10.7%	0.0%
JLR	15.2%	13.2%	19.8%	0.0%	0.0%	0.0%	0.0%	92.1%	72.0%	20.1%	92.1%	72.0%	11.4%	6.3%	2.5%	0.3%	72.0%	72.0%	6.7%	73.7%	0.0%
MAZDA	7.7%	7.7%	8.7%	0.0%	0.0%	0.0%	81.9%	0.0%	30.1%	0.0%	96.5%	30.1%	0.0%	1.6%	1.9%	0.0%	87.8%	0.0%	0.0%	0.0%	0.0%
MERCEDES-BENZ	9.7%	7.8%	19.1%	28.2%	0.0%	0.0%	1.3%	89.3%	42.1%	22.5%	89.4%	71.2%	0.0%	7.0%	2.7%	0.0%	42.1%	32.6%	14.4%	74.9%	1.2%
MITSUBISHI	7.2%	7.2%	9.6%	0.0%	0.0%	0.0%	68.4%	1.9%	72.8%	0.0%	96.5%	54.6%	0.0%	2.2%	1.4%	0.0%	54.6%	0.0%	0.0%	0.0%	0.0%
NISSAN	7.7%	7.6%	32.9%	6.3%	0.5%	0.0%	82.1%	10.8%	54.7%	0.5%	96.5%	42.4%	0.9%	1.8%	1.7%	0.0%	37.4%	0.0%	5.0%	0.9%	0.0%
SUBARU	8.5%	8.4%	6.9%	0.0%	1.6%	0.0%	87.7%	0.0%	10.8%	0.0%	96.2%	12.0%	1.6%	1.7%	2.0%	0.0%	1.0%	0.0%	0.0%	0.0%	0.0%
TESLA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TOYOTA	5.5%	5.2%	21.1%	9.9%	10.7%	0.0%	75.7%	8.8%	52.2%	0.0%	96.9%	49.9%	10.1%	1.6%	1.9%	10.2%	29.5%	0.0%	7.9%	0.0%	0.0%
VOLKSWAGEN	9.8%	7.9%	16.8%	28.9%	0.0%	0.0%	0.6%	88.2%	41.6%	20.9%	87.4%	71.7%	0.6%	8.5%	2.0%	0.0%	41.6%	37.2%	17.7%	71.5%	2.4%
VOLVO	7.9%	6.4%	22.8%	16.8%	0.0%	0.0%	0.0%	96.0%	56.4%	34.0%	96.0%	72.0%	0.0%	1.8%	2.1%	0.0%	55.2%	17.5%	35.1%	60.9%	0.0%
Fleet	6.6%	6.0%	22.4%	11.0%	2.6%	0.0%	51.5%	38.7%	53.6%	8.3%	95.7%	53.4%	2.6%	2.6%	1.7%	2.1%	44.4%	3.6%	20.4%	18.3%	0.3%

Table 12.34 Absolute Technology Penetrations for the Fleet in the MY2025 Control Case Using RPEs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	5.4%	4.3%	18.3%	0.0%	0.9%	0.0%	5.0%	80.2%	69.9%	18.3%	88.2%	70.4%	0.1%	7.4%	3.5%	0.0%	69.0%	12.3%	45.6%	42.1%	1.9%
FCA	5.9%	4.6%	14.1%	0.0%	0.0%	0.0%	3.5%	92.9%	82.6%	13.5%	96.7%	71.9%	0.0%	1.0%	1.2%	0.0%	77.0%	0.0%	31.8%	54.2%	1.1%
FORD	4.5%	4.4%	36.2%	0.0%	1.9%	0.0%	58.0%	36.0%	59.9%	1.2%	98.0%	51.0%	1.5%	1.0%	1.3%	1.5%	51.5%	0.0%	46.6%	1.5%	0.0%
GM	5.2%	4.9%	23.3%	0.0%	0.3%	0.0%	31.5%	64.9%	72.3%	6.3%	98.5%	55.7%	0.0%	0.9%	1.4%	0.5%	58.0%	0.0%	51.2%	8.2%	0.3%
HONDA	4.1%	4.1%	17.4%	0.0%	6.3%	0.0%	79.0%	3.7%	65.5%	16.1%	96.1%	38.1%	6.4%	1.8%	2.1%	3.4%	37.5%	0.0%	3.7%	0.0%	0.0%
HYUNDAI/KIA	4.1%	3.8%	4.5%	0.0%	2.0%	0.0%	41.5%	51.4%	90.8%	4.2%	97.3%	71.5%	2.0%	1.3%	1.5%	1.1%	83.3%	0.0%	51.9%	9.4%	0.0%
JLR	14.2%	12.1%	19.8%	0.0%	0.0%	0.0%	0.0%	92.1%	71.6%	20.5%	92.1%	71.6%	13.3%	6.3%	2.9%	0.7%	71.6%	71.6%	6.7%	71.4%	0.0%
MAZDA	6.6%	6.6%	7.6%	0.0%	0.0%	0.0%	81.9%	0.0%	31.2%	0.0%	96.5%	31.2%	0.0%	1.6%	1.9%	0.0%	88.9%	0.0%	1.1%	0.0%	0.0%
MERCEDES-BENZ	6.6%	5.1%	17.5%	0.0%	0.0%	0.0%	1.3%	87.8%	70.3%	17.5%	87.9%	71.2%	0.0%	8.6%	2.7%	0.0%	70.3%	34.5%	31.6%	56.1%	1.2%
MITSUBISHI	6.1%	6.1%	5.0%	0.0%	0.0%	0.0%	68.4%	1.9%	77.4%	0.0%	96.5%	59.2%	0.0%	2.2%	1.4%	0.0%	59.2%	0.0%	0.0%	0.0%	0.0%
NISSAN	6.6%	6.5%	22.8%	0.0%	0.5%	0.0%	85.0%	7.6%	64.8%	0.5%	96.5%	43.8%	0.9%	1.8%	1.7%	0.0%	44.0%	0.0%	21.4%	0.3%	0.0%
SUBARU	4.5%	4.4%	6.9%	0.0%	1.6%	0.0%	87.7%	0.0%	31.0%	0.0%	96.2%	31.9%	1.6%	1.7%	2.0%	0.0%	21.1%	0.0%	0.0%	0.0%	0.0%
TESLA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TOYOTA	4.7%	4.6%	22.3%	0.0%	10.7%	0.0%	75.7%	8.8%	61.0%	0.0%	96.9%	48.8%	10.1%	1.6%	1.9%	10.2%	37.7%	0.0%	16.7%	0.0%	0.0%
VOLKSWAGEN	8.1%	6.3%	15.7%	0.0%	0.0%	0.0%	0.6%	86.0%	67.7%	15.5%	83.4%	71.7%	0.6%	9.6%	2.0%	0.0%	67.7%	37.0%	24.5%	63.5%	5.3%
VOLVO	7.0%	5.9%	20.6%	0.0%	0.0%	0.0%	0.0%	93.8%	73.2%	20.6%	93.8%	72.0%	0.0%	4.2%	2.1%	0.0%	72.0%	7.3%	51.4%	42.4%	0.0%
Fleet	5.3%	4.8%	19.7%	0.0%	2.6%	0.0%	47.3%	42.9%	67.3%	6.7%	95.4%	54.7%	2.6%	2.7%	1.7%	2.1%	55.8%	3.6%	30.4%	15.6%	0.5%

Table 12.35 Incremental Technology Penetrations for Cars in the MY2025 Central Analysis Using ICMs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	2%	3%	-29%	7%	0%	0%	-56%	53%	23%	-31%	-2%	40%	0%	4%	0%	0%	35%	0%	-31%	37%	-3%
FCA	1%	1%	-26%	22%	0%	0%	-49%	51%	11%	-9%	0%	53%	0%	0%	0%	0%	43%	0%	36%	12%	0%
FORD	2%	1%	11%	0%	-19%	0%	19%	0%	41%	0%	0%	31%	0%	0%	0%	0%	31%	0%	0%	0%	0%
GM	2%	1%	-9%	0%	-9%	0%	-4%	13%	45%	-6%	0%	41%	0%	0%	0%	0%	44%	0%	9%	3%	0%
HONDA	1%	1%	12%	0%	-64%	0%	64%	0%	49%	-69%	0%	39%	0%	0%	0%	0%	39%	0%	0%	0%	0%
HYUNDAI/KIA	0%	0%	-10%	9%	-1%	0%	-19%	20%	38%	2%	0%	61%	0%	0%	0%	0%	73%	0%	24%	5%	0%
JLR	4%	2%	-51%	-4%	0%	0%	-51%	38%	40%	-50%	-13%	36%	0%	15%	1%	1%	40%	60%	-35%	20%	0%
MAZDA	0%	0%	0%	0%	-75%	0%	75%	0%	21%	0%	0%	21%	0%	0%	0%	0%	0%	0%	0%	0%	0%
MERCEDES-BENZ	1%	-1%	-47%	30%	0%	0%	-62%	55%	11%	-41%	-6%	41%	0%	7%	0%	0%	11%	8%	-66%	59%	-1%
MITSUBISHI	1%	1%	0%	0%	-10%	0%	8%	2%	44%	0%	0%	48%	0%	0%	0%	0%	48%	0%	0%	0%	0%
NISSAN	1%	1%	9%	0%	-26%	0%	26%	0%	63%	-5%	0%	39%	0%	0%	0%	0%	39%	0%	0%	0%	0%
SUBARU	0%	0%	1%	0%	-78%	0%	78%	0%	48%	0%	0%	5%	0%	0%	0%	0%	5%	0%	0%	0%	0%
TESLA	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TOYOTA	1%	1%	14%	0%	-50%	0%	49%	0%	58%	-1%	0%	24%	0%	0%	0%	0%	24%	0%	0%	0%	0%
VOLKSWAGEN	1%	0%	-40%	34%	0%	0%	-60%	56%	7%	-26%	1%	35%	0%	9%	0%	0%	7%	16%	-46%	38%	-11%
VOLVO	1%	0%	-64%	8%	0%	0%	-73%	73%	56%	20%	0%	62%	0%	0%	0%	0%	54%	0%	46%	40%	0%
Fleet	1%	1%	-5%	6%	-23%	0%	7%	16%	40%	-13%	0%	39%	0%	1%	0%	0%	37%	1%	1%	8%	-1%

Table 12.36 Incremental Technology Penetrations for Cars in the MY2025 Central Analysis Using RPEs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	0%	0%	-33%	0%	0%	0%	-55%	50%	30%	-35%	-5%	40%	0%	6%	0%	0%	40%	1%	-20%	18%	-1%
FCA	1%	0%	-26%	0%	0%	0%	-60%	61%	39%	-8%	0%	53%	0%	0%	0%	0%	65%	0%	55%	15%	0%
FORD	0%	0%	19%	0%	-14%	0%	17%	-3%	41%	0%	0%	31%	0%	0%	0%	0%	31%	0%	0%	0%	0%
GM	1%	1%	-9%	0%	-1%	0%	-13%	15%	44%	-6%	0%	41%	0%	0%	0%	0%	44%	0%	9%	6%	0%
HONDA	0%	0%	4%	0%	-48%	0%	51%	0%	57%	-64%	0%	28%	0%	0%	0%	0%	28%	0%	0%	0%	0%
HYUNDAI/KIA	0%	0%	-10%	0%	0%	0%	-27%	27%	18%	3%	0%	61%	0%	0%	0%	0%	73%	0%	56%	4%	0%
JLR	2%	1%	-49%	0%	0%	0%	-49%	38%	35%	-43%	-10%	35%	0%	12%	3%	4%	35%	59%	-35%	21%	0%
MAZDA	0%	0%	0%	0%	-53%	0%	53%	0%	21%	0%	0%	21%	0%	0%	0%	0%	0%	0%	0%	0%	0%
MERCEDES-BENZ	0%	0%	-49%	0%	0%	0%	-61%	53%	41%	-43%	-8%	41%	0%	9%	0%	0%	41%	11%	-5%	-3%	0%
MITSUBISHI	0%	0%	-7%	0%	-4%	0%	8%	-4%	44%	0%	0%	55%	0%	0%	0%	0%	55%	0%	0%	0%	0%
NISSAN	0%	0%	18%	0%	-14%	0%	17%	-3%	53%	-10%	0%	25%	0%	0%	0%	0%	25%	0%	0%	0%	0%
SUBARU	0%	0%	1%	0%	-77%	0%	77%	0%	49%	0%	0%	5%	0%	0%	0%	0%	5%	0%	0%	0%	0%
TESLA	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TOYOTA	0%	0%	14%	0%	-17%	0%	17%	0%	58%	-1%	0%	24%	0%	0%	0%	0%	24%	0%	0%	0%	0%
VOLKSWAGEN	1%	0%	-36%	0%	0%	0%	-59%	52%	32%	-24%	-3%	35%	0%	9%	0%	0%	37%	16%	-34%	25%	-6%
VOLVO	0%	-1%	-68%	0%	0%	0%	-73%	69%	63%	16%	-5%	60%	0%	5%	0%	0%	60%	0%	34%	36%	0%
Fleet	0%	0%	-4%	0%	-13%	0%	-4%	17%	42%	-13%	-1%	36%	0%	1%	0%	0%	39%	1%	10%	5%	0%

Table 12.37 Incremental Technology Penetrations for Trucks in the MY2025 Central Analysis Using ICMs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	0%	-1%	-44%	8%	0%	0%	-71%	71%	38%	-33%	2%	44%	0%	0%	0%	0%	38%	45%	-35%	35%	-2%
FCA	1%	-1%	-34%	22%	0%	0%	-78%	79%	14%	26%	1%	55%	0%	0%	0%	0%	30%	0%	-11%	71%	-1%
FORD	0%	0%	-38%	8%	-9%	0%	-41%	50%	63%	7%	0%	63%	0%	0%	0%	0%	56%	0%	64%	8%	0%
GM	0%	-1%	-19%	14%	0%	0%	-41%	41%	11%	6%	0%	71%	0%	0%	0%	0%	58%	0%	65%	24%	0%
HONDA	2%	2%	56%	0%	-36%	0%	28%	8%	-13%	-98%	0%	26%	0%	0%	0%	0%	26%	0%	0%	0%	0%
HYUNDAI/KIA	3%	2%	-37%	27%	0%	0%	-79%	79%	10%	12%	0%	62%	0%	0%	0%	0%	46%	0%	-2%	52%	0%
JLR	1%	1%	-45%	0%	0%	0%	-70%	70%	45%	-45%	0%	45%	3%	0%	0%	0%	45%	45%	-30%	27%	0%
MAZDA	3%	3%	28%	0%	-19%	0%	19%	0%	52%	0%	0%	52%	0%	0%	0%	0%	0%	0%	0%	0%	0%
MERCEDES-BENZ	0%	-1%	-41%	-12%	0%	0%	-70%	70%	58%	-54%	5%	41%	0%	0%	0%	0%	58%	58%	-30%	30%	-5%
MITSUBISHI	2%	2%	10%	0%	0%	0%	20%	-20%	88%	-53%	10%	66%	0%	0%	0%	0%	66%	0%	0%	0%	0%
NISSAN	1%	1%	-16%	16%	-16%	0%	-6%	23%	42%	-1%	0%	48%	0%	0%	0%	0%	35%	0%	13%	2%	0%
SUBARU	5%	4%	3%	0%	-90%	0%	90%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TESLA	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TOYOTA	1%	1%	-22%	22%	-16%	0%	0%	15%	45%	0%	0%	53%	0%	0%	0%	0%	36%	0%	17%	0%	0%
VOLKSWAGEN	1%	0%	-40%	-8%	0%	0%	-69%	69%	55%	-49%	6%	40%	0%	0%	0%	0%	55%	55%	-30%	30%	-6%
VOLVO	0%	-1%	-48%	10%	0%	0%	-76%	76%	38%	31%	0%	48%	0%	0%	0%	0%	38%	34%	-23%	61%	0%
Fleet	1%	1%	-18%	12%	-14%	0%	-28%	42%	28%	-6%	0%	51%	0%	0%	0%	0%	40%	5%	19%	23%	0%

Table 12.38 Incremental Technology Penetrations for Trucks in the MY2025 Central Analysis Using RPEs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	0%	-1%	-41%	0%	0%	0%	-77%	77%	46%	-36%	4%	41%	0%	0%	0%	0%	46%	35%	-62%	64%	-4%
FCA	0%	-1%	-31%	0%	0%	0%	-77%	78%	35%	12%	1%	50%	0%	0%	0%	0%	54%	0%	-10%	70%	-1%
FORD	0%	0%	-33%	0%	-3%	0%	-42%	45%	74%	2%	0%	66%	0%	0%	0%	0%	66%	0%	80%	3%	0%
GM	0%	0%	-22%	0%	0%	0%	-78%	78%	27%	6%	0%	68%	0%	0%	0%	0%	70%	0%	76%	10%	0%
HONDA	0%	0%	33%	0%	-20%	0%	12%	8%	9%	-98%	0%	48%	0%	0%	0%	0%	48%	0%	8%	0%	0%
HYUNDAI/KIA	1%	-1%	-25%	0%	0%	0%	-79%	79%	25%	12%	0%	49%	0%	0%	0%	0%	61%	0%	10%	52%	0%
JLR	2%	1%	-45%	0%	0%	0%	-70%	70%	45%	-45%	0%	45%	5%	0%	0%	0%	45%	45%	-30%	25%	0%
MAZDA	1%	1%	25%	0%	-19%	0%	19%	0%	55%	0%	0%	55%	0%	0%	0%	0%	4%	0%	4%	0%	0%
MERCEDES-BENZ	0%	0%	-42%	0%	0%	0%	-70%	70%	47%	-42%	5%	42%	0%	0%	0%	0%	47%	65%	-30%	30%	-5%
MITSUBISHI	2%	2%	10%	0%	0%	0%	20%	-20%	86%	-51%	7%	66%	0%	0%	0%	0%	66%	0%	0%	0%	0%
NISSAN	1%	1%	-11%	0%	-4%	0%	1%	3%	82%	-1%	0%	72%	0%	0%	0%	0%	73%	0%	54%	1%	0%
SUBARU	0%	0%	3%	0%	-86%	0%	86%	0%	26%	0%	0%	26%	0%	0%	0%	0%	26%	0%	0%	0%	0%
TESLA	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TOYOTA	1%	1%	26%	0%	-5%	0%	0%	5%	64%	0%	0%	50%	0%	0%	0%	0%	55%	0%	37%	0%	0%
VOLKSWAGEN	0%	0%	-40%	0%	0%	0%	-69%	69%	47%	-40%	6%	40%	0%	0%	0%	0%	47%	58%	-30%	30%	-6%
VOLVO	0%	-1%	-47%	0%	0%	0%	-80%	80%	47%	1%	0%	47%	0%	0%	0%	0%	47%	14%	5%	29%	0%
Fleet	0%	0%	-13%	0%	-9%	0%	-35%	44%	46%	-9%	1%	55%	0%	0%	0%	0%	56%	5%	30%	19%	0%

Table 12.39 Incremental Technology Penetrations for the Fleet in the MY2025 Central Analysis Using ICMs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	1%	2%	-33%	7%	0%	0%	-59%	57%	27%	-31%	-1%	41%	0%	3%	0%	0%	35%	11%	-32%	36%	-3%
FCA	1%	0%	-31%	22%	0%	0%	-70%	71%	13%	16%	0%	54%	0%	0%	0%	0%	34%	0%	3%	53%	0%
FORD	1%	1%	-17%	5%	-13%	0%	-16%	29%	54%	4%	0%	49%	0%	0%	0%	0%	45%	0%	37%	5%	0%
GM	1%	0%	-14%	7%	-4%	0%	-23%	27%	28%	0%	0%	56%	0%	0%	0%	0%	51%	0%	37%	14%	0%
HONDA	1%	1%	32%	0%	-51%	0%	47%	4%	20%	-83%	0%	33%	0%	0%	0%	0%	33%	0%	0%	0%	0%
HYUNDAI/KIA	1%	0%	-13%	11%	-1%	0%	-26%	27%	34%	3%	0%	61%	0%	0%	0%	0%	69%	0%	21%	11%	0%
JLR	2%	1%	-46%	-1%	0%	0%	-66%	63%	44%	-46%	-3%	43%	2%	3%	0%	0%	44%	48%	-31%	26%	0%
MAZDA	1%	1%	9%	0%	-58%	0%	58%	0%	30%	0%	0%	30%	0%	0%	0%	0%	0%	0%	0%	0%	0%
MERCEDES-BENZ	1%	-1%	-45%	14%	0%	0%	-65%	61%	29%	-46%	-2%	41%	0%	4%	0%	0%	29%	27%	-52%	48%	-2%
MITSUBISHI	2%	2%	4%	0%	-7%	0%	12%	-6%	60%	-19%	4%	55%	0%	0%	0%	0%	55%	0%	0%	0%	0%
NISSAN	1%	1%	-1%	6%	-22%	0%	13%	10%	55%	-3%	0%	42%	0%	0%	0%	0%	37%	0%	5%	1%	0%
SUBARU	4%	3%	3%	0%	-87%	0%	87%	0%	11%	0%	0%	1%	0%	0%	0%	0%	1%	0%	0%	0%	0%
TESLA	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TOYOTA	1%	1%	-2%	10%	-34%	0%	27%	7%	52%	-1%	0%	37%	0%	0%	0%	0%	29%	0%	8%	0%	0%
VOLKSWAGEN	1%	0%	-40%	18%	0%	0%	-64%	61%	25%	-35%	3%	37%	0%	6%	0%	0%	25%	30%	-40%	35%	-9%
VOLVO	1%	0%	-56%	9%	0%	0%	-75%	75%	47%	26%	0%	55%	0%	0%	0%	0%	46%	17%	10%	51%	0%
Fleet	1%	1%	-11%	9%	-19%	0%	-10%	28%	34%	-10%	0%	44%	0%	1%	0%	0%	38%	3%	10%	15%	-1%

Table 12.40 Incremental Technology Penetrations for the Fleet in the MY2025 Central Analysis Using RPEs

	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
BMW	0%	0%	-35%	0%	0%	0%	-60%	57%	34%	-35%	-3%	40%	0%	5%	0%	0%	41%	9%	-30%	29%	-2%
FCA	0%	-1%	-29%	0%	0%	0%	-72%	73%	36%	6%	0%	51%	0%	0%	0%	0%	57%	0%	10%	53%	0%
FORD	0%	0%	-11%	0%	-8%	0%	-17%	25%	60%	1%	0%	51%	0%	0%	0%	0%	51%	0%	47%	2%	0%
GM	1%	0%	-15%	0%	-1%	0%	-45%	46%	36%	0%	0%	54%	0%	0%	0%	0%	57%	0%	42%	8%	0%
HONDA	0%	0%	17%	0%	-35%	0%	32%	4%	35%	-80%	0%	38%	0%	0%	0%	0%	38%	0%	4%	0%	0%
HYUNDAI/KIA	0%	0%	-12%	0%	0%	0%	-33%	33%	19%	4%	0%	60%	0%	0%	0%	0%	72%	0%	51%	9%	0%
JLR	2%	1%	-46%	0%	0%	0%	-66%	63%	43%	-45%	-2%	43%	4%	3%	1%	1%	43%	48%	-31%	24%	0%
MAZDA	0%	0%	8%	0%	-43%	0%	43%	0%	31%	0%	0%	31%	0%	0%	0%	0%	1%	0%	1%	0%	0%
MERCEDES-BENZ	0%	0%	-46%	0%	0%	0%	-65%	59%	43%	-43%	-3%	41%	0%	6%	0%	0%	43%	32%	-15%	9%	-2%
MITSUBISHI	1%	1%	-1%	0%	-2%	0%	12%	-10%	59%	-18%	3%	59%	0%	0%	0%	0%	59%	0%	0%	0%	0%
NISSAN	0%	0%	7%	0%	-10%	0%	11%	-1%	65%	-6%	0%	44%	0%	0%	0%	0%	44%	0%	21%	0%	0%
SUBARU	0%	0%	3%	0%	-84%	0%	84%	0%	31%	0%	0%	21%	0%	0%	0%	0%	21%	0%	0%	0%	0%
TESLA	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TOYOTA	1%	1%	20%	0%	-12%	0%	10%	2%	61%	-1%	0%	36%	0%	0%	0%	0%	38%	0%	17%	0%	0%
VOLKSWAGEN	0%	0%	-38%	0%	0%	0%	-63%	59%	38%	-30%	0%	37%	0%	6%	0%	0%	41%	32%	-32%	27%	-6%
VOLVO	0%	-1%	-57%	0%	0%	0%	-77%	75%	55%	8%	-2%	53%	0%	2%	0%	0%	53%	7%	19%	32%	0%
Fleet	0%	0%	-8%	0%	-11%	0%	-19%	30%	43%	-11%	0%	45%	0%	1%	0%	0%	47%	3%	20%	12%	0%

Table 12.41 Summary of Absolute Technology Penetrations in the MY2025 Control Case

Indirect Cost Approach	C/T/Fleet	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
ICM	C	6.3%	5.8%	20.5%	7.6%	4.7%	0.0%	58.9%	24.2%	54.3%	6.2%	93.1%	48.4%	4.5%	4.6%	2.7%	4.0%	43.9%	1.4%	12.1%	10.4%	0.2%
ICM	T	6.9%	6.2%	24.5%	14.8%	0.3%	0.0%	43.4%	54.7%	52.8%	10.5%	98.5%	58.9%	0.5%	0.4%	0.5%	0.0%	45.0%	5.9%	29.5%	26.9%	0.5%
ICM	Fleet	6.6%	6.0%	22.4%	11.0%	2.6%	0.0%	51.5%	38.7%	53.6%	8.3%	95.7%	53.4%	2.6%	2.6%	1.7%	2.1%	44.4%	3.6%	20.4%	18.3%	0.3%
RPE	C	4.5%	4.2%	19.3%	0.0%	4.7%	0.0%	55.7%	27.1%	61.4%	6.5%	92.5%	46.1%	4.5%	4.8%	2.7%	4.0%	47.6%	1.5%	19.9%	8.4%	0.5%
RPE	T	6.1%	5.6%	20.1%	0.0%	0.3%	0.0%	38.0%	60.1%	73.8%	7.0%	98.5%	64.2%	0.6%	0.4%	0.5%	0.0%	64.8%	5.8%	41.9%	23.4%	0.5%
RPE	Fleet	5.3%	4.8%	19.7%	0.0%	2.6%	0.0%	47.3%	42.9%	67.3%	6.7%	95.4%	54.7%	2.6%	2.7%	1.7%	2.1%	55.8%	3.6%	30.4%	15.6%	0.5%

Table 12.42 Summary of Incremental Technology Penetrations in the MY2025 Control Case

Indirect Cost Approach	C/T/Fleet	WR Tech	WR Net	TDS 18	TDS 24	TRX 11	TRX 12	TRX 21	TRX 22	Deac	VVLT	VVT	CEGR	Strong HEV	EV	PHEV	ATK1	ATK2	Miller	Stop-Start	Mild HEV	DSL
ICM	C	1%	1%	-5%	6%	-23%	0%	7%	16%	40%	-13%	0%	39%	0%	1%	0%	0%	37%	1%	1%	8%	-1%
ICM	T	1%	1%	-18%	12%	-14%	0%	-28%	42%	28%	-6%	0%	51%	0%	0%	0%	0%	40%	5%	19%	23%	0%
ICM	Fleet	1%	1%	-11%	9%	-19%	0%	-10%	28%	34%	-10%	0%	44%	0%	1%	0%	0%	38%	3%	10%	15%	-1%
RPE	C	0%	0%	-4%	0%	-13%	0%	-4%	17%	42%	-13%	-1%	36%	0%	1%	0%	0%	39%	1%	10%	5%	0%
RPE	T	0%	0%	-13%	0%	-9%	0%	-35%	44%	46%	-9%	1%	55%	0%	0%	0%	0%	56%	5%	30%	19%	0%
RPE	Fleet	0%	0%	-8%	0%	-11%	0%	-19%	30%	43%	-11%	0%	45%	0%	1%	0%	0%	47%	3%	20%	12%	0%

Not readily apparent in the technology penetration tables above is the number, or percentage, of vehicles that receive specific levels of mass reduction. Table 12.43 below provides more detail on mass reduction technology using the same approach as described in the text accompanying Table 12.28.

Table 12.43 Percentage of Vehicles Receiving the Mass Reduction Levels within the Indicated Ranges in the MY2025 Control Case Using ICMs and AEO Reference Case Fuel Prices

Fleet	%MR Range	Baseline	WRtech	WRnet
Including ZEV Program Vehicles	<=5%	87.0%	57.4%	61.0%
	5% to <=10%	9.1%	30.7%	28.0%
	10% to <=15%	0.9%	7.3%	8.3%
	15% to <=20%	3.0%	4.6%	2.7%
Excluding ZEV Program Vehicles	<=5%	89.3%	58.9%	62.6%
	5% to <=10%	9.3%	31.5%	28.8%
	10% to <=15%	0.9%	7.5%	8.5%
	15% to <=20%	0.5%	2.1%	0.2%

12.1.1.4 Comparisons to the 2012 Final Rule

Of interest is how the costs estimated in this Draft TAR analysis compare to those presented in the 2012 FRM. In that analysis, since we were setting standards for MY2017-2025, we did not present costs relative to a reference case consisting of the MY2021 standards. Instead, we presented costs relative to a reference case consisting of the MY2016 standards. In Table 12.44 we have broken out the Draft TAR costs/vehicle along with the closest matching costs/vehicle from the 2012 FRM. The entries of perhaps most interest are those shown for the incremental costs to bring the fleet down to the 2025 standards, shown as $1070 for the 2012 FRM and $894 for the Draft TAR. Because the baseline fleets are completely different, comparisons of the costs to bring the baseline fleets down to the 2016 standards are not valid comparisons. Instead, the relative values of these entries simply show that the 2014 fleet is nearly complying with the 2016 standards, as one would expect. The same is true for the bottom row showing total costs. The costs to bring the 2008 fleet, projected forward to MY2025, into compliance with the 2025 standards should be considerably higher than the costs to bring the 2014 fleet, projected forward to MY2025, into compliance with those standards. This is reflected in the bottom-row values in the table. The differences in the costs to bring the respective baseline fleets down to the each incrementally lower standard level are driven by many factors including, but not limited to: car/truck fleet mix and footprint characteristics are more favorable to lower costs because of the relatively larger number of car-like trucks that emit more like cars but are actually subject to the less stringent truck curve; new and very cost effective technologies like Atkinson 2 and mild hybrid 48V technologies that were not even considered in the 2012 FRM; updated and more comprehensive studies informing our mass reduction cost estimates; inclusion of ZEV required EV and PHEV sales which was not considered for the FRM. To better understand the impact some of these factors have on the overall analysis, EPA has also performed several sensitivity analyses which are described below in Chapter 12.2.4.

Table 12.44 Cost per Vehicle Comparison – 2012 FRM (2010$) vs Draft TAR (2013$)

Note: Due to large differences in the baseline fleets used (2008 vs. 2014), the 2012 FRM values and the Draft TAR results are not directly comparable.	FRM (2008 baseline fleet in MY2025)	Draft TAR (2014 baseline fleet in MY2025)
Cost to bring the baseline fleet down to the 2016 standards	$719	$279
Incremental cost to bring that fleet down to the 2021 standards	$766	$393
Incremental cost to bring that baseline fleet down to the 2025 standards	$1070	$894
Total costs to bring the baseline fleet down to the 2025 standards	$2555	$1565

Note: The $719 value can be found in EPA's final RIA (EPA-420-R-12-016) at Table 3.6-1; the $766 value can be found in EPA's final RIA at Table 3.6-2 and is actually a MY2021 cost presented here as a proxy for a MY2025 cost; the $1070 value is calculated as $2555 (see final RIA Table 7.4-5) minus $766 minus $719; the $393 value is calculated as $671 (see Table 12.97, "Reference Case in MY2025" entry for the Combined Fleet) minus $279; the $894 value can be found in Table 12.17 and the $1565 value can be found in Table 12.97, "Control Case in MY2025" entry for the Combined Fleet.

We can also consider the technology penetration rate differences between the 2012 FRM and this Draft TAR. Here we focus only on the final, absolute technology penetrations projected in the 2012 FRM and those projected in this Draft TAR in the ICM-based central analysis. The absolute technology penetrations for the technologies generally considered to be of most interest are shown in the table below.

Table 12.45 Final Technology Penetration Comparison – 2012 FRM vs Draft TAR

Technology	2012 FRM	Draft TAR
Gasoline direct injection engine	94%	79%
8+ speeds & improved CVTs	91%	90%
Turbocharged and downsized gasoline engine	93%	33%
Higher compression ratio/naturally aspirated gasoline engine (Atkinson-2)	n/a	44%
Stop-start	15%	20%
Mild HEV	26%	18%
Strong HEV	5%	3%
EV+PHEV	2%	4%

Note: 2012 FRM values taken from EPA's final RIA Table 3.5-25; Atkinson-2 was not considered in the 2012 FRM; mild HEV used a 110/115V battery in the 2012 FRM but uses a 48V battery in this Draft TAR.

This table highlights two important results: (1) EPA's 2012 FRM analysis featured a high penetration of turbocharged/downsized engine technology, a technology that is projected less in EPA's Draft TAR analysis due to the inclusion of the new and more cost-effective Atkinson-2 technology which provides dual non-electrified pathways toward compliance with the MY2022-2025 standards (both turbocharging/downsizing and Atkinson-2); and, (2) just two years into the 2012-2016 GHG program, a new technology—Atkinson-2—which was not previously considered by the agencies, has emerged as one of the most promising non-electrified technologies capable of playing a major role in compliance with the standards through 2025. Further, while not as highly projected as Atkinson-2 in our analysis, the mild HEV 48V technology represents yet another cost effective technology that can provide another pathway toward compliance. EPA has confidence that other technologies will emerge in the coming years and we will consider further developments as the midterm evaluation progresses.

12.1.2 Sensitivity Analysis Results

12.1.2.1 Reference Case: CO_2 Targets

The different AEO 2015 fuel price cases (shown in Chapter 3, Figure 3.3) carry with them unique fleet projections since higher fuel prices are projected to result in fewer truck and more car sales, while lower fuel prices are projected to result in fewer car sales and more truck sales. As a result of these fleet mix differences, the manufacturer-specific footprint based standards would result in different fleet-wide CO_2 target values for each AEO 2015 fuel price case and projected fleet. While we have conducted additional sensitivity runs beyond varying the fuel price projections, only these two fuel price sensitivities (high and low) result in unique CO_2 target values. All other sensitivity runs use the AEO 2015 reference case fuel prices, fleets and resultant targets.

Table 12.46 Reference Case CO_2 Targets in MY2025 for Each Sensitivity Case (g/mi)

	Car			Truck			Combined		
Manufacturer	AEO Ref	AEO High	AEO Low	AEO Ref	AEO High	AEO Low	AEO Ref	AEO High	AEO Low
BMW	177.5	177.2	177.5	237.0	236.8	237.0	191.7	187.9	193.6
FCA	182.3	182.2	182.3	247.2	246.2	247.5	227.9	221.9	230.3
Ford	179.6	179.4	179.7	280.0	278.3	280.6	237.9	227.2	242.5
GM	178.8	178.6	178.9	277.3	276.4	277.6	227.9	217.7	232.4
Honda	172.8	172.6	172.9	232.9	232.4	233.0	200.8	195.2	203.4
Hyundai/Kia	177.1	176.9	177.1	227.9	227.9	227.8	183.1	181.4	184.1
JLR	189.7	189.8	189.6	235.0	234.7	235.0	225.5	222.6	226.6
Mazda	175.2	175.2	175.2	223.4	223.1	223.5	190.0	186.5	191.7
Mercedes-Benz	180.0	179.9	180.0	237.0	236.8	237.0	201.7	196.9	204.0
Mitsubishi	164.8	164.8	164.8	208.4	208.3	208.4	180.4	176.8	182.1
Nissan	173.3	173.2	173.3	243.0	242.1	243.2	200.9	194.5	203.8
Subaru	170.0	169.7	170.1	210.5	210.4	210.5	201.4	198.4	202.5
Tesla	205.7	205.7	205.7	0.0	0.0	0.0	205.7	205.7	205.7
Toyota	174.5	174.4	174.6	246.3	245.1	246.7	207.0	199.9	210.2
Volkswagen	174.6	174.5	174.6	230.4	230.3	230.5	195.7	191.1	197.8
Volvo	182.0	182.0	182.0	227.7	227.7	227.7	205.8	201.9	207.6
Fleet	176.9	176.8	177.0	251.3	249.9	251.7	212.4	204.9	215.7

12.1.2.2 Control Case: CO_2 Targets

Table 12.47 Control Case CO_2 Targets in MY2025 for Each Sensitivity Case (g/mi)

	Car			Truck			Combined		
Manufacturer	AEO Ref	AEO High	AEO Low	AEO Ref	AEO High	AEO Low	AEO Ref	AEO High	AEO Low
BMW	147.7	147.5	147.7	193.8	193.7	193.8	158.7	155.7	160.2
FCA	151.8	151.7	151.8	202.3	201.5	202.6	187.3	182.6	189.2
Ford	149.5	149.3	149.6	229.7	228.2	230.1	196.1	187.5	199.7
GM	148.8	148.6	148.9	227.4	226.6	227.6	188.0	179.9	191.6
Honda	143.7	143.6	143.8	190.4	190.0	190.5	165.5	161.1	167.5
Hyundai/Kia	147.3	147.2	147.4	186.2	186.2	186.1	152.0	150.6	152.7
JLR	158.1	158.2	158.0	192.1	191.9	192.1	185.0	182.8	185.9
Mazda	145.8	145.7	145.8	182.4	182.2	182.5	157.0	154.4	158.3
Mercedes-Benz	149.8	149.7	149.8	193.8	193.6	193.8	166.6	162.9	168.4
Mitsubishi	137.0	136.9	137.0	169.9	169.9	169.9	148.8	146.0	150.1
Nissan	144.1	144.0	144.2	198.8	198.1	199.0	165.8	160.8	168.1
Subaru	141.3	141.1	141.4	171.7	171.6	171.7	164.9	162.7	165.7
Tesla	171.6	171.6	171.6	0.0	0.0	0.0	171.6	171.6	171.6
Toyota	145.2	145.1	145.2	201.5	200.6	201.9	170.7	165.1	173.3
Volkswagen	145.2	145.2	145.2	188.3	188.2	188.4	161.5	158.0	163.2
Volvo	151.5	151.5	151.6	186.1	186.0	186.1	169.5	166.5	170.9
Fleet	147.2	147.1	147.3	205.7	204.6	206.1	175.1	169.2	177.8

Note that none of the total fleet targets presented in Table 12.47 achieve the 163 g/mi CO_2 target (54.5 mpg, if all reductions achieved through fuel economy improvements) projected in the 2012 FRM. This is due to changes in the fleet makeup, mainly-car/truck mix and also footprint characteristics in the AEO 2015 fleet projections relative to the 2012 FRM projections.

12.1.2.3 Cost per Vehicle and Technology Penetrations

In the previous section, EPA presented our projections for the technology penetrations and cost per vehicle for the MY2025 central analysis control case. We recognize there are many uncertainties involved when making projections to MY2025, including the makeup of the future fleet, which will be influenced in part by future gasoline prices, which technologies manufacturers will actually adopt, how manufacturers will respond to compliance with the standards given the range of credit programs available, including credit trading across manufacturers. As a way to inform how changes in such factors would affect our analysis of the MY2025 standards, we have conducted a wide range of sensitivity analyses, including:

1) AEO 2015 high fuel price case, which changes both fuel prices and projected fleet characteristics (using both ICMs and RPEs).
2) AEO 2015 low fuel price case, which changes both fuel prices and projected fleet characteristics (using both ICMs and RPEs).
3) "Perfect" credit trading across all manufacturers. This sensitivity should represent the most cost effective case since any manufacturer in need of credits is assumed to acquire them if they exist (using ICMs).
4) No Car/Truck transfers across a single manufacturer's fleet, which forces cars to meet the car curve standards and trucks to meet the truck curve standards (using ICMs).

This sensitivity illustrates a more restrictive scenario, since the GHG program in fact allows full transfers across a manufacturer's car and truck fleets, and thus highlights the importance of this flexibility provision.

5) No additional mass reduction beyond that included in the projected baseline fleet. That is, no mass reduction allowed to comply with MY2021 or MY2025 standards. Though EPA believes our mass reduction estimates are fully feasible, this sensitivity shows the impacts of our updated mass reduction costs on the results (using ICMs).A non-Atkinson engine technology path which sets a penetration cap on Atkinson-2 technology at 10 percent in both the reference and control cases. This sensitivity shows the impacts of manufacturers choosing a path less dependent on that technology (using ICMs).

Table 12.48 MY2025 Absolute Technology Penetrations & Incremental Costs for Cars in Each OMEGA Run (2013$)

Technology	AEO Ref ICM	AEO High ICM	AEO Low ICM	AEO Ref RPE	AEO High RPE	AEO Low RPE	Perfect Trading ICM	No C/T Transfers ICM	No Additional MR Beyond Baseline Levels ICM	Non-ATK2 Path ICM
VVT	93%	93%	93%	93%	93%	92%	93%	93%	93%	93%
VVLT	6%	6%	6%	6%	6%	7%	6%	10%	8%	13%
Deac	54%	57%	54%	61%	65%	60%	54%	63%	56%	42%
TRX11	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
TRX12	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TRX21	59%	60%	61%	56%	60%	61%	78%	42%	55%	39%
TRX22	24%	23%	22%	27%	23%	21%	6%	42%	28%	44%
TDS18	20%	18%	20%	19%	16%	19%	29%	12%	18%	14%
TDS24	8%	7%	8%	0%	0%	0%	3%	8%	9%	24%
ATK2	44%	47%	43%	48%	52%	47%	44%	55%	49%	10%
Cooled EGR	48%	51%	48%	46%	49%	44%	49%	57%	55%	35%
Miller	1%	1%	1%	2%	1%	1%	0%	0%	2%	0%
Stop-Start	12%	19%	16%	20%	25%	22%	7%	29%	16%	14%
Mild Hybrid	10%	8%	7%	8%	7%	7%	0%	16%	13%	20%
Full Hybrid	4%	5%	4%	4%	5%	4%	4%	4%	4%	4%
REEV	3%	2%	3%	3%	2%	3%	3%	3%	3%	3%
EV	5%	5%	5%	5%	5%	5%	3%	4%	5%	5%
WR tech	6%	6%	6%	4%	4%	5%	6%	7%	3%	7%
WR net	6%	5%	6%	4%	4%	4%	5%	6%	3%	6%
$/vehicle	$707	$701	$707	$789	$778	$782	$549	$775	$709	$828

Table 12.49 MY2025 Absolute Technology Penetrations & Incremental Costs for Trucks in Each OMEGA Run (2013$)

Technology	AEO Ref ICM	AEO High ICM	AEO Low ICM	AEO Ref RPE	AEO High RPE	AEO Low RPE	Perfect Trading ICM	No C/T Transfers ICM	No Additional MR Beyond Baseline Levels ICM	Non-ATK2 Path ICM
VVT	99%	99%	98%	99%	99%	98%	98%	99%	98%	98%
VVLT	11%	15%	13%	7%	8%	7%	11%	7%	14%	27%
Deac	53%	53%	51%	74%	74%	73%	66%	51%	59%	35%
TRX11	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TRX12	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TRX21	43%	37%	44%	38%	36%	42%	35%	49%	31%	16%
TRX22	55%	61%	54%	60%	62%	56%	63%	49%	67%	82%
TDS18	25%	23%	24%	20%	19%	20%	14%	23%	16%	15%
TDS24	15%	18%	17%	0%	2%	0%	17%	18%	21%	42%
ATK2	45%	45%	42%	65%	66%	63%	56%	36%	52%	10%
Cooled EGR	59%	62%	58%	64%	68%	62%	69%	53%	71%	52%
Miller	6%	8%	6%	6%	6%	6%	0%	6%	8%	1%
Stop-Start	30%	26%	28%	42%	37%	40%	48%	24%	30%	17%
Mild Hybrid	27%	30%	25%	23%	28%	23%	26%	22%	33%	57%
Full Hybrid	1%	0%	1%	1%	1%	1%	0%	2%	1%	1%
REEV	1%	0%	1%	1%	0%	1%	1%	1%	1%	1%
EV	0%	1%	1%	0%	1%	1%	0%	0%	1%	1%
WR tech	7%	7%	7%	6%	6%	6%	7%	7%	3%	7%
WR net	6%	6%	6%	6%	6%	6%	6%	6%	2%	6%
$/vehicle	$1099	$1144	$1077	$1267	$1304	$1251	$1211	$1086	$1137	$1269

Table 12.50 MY2025 Absolute Technology Penetrations & Incremental Costs for the Fleet in Each OMEGA Run (2013$)

Technology	AEO Ref ICM	AEO High ICM	AEO Low ICM	AEO Ref RPE	AEO High RPE	AEO Low RPE	Perfect Trading ICM	No C/T Transfers ICM	No Additional MR Beyond Baseline Levels ICM	Non-ATK2 Path ICM
VVT	96%	95%	96%	95%	95%	95%	95%	96%	96%	95%
VVLT	8%	9%	10%	7%	7%	7%	8%	8%	11%	19%
Deac	54%	55%	52%	67%	69%	67%	60%	57%	57%	38%
TRX11	3%	3%	2%	3%	3%	2%	3%	3%	3%	3%
TRX12	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TRX21	52%	51%	52%	47%	51%	51%	58%	45%	44%	28%
TRX22	39%	38%	38%	43%	38%	39%	33%	45%	46%	62%
TDS18	22%	20%	22%	20%	17%	20%	22%	17%	17%	15%
TDS24	11%	11%	13%	0%	1%	0%	10%	13%	15%	32%
ATK2	44%	46%	42%	56%	58%	55%	50%	46%	50%	10%
Cooled EGR	53%	55%	53%	55%	56%	53%	59%	55%	62%	43%
Miller	4%	4%	4%	4%	3%	4%	0%	3%	4%	1%
Stop-Start	20%	22%	23%	30%	29%	31%	27%	26%	23%	15%
Mild Hybrid	18%	16%	16%	16%	15%	15%	13%	19%	22%	38%
Full Hybrid	3%	3%	2%	3%	3%	2%	3%	3%	3%	3%
REEV	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
EV	3%	3%	3%	3%	3%	3%	2%	2%	3%	3%
WR tech	7%	6%	6%	5%	5%	5%	6%	7%	3%	7%
WR net	6%	6%	6%	5%	5%	5%	6%	6%	2%	6%
$/vehicle	$894	$872	$899	$1017	$980	$1025	$865	$923	$913	$1038

12.1.2.4 Observations on Sensitivity Analyses

EPA notes the following observations on each of the sensitivity analyses shown above.

1. Fuel prices have little impact on the cost per vehicle outcomes. This result is driven by the fact that the projected fleet changes depending on the projected fuel price. The AEO 2015 high fuel price case has more cars than the reference price case, while the low fuel price case has more trucks than the reference price case. This observation holds true within the ICM fuel price cases and within the RPE fuel price cases.

2. Fuel prices have little impact on the technology penetration outcomes. Within the ICM fuel price cases, the technology penetrations vary only slightly. The same is true with the RPE fuel price cases.

3. Higher fuel prices do not result in substantially different fleet electrification. Full electric and plug-in hybrid electric vehicle penetrations are essentially constant across all sensitivities. This is largely driven by the EVs and PHEVs projected in the reference fleet as a result of the ZEV program. Only the mild hybrid technology shows notable differences, ranging from 13 percent to 38 percent of the fleet depending on the sensitivity case.

4. Using RPEs to account for indirect costs increases $/vehicle, as would be expected, but only on the order of $100 to $125 per vehicle, depending on fuel price case.

5. The $/vehicle result is not heavily dependent on mass reduction and, therefore, the mass reduction cost curves. Disallowing any mass reduction beyond that estimated in the baseline fleet increased $/vehicle by just $19 ($2 per car, $38 per truck, $19 combined). There are enough technologies available with similar cost effectiveness such that the fleet compliance costs are not dependent on any one of those technologies.

6. Limiting estimated penetration of the Atkinson-2 engine technology would increase estimated cost per vehicle from $894 to $1,038, a $144 increase.

7. While the case where car/truck transfers has little impact on overall $/vehicle, the limitation of transfers impacts car costs more significantly increasing their costs from $707 to $775 (+$68) while decreasing truck costs from $1099 to $1086 (-$13). This indicates that, in the central analysis, it is more cost effective to reduce truck emissions (as discussed in Section 12.1.1.4 and in observation 8 below) and transfer over compliance credits to the less cost effective car fleet. This can also be seen in Table 12.3 and Table 12.4 which show achieved car CO_2 higher than respective targets and achieved truck CO_2 lower than respective targets. Elimination of transfers also drives the car fleet further into the advanced technologies (TRX22, ATK2, stop-start, mild HEV) while simultaneously limiting advanced technology penetrations on trucks.

8. The perfect trading sensitivity illustrates the potential value of trading across firms and illustrates the greater value of truck credits given the higher VMT of trucks when determining the credit. The overall $/vehicle impact is not great ($894 down to $865), but the car $/vehicle decreases from $707 down to $549 (-$158) while the truck $/vehicle increases from $1099 to $1211 (+$112). OMEGA is putting more technology on trucks to generate credits that can be used to offset under compliance (and less technology) on cars. This also illustrates the movement of the fleet to car-like trucks that emit at levels more like cars and have car-like (i.e., generally less costly) technologies for use in reducing CO_2 emissions but are on the less stringent truck curve. Those car-like trucks can cost effectively generate credits that can then be traded to another firm.

12.1.3 Payback Period & Lifetime Savings

Here EPA looks at the cost of owning a new vehicle complying with the MY2025 standards and the payback period – the point at which savings exceed costs. For example, relative to the reference case (i.e., the MY2021 standards), a new MY2025 vehicle is estimated to cost roughly $900 to $1,000 more due to the addition of new GHG reducing/fuel economy improving technology. This new technology will result in lower fuel consumption and, therefore, savings in fuel expenditures. But how many months or years would pass before the fuel savings exceed the cumulative costs?

The tables below present EPA's estimates of increased costs associated with owning a new MY2025 vehicle. For purposes of this analysis, we are using a "sales weighted average vehicle" which means the combined car/truck fleet, weighted by sales on the cost side and usage on the fuel savings side, to arrive at a single weighted vehicle analysis. The table uses results from the OMEGA Inventory, Costs and Benefits Tool analysis discussed in the section 12.2. Included in the analysis are maintenance costs (see Chapter 5.3.2.3), sales taxes and insurance costs (see

Chapter 10). This analysis does not include other impacts such as reduced refueling events, or other societal impacts, such as the potential rebound miles driven or the value of driving those rebound miles, or noise, congestion and accidents, since the focus is meant to be on those factors consumers likely think about most while in the showroom considering a new car purchase, and on those factors that result in more or fewer dollars in their pockets. As noted, to estimate the cumulative vehicle costs, we have included not only the sales tax on the new car purchase but also the increased insurance premiums that would result from the more valuable vehicle (see Chapter 10). The payback periods were calculated using both 3 percent and 7 percent discount rates with lifetime discounted costs shown in the last 2 rows of the table, again at both 3 percent and 7 percent discount rates.

As shown in these tables, payback occurs in the 5th year of ownership in the ICM case and the 6th year in the RPE case, regardless of the discount rate used. Note that, in the first table, the cost per vehicle is shown as $881 when the cost per vehicle presented earlier was $894. The $881 value is $894 discounted at 3 percent to the mid-year point of the first year of ownership.

Table 12.51 Payback Period for the Sales Weighted Average MY2025 Vehicle in the Central Analysis using ICMs Relative to the Reference Case Standards (3% discounting, 2013$)

Vehicle Age	Delta Cost per Vehicle	Delta Taxes per Vehicle	Delta Insurance per Vehicle	Delta Purchase Costs per Vehicle	Delta Maintenance Costs per Vehicle	Delta Fuel Costs per Vehicle	Cumulative Delta Operating Costs per Vehicle
0	$881	$48	$16	$945	$5	-$239	$711
1	$0	$0	$16	$16	$4	-$231	$501
2	$0	$0	$15	$15	$4	-$222	$298
3	$0	$0	$14	$14	$4	-$214	$103
4	$0	$0	$13	$13	$4	-$202	-$82
5	$0	$0	$12	$12	$4	-$191	-$257
6	$0	$0	$11	$11	$3	-$178	-$420
7	$0	$0	$11	$11	$3	-$167	-$573

Note: Costs are discounted to the first mid-year of vehicle ownership.

Table 12.52 Payback Period for the Sales Weighted Average MY2025 Vehicle in the Central Analysis using RPEs Relative to the Reference Case Standards (3% discounting, 2013$)

Age	Delta Cost per Vehicle	Delta Taxes per Vehicle	Delta Insurance per Vehicle	Delta Purchase Costs per Vehicle	Delta Maintenance Costs per Vehicle	Delta Fuel Costs per Vehicle	Cumulative Delta Operating Costs per Vehicle
0	$1,002	$55	$19	$1,075	$5	-$238	$842
1	$0	$0	$18	$18	$5	-$230	$634
2	$0	$0	$17	$17	$4	-$221	$434
3	$0	$0	$16	$16	$4	-$213	$241
4	$0	$0	$15	$15	$4	-$201	$58
5	$0	$0	$14	$14	$4	-$190	-$115
6	$0	$0	$13	$13	$4	-$178	-$276
7	$0	$0	$12	$12	$3	-$167	-$428

Note: Costs are discounted to the first mid-year of vehicle ownership.

Table 12.53 Payback Period for the Sales Weighted Average MY2025 Vehicle in the Central Analysis using ICMs Relative to the Reference Case Standards (7% discounting, 2013$)

Age	Delta Cost per Vehicle	Delta Taxes per Vehicle	Delta Insurance per Vehicle	Delta Purchase Costs per Vehicle	Delta Maintenance Costs per Vehicle	Delta Fuel Costs per Vehicle	Cumulative Delta Operating Costs per Vehicle
0	$864	$47	$16	$928	$5	-$234	$698
1	$0	$0	$15	$15	$4	-$218	$499
2	$0	$0	$14	$14	$4	-$202	$315
3	$0	$0	$12	$12	$4	-$187	$144
4	$0	$0	$11	$11	$3	-$170	-$12
5	$0	$0	$10	$10	$3	-$155	-$154
6	$0	$0	$9	$9	$3	-$139	-$281
7	$0	$0	$8	$8	$2	-$125	-$396

Note: Costs are discounted to the first mid-year of vehicle ownership.

Table 12.54 Payback Period for the Sales Weighted Average MY2025 Vehicle in the Central Analysis using RPEs Relative to the Reference Case Standards (7% discounting, 2013$)

Age	Delta Cost per Vehicle	Delta Taxes per Vehicle	Delta Insurance per Vehicle	Delta Purchase Costs per Vehicle	Delta Maintenance Costs per Vehicle	Delta Fuel Costs per Vehicle	Cumulative Delta Operating Costs per Vehicle
0	$983	$54	$18	$1,055	$5	-$234	$826
1	$0	$0	$17	$17	$4	-$218	$629
2	$0	$0	$15	$15	$4	-$201	$448
3	$0	$0	$14	$14	$4	-$187	$279
4	$0	$0	$13	$13	$3	-$170	$125
5	$0	$0	$11	$11	$3	-$154	-$15
6	$0	$0	$10	$10	$3	-$139	-$142
7	$0	$0	$9	$9	$2	-$125	-$255

Note: Costs are discounted to the first mid-year of vehicle ownership.

EPA has also calculated the payback periods using the AEO 2015 High and Low fuel price scenarios, at both the 3 percent and 7 percent discount rates. Those results are shown in the tables below and show, again, that payback occurs in the 5th year of ownership for the ICM cases and in the 6th year when using RPEs, regardless of discount rate.

Table 12.55 Payback Period for the Sales Weighted Average MY2025 Vehicle using AEO High Fuel Prices and ICMs Relative to the Reference Case Standards (3% discounting, 2013$)

Age	Delta Cost per Vehicle	Delta Taxes per Vehicle	Delta Insurance per Vehicle	Delta Purchase Costs per Vehicle	Delta Maintenance Costs per Vehicle	Delta Fuel Costs per Vehicle	Cumulative Delta Operating Costs per Vehicle
0	$859	$47	$16	$922	$4	-$225	$701
1	$0	$0	$16	$16	$4	-$218	$502
2	$0	$0	$15	$15	$4	-$209	$311
3	$0	$0	$14	$14	$3	-$202	$126
4	$0	$0	$13	$13	$3	-$191	-$49
5	$0	$0	$12	$12	$3	-$181	-$215
6	$0	$0	$11	$11	$3	-$170	-$370
7	$0	$0	$10	$10	$3	-$159	-$516

Note: Costs are discounted to the first mid-year of vehicle ownership.

Table 12.56 Payback Period for the Sales Weighted Average MY2025 Vehicle using AEO High Fuel Prices and ICMs Relative to the Reference Case Standards (7% discounting, 2013$)

Age	Delta Cost per Vehicle	Delta Taxes per Vehicle	Delta Insurance per Vehicle	Delta Purchase Costs per Vehicle	Delta Maintenance Costs per Vehicle	Delta Fuel Costs per Vehicle	Cumulative Delta Operating Costs per Vehicle
0	$843	$46	$16	$904	$4	-$221	$687
1	$0	$0	$15	$15	$4	-$206	$500
2	$0	$0	$13	$13	$3	-$190	$326
3	$0	$0	$12	$12	$3	-$177	$164
4	$0	$0	$11	$11	$3	-$161	$17
5	$0	$0	$10	$10	$2	-$147	-$118
6	$0	$0	$9	$9	$2	-$132	-$239
7	$0	$0	$8	$8	$2	-$119	-$348

Note: Costs are discounted to the first mid-year of vehicle ownership.

Table 12.57 Payback Period for the Sales Weighted Average MY2025 Vehicle using AEO Low Fuel Prices and ICMs Relative to the Reference Case Standards (3% discounting, 2013$)

Age	Delta Cost per Vehicle	Delta Taxes per Vehicle	Delta Insurance per Vehicle	Delta Purchase Costs per Vehicle	Delta Maintenance Costs per Vehicle	Delta Fuel Costs per Vehicle	Cumulative Delta Operating Costs per Vehicle
0	$886	$48	$17	$951	$5	-$244	$711
1	$0	$0	$16	$16	$4	-$236	$495
2	$0	$0	$15	$15	$4	-$227	$287
3	$0	$0	$14	$14	$4	-$219	$87
4	$0	$0	$13	$13	$4	-$206	-$102
5	$0	$0	$12	$12	$4	-$195	-$281
6	$0	$0	$11	$11	$3	-$182	-$449
7	$0	$0	$11	$11	$3	-$170	-$605

Note: Costs are discounted to the first mid-year of vehicle ownership.

Table 12.58 Payback Period for the Sales Weighted Average MY2025 Vehicle using AEO Low Fuel Prices and ICMs Relative to the Reference Case Standards (7% discounting, 2013$)

Age	Delta Cost per Vehicle	Delta Taxes per Vehicle	Delta Insurance per Vehicle	Delta Purchase Costs per Vehicle	Delta Maintenance Costs per Vehicle	Delta Fuel Costs per Vehicle	Cumulative Delta Operating Costs per Vehicle
0	$869	$47	$16	$933	$4	-$240	$698
1	$0	$0	$15	$15	$4	-$223	$494
2	$0	$0	$14	$14	$4	-$206	$305
3	$0	$0	$12	$12	$4	-$191	$129
4	$0	$0	$11	$11	$3	-$174	-$30
5	$0	$0	$10	$10	$3	-$158	-$175
6	$0	$0	$9	$9	$3	-$142	-$306
7	$0	$0	$8	$8	$2	-$128	-$423

Note: Costs are discounted to the first mid-year of vehicle ownership.

The table below shows the cumulative increased lifetime savings associated with the standards using each the 3 fuel price cases, both ICMs and RPEs, and at both the 3 percent and 7 percent discount rates. Note that the values shown in the table include added costs associated with maintenance, insurance and taxes, and the fuel savings resulting from less fuel usage. These analyses compare the lifetime savings associated with a vehicle meeting the MY2025 standards under the various control cases to a vehicle meeting the MY2021 standards in MY2025 (the reference case). Lifetime savings across the central analysis scenarios range from $879 (for the AEO 2015 Reference/RPE/7 percent discounting case) to $1,621 (for the AEO 2015 Reference/ICM/3 percent discounting case). Note that comparisons to the 2012 FRM lifetime savings metrics are difficult, because in the FRM establishing standards for MY2017-2025, we were comparing a vehicle meeting the 2025 standards to a vehicle meeting the 2016 standards as the reference case, and thus, the accumulated lifetime savings were significantly higher (on the order of $5,700 - $7,400 in 2010 dollars). The lifetime savings reflected in this Draft TAR for a vehicle meeting the 2025 standards compared to a vehicle meeting the 2021 standards are naturally covering a much smaller fraction of accumulated fuel savings as compared to the FRM analysis.

Table 12.59 Lifetime Net Savings Associated with the Indicated Control Case Relative to the Reference Case for the Sales-Weighted Average MY2025 Vehicle

Case	Lifetime Savings 3% discounting	Lifetime Savings 7% discounting
AEO Reference Fuel Price Case Using ICMs	$1,621	$1,030
AEO Reference Fuel Price Case Using RPEs	$1,460	$879
AEO High Fuel Price Case Using ICMs	$1,506	$948
AEO Low Fuel Price Case Using ICMs	$1,679	$1,072

12.2 EPA's Projected Impacts on Emissions Inventories & Fuel Consumption

12.2.1 Analytical Tools Used

As in the 2012 final rule establishing MY2017-2025 standards, EPA used its OMEGA Inventory Costs and Benefits Tool (ICBT) to project the emissions and fuel consumption impacts of this analysis. The projections of the emission inventory and fleetwide fuel consumption are conducted in the OMEGA ICBT[J] which produces a national scale analysis of the impacts (emission inventory and fuel consumption impacts, monetized co-benefits) of the analyzed program. The OMEGA ICBT incorporates the inputs discussed in Chapter 4 (baseline fleet), Chapter 5 (technology costs and effectiveness) and Chapter 10 (vehicle miles traveled (VMT), rebound, and other economic inputs).

The remainder of this chapter provides a summary of the analytical inputs, methodology, and the results of the analysis.

12.2.2 Inputs to the Emissions and Fuel Consumption Analysis

12.2.2.1 Methods

EPA estimated GHG impacts from several sources including: (a) the impact of the standards on tailpipe CO_2 emissions, (b) projected improvements in the efficiency of vehicle air conditioning systems, (c) reductions in direct emissions of the potent greenhouse gas refrigerant HFC-134a from air conditioning systems, (d) "upstream" emission reductions from gasoline extraction, production and distribution processes as a result of reduced gasoline demand associated with standards, and (e) "upstream" emission increases from power plants as electric powertrain vehicles are projected to increase slightly as a result of the MY2022-2025 standards. EPA additionally accounted for the greenhouse gas impacts of additional vehicle miles traveled (VMT) due to the "rebound" effect discussed in Chapter 10.

EPA's estimates of non-GHG emission impacts from the MY2022-2025 standards are broken down by the three drivers of these changes: a) "downstream" emission changes, reflecting the estimated effects of VMT rebound (discussed in Chapter 10) and decreased consumption of motor vehicle fuel; b) "upstream" emission reductions due to decreased extraction, production and distribution of motor vehicle gasoline; c) "upstream" emission increases from power plants as electric powertrain vehicles are projected to be slightly more prevalent in future years.[K] For all criteria and air toxic pollutants, the overall impact of the MY2022-2025 standards is small compared to total U.S. inventories across all sectors.

[J] Essentially the relevant ICBT elements are a post-processing tool to OMEGA used to incorporate inventory and cost-specific data not needed in OMEGA for use in this analysis.

[K] Note that the reference case used by EPA includes vehicle sales in response to the ZEV program. As such, increased power plant emissions associated with those ZEV-program vehicle sales are not attributable to the 2022-2025 GHG standards. However, OMEGA projects a very small increase in EV and PHEV sales above those needed for ZEV compliance; the increased power plant emissions due to those additional EV/PHEV vehicles are attributable to the 2022-2025 GHG standards. Note that EPA has not yet updated the electricity emissions factors from those used in the 2012 FRM, though it is possible that emissions factors would change in the future due in part to EPA's Clean Power Plan regulations. This issue is discussed further in Chapter 11.5.

Although electric vehicles have zero tailpipe emissions, EPA assumes that manufacturers will plan for these vehicles in their regulatory compliance strategy for criteria pollutant and air toxics emissions, and will not over-comply with applicable Tier 3 emissions standards for non-GHG air pollutants. Since the Tier 3 emissions standards are fleet-average standards, EPA assumes that if a manufacturer introduces EVs into its fleet, then it would correspondingly compensate through changes to vehicles elsewhere in its fleet, rather than produce an overall lower fleet-average emissions level. Consequently, consistent with the 2012 FRM, EPA assumes neither tailpipe pollutant (other than CO_2), evaporative emissions, nor brake and tire wear particulate matter reductions from the introduction of electric vehicles into the fleet.

Two basic elements feed into the OMEGA ICBT calculation of vehicle tailpipe emissions. These elements are vehicle miles traveled (VMT) and emission rates, where the total emissions are the vehicle miles traveled multiplied by the emission rate in grams/mile. This equation is adjusted in calculations for various emissions, but provides the basic form used throughout this analysis. As an example, in an analysis of a single calendar year, the emissions equation is repeatedly applied to determine the contribution of each model year in the calendar year's particular fleet. Appropriate VMT and emission factors by age are applied to each model year within the calendar year, and the products are then summed. Similarly, to determine the emissions of a single model year, appropriate VMT and emission factors by age are applied to each calendar year between when the model year fleet is produced and projected to be scrapped.

Tailpipe sulfur dioxide (SO_2) emissions, which are largely controlled by the sulfur content of the fuel, are an exception to this basic equation. Decreasing the quantity of fuel consumed decreases tailpipe SO_2 emissions proportionally to the decrease in fuel combusted. Therefore, rather than multiplying the SO_2 emission factor by miles traveled, we multiply by gallons consumed. As such, the SO_2 emission factor is expressed in terms of grams/gallon rather than grams/mile.

12.2.2.2 Global Warming Potentials

In general, when we refer to the four inventoried greenhouse gases on an equivalent basis, Global Warming Potentials (GWPs) are used. In simple terms, GWPs provide a common basis with which to combine several gases with different heat trapping abilities into a single inventory. When expressed in CO_2 equivalent (CO_2e) terms, each gas is weighted by its heat trapping ability relative to that of carbon dioxide. The GWPs used are shown in Table 12.60.[L]

Table 12.60 Global Warming Potentials (GWP) for Inventoried GHGs

GHG	GWP (CO_2e)
CO_2	1
CH_4	25
N_2O	298
HFC (R134a)	1430

[L] As with the MY 2017-2025 Light Duty rule and the MY 2014-2018 Medium and Heavy Duty rule, the GWPs used in this rule are consistent with 100-year time frame values in the 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4).

12.2.2.3 Years Considered

This analysis presents the projected impacts of the standards in calendar years 2025, 2030, 2040 and 2050. We also present the emission impacts over the estimated full lifetime of MYs 2022-2025 vehicles. The program was quantified as the difference in mass emissions between a control case under the final MY2022-2025 standards and a reference case under the MY2021 standards in place indefinitely. As such, negative values represent emissions decreases due to the policy and positive values represent emissions increases due to the policy.

12.2.2.4 Fleet Activity

12.2.2.4.1 Vehicle Sales, Survival Schedules, and VMT

Vehicle sales projections from MY2014 through MY2030 are discussed in Chapter 4. Vehicle survival schedules and VMT by vehicle age were updated to be consistent with the most recent publicly released EPA MOVES model (MOVES2014a). These updates are described in more detail in Chapter 10.

12.2.2.5 Upstream Emission Factors

12.2.2.5.1 Gasoline Production and Transport Emission Rates

The gasoline production and transport sector is composed of four distinct components:

- Domestic crude oil production and transport
- Petroleum production and refining emissions
- Production of energy for refinery use
- Gasoline transport, storage and distribution

For this Draft TAR analysis, the emission factors associated with on-road combustion emissions allocated to gasoline transport and distribution were updated based on the emission factors calculated as part of the HD GHG Phase 2 rule.[5] Refinery related emissions were updated to reconcile the emission totals with those in the most recent national emission inventory.[6] Otherwise, the upstream emission rate analysis remains the same as that performed in the 2012 FRM Regulatory Impacts Analysis (RIA), Chapters 4.2 and 4.6.[7] Table 12.61, below, shows the gasoline upstream emission rates used in the cost-benefit calculations for this analysis.

Table 12.61 Gasoline Production Emission Rates

Pollutant	Emission Rate (g/MMbtu of E10 gasoline)
CO	5.472145
NOx	13.87269
PM2.5	2.07292
PM10	6.048208
SOx	8.089376
VOC	47.4966
1,3-Butadiene	0.001442
Acetaldehyde	0.009798
Acrolein	0.000816
Benzene	0.322958
Formaldehyde	0.081647
Naphthalene	0.015177
CH4	95.454
N2O	0.369224
CO2	19145.2

12.2.2.5.2 *Electricity Generation Emission Rates*

For the 2012 FRM, EPA conducted an Integrated Planning Model (IPM) analysis of the electricity sector in order to gauge the impacts upon the power grid of the additional electric charging projected to be needed to meet the MY2017-2025 standards.[8] Since the 2012 final rule, EPA has adopted a GHG program for electricity generation, known as the Clean Power Plan.[M] These rules are expected to significantly decrease GHG emissions associated with future electricity generation. The 2012 FRM's IPM modeling projected that the average power plant electricity GHG emissions factor in 2030 for vehicle electricity use would be 0.445 grams/watt-hour.[9] The overall vehicle electricity GHG emissions factor was projected to be 0.534 grams/watt-hour when using a multiplicative value of 1.20 to account for feedstock-related GHG emissions upstream of the power plant. EPA is currently exploring whether there are appropriate updates to these projected emissions factors for the incremental electricity that would be necessary for electric vehicle operation in the 2030 timeframe, which we plan to assess in more detail further in the midterm evaluation process. For this Draft TAR, EPA is continuing to apply the FRM IPM results as a representation of the electrical grid in the time period surrounding 2030. The emission factors are shown in Table 12.62 below.

The 2030 IPM results were post-processed to develop gram per kWh emission factors for use in the OMEGA model and inventory cost-benefit analysis. For those emissions that IPM does not generate, we relied upon the National Emissions Inventory (NEI) for air toxic emissions and eGrid for N_2O and CH_4. There are also additional emissions attributable to feedstock generation, or the gathering and transport of fuel to the power plant. Emission factors from the version of GREET 1.8c (as modified for the EPA upstream analysis discussed above) were used to generate feedstock emission factors. Retail electricity price projections from the 2030 FRM

[M] EPA issued a final GHG emissions program, known as the Clean Power Plan, addressing fossil fuel-fired electric generating units. 80 FR 64661, October 23, 2015.

IPM run were used in our analysis of electricity fuel costs to drivers. More information regarding the integration of GREET emission factors and IPM modeling can be found in the FRM RIA, Chapter 4.6.

Table 12.62 Emission Factors Used in Analysis of Electricity Generation

Pollutant	IPM (g/kWh)	Feedstock (g/kWh)	Total (g/kWh)
VOC	8.28E-03	4.69E-02	5.52E-02
CO	2.89E-01	5.01E-02	3.39E-01
NOx	1.13E-01	1.27E-01	2.41E-01
PM2.5	5.81E-03	6.51E-02	7.09E-02
SO_2	1.90E-01	4.69E-02	2.37E-01
CO_2	4.45E+02	3.55E+01	4.80E+02
N_2O	6.76E-03	6.81E-04	7.44E-03
CH_4	8.60E-03	3.31E+00	3.32E+00
1,3-butadiene	0.0E+00	0.00E+00	0.00E+00
Acetaldehyde	5.5E-05	9.47E-06	6.40E-05
Acrolein	2.8E-05	3.15E-05	5.95E-05
Benzene	1.3E-04	1.41E-03	1.54E-03
Formaldehyde	3.0E-05	7.51E-06	3.79E-05

12.2.2.6 Reference Case CO_2 g/mi & kWh/mi

As described in Section 12.1, EPA assumes that the reference case fleet continues to meet the MY2021 standards indefinitely. Importantly, we model the fleet as meeting the reference (or control) case targets rather than the achieved CO_2 values as reported by the OMEGA core model. We do this because we consider OMEGA core model results to be a possible, feasible path toward compliance and not necessarily the actually path that any given manufacturer will choose. For that reason, we choose to model the target values. Compliance flexibilities such as A/C credits and fleet averaging are included in the modeling. The A/C direct credit is added here to the 2-cycle target value to arrive at the 2-cycle tailpipe CO_2 value because, while that credit results in real GHG reductions, it does not result in real tailpipe CO_2 reductions (or real on-road fuel economy improvements). The benefits of off-cycle and A/C indirect credits are implicitly included in the values below because they result in real CO_2 reductions. The CO_2 targets presented here were also presented in Section 12.1.1. The fleet CO_2 g/mi and kWh/mi emission rates used for inventory modeling are as shown in the tables below. In the CO_2 g/mi tables, the on-road tailpipe CO_2 values are the values used in generating CO_2 inventory impacts in the reference case. The "gap" noted in the tables below is the gap between compliance and real world fuel economy/tailpipe CO_2, discussed further in Chapter 10.1. Entries change slightly year-over-year due to fleet changes.

Table 12.63 Reference Case Car On-Road CO_2 g/mi Used in All OMEGA ICBT Runs

MY	2-cycle CO2 Target, g/mi	A/C Direct Credit, g/mi	Adjusted 2-cycle Tailpipe CO2, g/mi	Adjusted MPG	Gap	On-road MPG	On-road CO2 Tailpipe, g/mi
2021	177.0	13.8	190.8	46.6	0.77	35.9	236.1
2022	177.0	13.8	190.8	46.6	0.77	35.9	236.2
2023	177.0	13.8	190.8	46.6	0.77	36.0	236.1
2024	176.9	13.8	190.7	46.6	0.77	36.0	236.0
2025	177.0	13.8	190.8	46.6	0.77	36.0	236.1
2026	176.9	13.8	190.7	46.6	0.77	36.0	236.0
2027	176.9	13.8	190.7	46.6	0.77	36.0	235.9
2028	176.8	13.8	190.6	46.6	0.77	36.0	235.9
2029	176.7	13.8	190.5	46.6	0.77	36.0	235.8
2030	176.7	13.8	190.5	46.6	0.77	36.0	235.8

Note: The on-road values reflect adjustments for both the historical 2-cycle-to-5-cycle gap as well as the projected ethanol content in retail gasoline, and corresponding energy content. The on-road CO_2 is calculated by dividing 8488, the estimated CO_2 grams/gallon from combustion of a gallon of retail gasoline, by the on-road MPG.

Table 12.64 Reference Case Truck On-Road CO_2 g/mi Used in All OMEGA ICBT Runs

MY	2-cycle CO2 Target, g/mi	A/C Direct Credit, g/mi	Adjusted 2-cycle Tailpipe CO2, g/mi	Adjusted MPG	Gap	On-road MPG	On-road CO2 Tailpipe, g/mi
2021	251.1	17.2	268.3	33.1	0.77	25.6	332.1
2022	251.1	17.2	268.3	33.1	0.77	25.6	332.1
2023	250.8	17.2	268.0	33.2	0.77	25.6	331.6
2024	250.8	17.2	268.0	33.2	0.77	25.6	331.6
2025	250.9	17.2	268.1	33.1	0.77	25.6	331.8
2026	250.9	17.2	268.1	33.2	0.77	25.6	331.7
2027	251.3	17.2	268.5	33.1	0.77	25.6	332.2
2028	251.3	17.2	268.5	33.1	0.77	25.5	332.2
2029	250.9	17.2	268.1	33.1	0.77	25.6	331.8
2030	250.9	17.2	268.1	33.2	0.77	25.6	331.7

Note: The on-road values reflect adjustments for both the historical 2-cycle-to-5-cycle gap as well as the projected ethanol content in retail gasoline, and corresponding energy content. The on-road CO_2 is calculated by dividing 8488, the estimated CO_2 grams/gallon from combustion of a gallon of retail gasoline, by the on-road MPG.

The reference case electricity consumption rates, including both electricity consumption by ZEV program vehicles and consumption by the very small fraction of EV and PHEV vehicles projected by OMEGA toward compliance with the reference case standards are shown in the table below. EPA accounts for all electricity consumed by the vehicle. For calculations of GHG emissions from electricity generation, the total energy consumed from the battery is divided by 0.9 to account for charging losses. This factor is included in the values presented in the table below. Within the OMEGA ICBT, a transmission loss divisor of 0.93 is applied to account for losses during transmission, the result being electricity demand at the electric plant. Both values were discussed in the 2012 FRM; the approach in this analysis is unchanged.[10] The estimate of charging losses is based upon engineering judgment and manufacturer CBI. The estimate of transmission losses is consistent, although not identical to the 8 percent estimate used in GREET, as well as the 6 percent estimate in eGrid 2010.[11,12] The upstream emission factor discussed above in Section 12.2.2.5.2 is applied to total electricity production, rather than simply power consumed at the wheel.[N] It is assumed that electrically powered vehicles drive the same drive schedule as the rest of the fleet.[O] Note that the values shown in the table already include a 0.8 on-road "gap" since the gap was considered in determining battery sizing and consumption.[P]

Because the kWh/mi inputs to the OMEGA ICBT differ based on fuel price case and whether ICMs or RPEs are used in each set of inputs are shown below. The values shown in the kWh/mi table are the values used to generate upstream emission inventory impacts in the applicable reference case.

Table 12.65 Reference Case Car & Truck On-Road kWh/mi Consumption used in the Indicated OMEGA ICBT Runs

	ICMs						RPEs	
	AEO Ref		AEO High		AEO Low		AEO Ref	
MY	Car	Truck	Car	Truck	Car	Truck	Car	Truck
2021	0.01260	0.00137	0.01226	0.00132	0.01324	0.00141	0.01296	0.00137
2022	0.01385	0.00167	0.01353	0.00162	0.01464	0.00171	0.01427	0.00167
2023	0.01510	0.00198	0.01481	0.00192	0.01604	0.00201	0.01559	0.00198
2024	0.01635	0.00228	0.01608	0.00222	0.01745	0.00232	0.01690	0.00228
2025	0.01760	0.00259	0.01735	0.00252	0.01885	0.00262	0.01821	0.00259
2026	0.01760	0.00259	0.01735	0.00252	0.01885	0.00262	0.01821	0.00259
2027	0.01760	0.00259	0.01735	0.00252	0.01885	0.00262	0.01821	0.00259
2028	0.01760	0.00259	0.01735	0.00252	0.01885	0.00262	0.01821	0.00259
2029	0.01760	0.00259	0.01735	0.00252	0.01885	0.00262	0.01821	0.00259
2030	0.01760	0.00259	0.01735	0.00252	0.01885	0.00262	0.01821	0.00259

For this Draft TAR analysis, EPA has considered the ZEV program in California and Section 177 states in the reference case for this analysis. That analysis fleet is described in detail in Chapter 4. Our central analysis also treats EVs and the electricity portion of PHEV operation as zero emitting for compliance purposes (although their upstream emissions are considered in our GHG emission inventory estimates). Given the ZEV program sales, it appears that some manufacturers are likely to exceed the sales levels beyond which net upstream emissions would have to be considered in their compliance determination.[13] However, other manufacturers appear unlikely to exceed that limit. In the current version of OMEGA, EPA does not have the capability to apply upstream emissions to only some manufacturers' fleets and not others. This is a change we plan to implement in future updates to the OMEGA model.

12.2.2.7 Control Case CO_2 g/mi & kWh/mi

As noted above, we model the fleet as meeting the compliance targets rather than the achieved CO_2 values as reported by the OMEGA core model. We do this because we consider OMEGA core model results to be a possible path toward compliance and not necessarily the path that will result. For that reason, we choose to model the target values since those represent the levels that are actually required. The off-cycle credits are implicitly included in the values below, as are all A/C credits, because their use is assumed in meeting the "2-cycle CO_2 Target" values shown.

[N] By contrast, consumer electricity costs would not include the power lost during transmission. While consumers indirectly pay for this lost power through higher rates, this power does not appear on their electric meter.
[O] The validity of this assumption will depend on the use of electric vehicles by their purchasers.
[P] See Chapter 5 for details on EPA's battery sizing methodology.

The A/C direct credit is added here to the 2-cycle target value to arrive at the adjusted 2-cycle tailpipe CO_2 value because, while that credit results in real GHG reductions, it does not result in real tailpipe CO_2 reductions (or real on-road fuel economy improvements). The CO_2 targets presented here were also presented in Section 12.1.1. The fleet CO_2 g/mi and kWh/mi emission rates used for inventory modeling are as shown in the tables below. In the CO_2 g/mi tables, the on-road tailpipe CO_2 value is the value used in generating CO_2 inventory impacts in the control case. The "Gap" noted in the tables below is the gap between compliance and real world fuel economy/tailpipe CO_2, discussed in Chapter 10.1. The gap, as shown, is applied to adjusted MPG values.

Table 12.66 Control Case Car On-Road CO_2 g/mi Used in All OMEGA ICBT Runs

MY	2-cycle CO2 Target, g/mi	A/C Direct Credit, g/mi	Adjusted 2-cycle Tailpipe CO2, g/mi	Adjusted MPG	Gap	On-road MPG	On-road CO2 Tailpipe, g/mi
2021	171.1	13.8	184.9	48.1	0.77	37.1	228.9
2022	164.8	13.8	178.6	49.8	0.77	38.4	221.1
2023	158.7	13.8	172.5	51.5	0.77	39.8	213.5
2024	152.8	13.8	166.6	53.3	0.77	41.2	206.3
2025	147.3	13.8	161.1	55.2	0.77	42.6	199.4
2026	147.2	13.8	161.0	55.2	0.77	42.6	199.4
2027	147.2	13.8	161.0	55.2	0.77	42.6	199.3
2028	147.1	13.8	160.9	55.2	0.77	42.6	199.3
2029	147.1	13.8	160.9	55.2	0.77	42.6	199.2
2030	147.1	13.8	160.9	55.2	0.77	42.6	199.2

Note: The on-road values reflect adjustments for both the historical 2-cycle-to-5-cycle gap as well as the projected ethanol content in retail gasoline, and corresponding energy content. The on-road CO_2 is calculated by dividing 8488, the estimated CO_2 grams/gallon from combustion of a gallon of retail gasoline, by the on-road MPG; off-cycle credits are not shown in the table since they are assumed to have been used in meeting the 2-cycle CO_2 Targets.

Table 12.67 Control Case Truck On-Road CO_2 g/mi Used in All OMEGA ICBT Runs

MY	2-cycle CO2 Target, g/mi	A/C Direct Credit, g/mi	Adjusted 2-cycle Tailpipe CO2, g/mi	Adjusted MPG	Gap	On-road MPG	On-road CO2 Tailpipe, g/mi
2021	242.0	17.2	259.2	34.3	0.77	26.5	321.0
2022	232.3	17.2	249.5	35.6	0.77	27.5	309.0
2023	222.7	17.2	239.9	37.0	0.77	28.6	297.1
2024	213.8	17.2	231.0	38.5	0.77	29.7	286.1
2025	205.5	17.2	222.7	39.9	0.77	30.8	275.8
2026	205.5	17.2	222.7	39.9	0.77	30.8	275.7
2027	205.8	17.2	223.0	39.9	0.77	30.8	276.1
2028	205.8	17.2	223.0	39.9	0.77	30.8	276.1
2029	205.5	17.2	222.7	39.9	0.77	30.8	275.8
2030	205.5	17.2	222.7	39.9	0.77	30.8	275.7

Note: The on-road values reflect adjustments for both the historical 2-cycle-to-5-cycle gap as well as the projected ethanol content in retail gasoline, and corresponding energy content. The on-road CO2 is calculated by dividing 8488, the estimated CO2 grams/gallon from combustion of a gallon of retail gasoline, by the on-road MPG; off-cycle credits are not shown in the table since they are assumed to have been used in meeting the 2-cycle CO_2 Targets and because they provide real-world CO_2 reductions so do not need to be backed out as do the A/C leakage, or A/C direct credit, values.

The table below shows the control case electricity emission factors, including both electricity consumption by ZEV program vehicles and projected EV and PHEV vehicles generated by OMEGA toward compliance with the control case standards. These consumption levels include charging losses (a 90 percent divisor) and the OMEGA ICBT applies a 93 percent transmission loss divisor (not included in the values below). Note that the values shown in the table already include a 0.8 on-road "gap" since the gap was considered in determining battery sizing and consumption.

The control case kWh/mi inputs to the OMEGA ICBT are shown in the table below. Because fuel prices, and choice of ICMs or RPEs, impact the projected penetration of EV and PHEV vehicles, unique kWh/mi inputs are presented for each combination fuel price and indirect cost scenario. The values shown in the kWh/mi table are the values used to generate upstream emission inventory impacts in the applicable control case.

Table 12.68 Reference Case Car & Truck On-Road kWh/mi Consumption used in the Indicated OMEGA ICBT Runs

	ICMs						RPEs	
	AEO Ref		AEO High		AEO Low		AEO Ref	
MY	Car	Truck	Car	Truck	Car	Truck	Car	Truck
2021	0.01350	0.00137	0.01304	0.00132	0.01412	0.00141	0.01423	0.00137
2022	0.01524	0.00167	0.01476	0.00178	0.01599	0.00186	0.01607	0.00167
2023	0.01698	0.00198	0.01649	0.00223	0.01786	0.00230	0.01790	0.00198
2024	0.01871	0.00228	0.01822	0.00268	0.01973	0.00275	0.01974	0.00228
2025	0.02045	0.00259	0.01995	0.00314	0.02160	0.00320	0.02157	0.00259
2026	0.02045	0.00259	0.01995	0.00314	0.02160	0.00320	0.02157	0.00259
2027	0.02045	0.00259	0.01995	0.00314	0.02160	0.00320	0.02157	0.00259
2028	0.02045	0.00259	0.01995	0.00314	0.02160	0.00320	0.02157	0.00259
2029	0.02045	0.00259	0.01995	0.00314	0.02160	0.00320	0.02157	0.00259
2030	0.02045	0.00259	0.01995	0.00314	0.02160	0.00320	0.02157	0.00259

It is important to emphasize that these CO_2 and kWh emission rate projections are based on EPA's current projections of a wide range of inputs, including the mix of cars and trucks, as well as the mix of vehicle footprint values in varying years. It is of course possible that the actual CO_2 emissions values, as well as the actual use of incentives and credits, will be either higher or lower than these projections.

12.2.2.8 Criteria Pollutant and Select Toxic Pollutant Emission Rates

For the analysis of criteria emissions in this rule, EPA estimates the increases in emissions of each criteria air pollutant from additional vehicle use by multiplying the increase in total miles driven by cars and light trucks of each model year and age by their estimated emission rates per vehicle-mile of each pollutant. These emission rates differ between cars and light trucks, between gasoline and diesel vehicles, and by age. With the exception of SO_2, EPA calculated the increase in emissions of these criteria pollutants from added car and light truck use by multiplying the estimated increases in vehicle use during each year over their expected lifetimes by per-mile emission rates appropriate to each vehicle type, fuel used, model year, and age as of that future year.

The relevant emission rates were estimated by EPA using the most recent version of the Motor Vehicle Emission Simulator (MOVES2014a). The MOVES model assumes that the per-mile rates at which these pollutants are emitted are determined by EPA regulations and the effectiveness of after-treatment of engine exhaust emissions, and are thus unaffected by changes in car and light truck fuel economy. As a consequence, the downstream impacts of required increases in fuel economy on emissions of these pollutants from car and light truck use are determined entirely by the increases in driving that result from the fuel economy rebound effect.

Emission factors in the MOVES database are expressed in the form of grams per vehicle-hour of operation. To convert these emission factors to grams per mile, MOVES was run for the year 2050, and was programmed to report aggregate emissions from vehicle start, running, brake and tire wear and crankcase exhaust operations. EPA analysts ran MOVES for every calendar year from 2014 to the year 2050 in order to generate emission factors for each age of each model year. Separate estimates were developed for each vehicle type, as well as for a winter and a summer month in order to reflect the effects of temporal variation in temperature and other relevant variables on emissions. All calendar years were run using national averages calculated from the aggregation of the county level default estimates (national aggregation).

The MOVES emissions estimates were then summed to the model year level and divided by total distance traveled by vehicles of that model year in order to produce per-mile emission factors for each pollutant. The resulting emission rates represent average values across the nation, and incorporate variation in temperature and other operating conditions affecting emissions over an entire calendar year. These national average rates also reflect county-specific differences in fuel composition, as well as in the presence and type of vehicle inspection and maintenance programs. Average emission rates were assumed not to increase after 30 years of age.

Emission rates for the criteria pollutant SO_2 were calculated by using average fuel sulfur content estimates supplied by EPA, together with the simplifying assumption that the entire sulfur content of fuel is emitted in the form of SO_2. These calculations assumed that national average gasoline and diesel sulfur levels would remain at current levels, because there are no current regulations that will change those levels, and we have no expectation that the market will cause such changes on its own.

12.2.3 <u>Outputs of the Emissions and Fuel Consumption Analysis</u>

In this section. EPA presents the emissions inventory impacts, fuel, and electricity consumption results. Section 12.2.3.1 shows impacts in a given calendar year resulting from the control case analysis. These results are not cumulative, and are presented to show the continued impacts of the analysis beyond the control case years. Section 12.2.3.2 shows impacts for a given model year cohort of vehicles, as well as cumulative sums of impacts due to vehicle model years included in the control case (over the whole vehicle lifetime, as discussed in Chapter 10). Tables presenting emissions inventory impacts are generally shown as reductions, such that emission decreases would be shown as a positive number. Tables presenting fuel and energy consumption are shown as absolute impact, such that fuel or energy consumption decreases would be show as a negative number. See specific table notes for more direction. Discussion of the inputs to this analysis can be found in section 12.2.2, above.

12.2.3.1 Calendar Year Results

Table 12.69 Annual Emissions Reductions of the MY2022-2025 Standards on GHGs in Select Calendar Years (MMT CO_2e) [Q]

Calendar Year	2025	2030	2040	2050
Net GHG	40.7	102	186	234
Net CO2	39.9	100	182	229
Net other GHG	0.9	2.3	4.1	5.2
Downstream GHG	32.4	81.6	148	186
CO2 (excluding A/C)	32.3	81.3	147	185
A/C – indirect CO2	0.1	0.3	0.6	0.7
A/C – direct HFCs	0	0	0	0
CH4 (rebound effect)	0	0	0	0
N2O (rebound effect)	0	0	-0.1	-0.1
Fuel Production and Distribution GHG	9.1	22.8	41.5	52.3
Fuel Production and Distribution CO2	8	20.2	36.7	46.2
Fuel Production and Distribution CH4	1	2.5	4.6	5.8
Fuel Production and Distribution N2O	0.1	0.1	0.2	0.3
Electricity Upstream GHG	-0.9 to -0.8	-2.3 to -1.9	-4.1 to -3.5	-5.1 to -4.4
Electricity Upstream CO2	-0.8 to -0.7	-1.9 to -1.6	-3.5 to -3.0	-4.3 to -3.7
Electricity Upstream CH4	-0.1	-0.3	-0.6 to -0.5	-0.7 to -0.6
Electricity Upstream N2O	0.0	0.0	0.0	0.0

Note: These values are expressed as emission reductions, such that positive values imply an emissions decrease, and negative values imply an emissions increase.

[Q] With the exception of upstream electricity generation due to differing technology mix, the differences in total inventory between ICM and RPE cases are negligible and have been omitted. Results are consistent with the ICM case where ranges are not shown.

Table 12.70 Annual Emission Reductions of the MY2022-2025 Standards on GHGs (MMT CO_2e)

Calendar Year	CO2	HFC	CH4	N2O	Total
2021	2.6	0.0	0.0	0.0	2.7
2022	8.0	0.0	0.2	0.0	8.2
2023	16.1	0.0	0.4	0.0	16.4
2024	26.7	0.0	0.6	0.0	27.3
2025	39.9	0.0	0.9	0.0	40.8
2026	52.8	0.0	1.2	0.0	54.0
2027	65.4	0.0	1.5	0.0	66.9
2028	77.6	0.0	1.7	0.0	79.4
2029	89.2	0.0	2.0	0.1	91.3
2030	100	0.0	2.2	0.1	102
2031	111	0.0	2.5	0.1	113
2032	121	0.0	2.7	0.1	124
2033	130	0.0	2.9	0.1	133
2034	139	0.0	3.1	0.1	143
2035	148	0.0	3.3	0.1	151
2036	156	0.0	3.5	0.1	159
2037	163	0.0	3.6	0.1	167
2038	170	0.0	3.8	0.1	174
2039	176	0.0	3.9	0.1	180
2040	182	0.0	4.0	0.1	186
2041	187	0.0	4.2	0.1	191
2042	192	0.0	4.3	0.1	197
2043	197	0.0	4.4	0.1	202
2044	202	0.0	4.5	0.1	207
2045	207	0.0	4.6	0.1	211
2046	211	0.0	4.7	0.1	216
2047	216	0.0	4.8	0.1	221
2048	220	0.0	4.9	0.1	225
2049	225	0.0	5.0	0.1	230
2050	229	0.0	5.1	0.1	234
Sum	**4060**	**0.0**	**90.4**	**2.2**	**4153**

Note: These values are expressed as emission reductions, such that positive values imply an emissions decrease, and negative values imply an emissions increase.

Table 12.71 Annual Emission Reductions of the MY2022-2025 Standards on non-GHG Criteria Pollutants in Select Years

		CY2030		CY2040	
	Pollutant	Impacts (short tons)	% of US Inventory[R]	Impacts (short tons)	% of US Inventory
Total	VOC	53672	0.091	96711	0.164
	CO	-30665	-0.038	-69582	-0.086
	NOx	13763	0.089	24334	0.157
	PM2.5	2066.5	0.034	3704	0.061
	SOx	8512.5	0.131	15426.4	0.238
Downstream (Rebound)	VOC	-1419	-0.002	-3203	-0.005
	CO	-35762	-0.044	-78807	-0.098
	NOx	-1483	-0.010	-3304	-0.021
	PM2.5	-80.5	-0.001	-186	-0.003
	SOx	-16.5	0.000	-29.6	0.000
Fuel production & distribution	VOC	55298	0.094	100293	0.170
	CO	6370	0.008	11554	0.014
	NOx	16151	0.104	29294	0.189
	PM2.5	2413	0.040	4377	0.072
	SOx	9418	0.145	17082	0.264
Electricity	VOC	-207	0.000	-379	-0.001
	CO	-1273	-0.002	-2329	-0.003
	NOx	-905	-0.006	-1656	-0.011
	PM2.5	-266	-0.004	-487	-0.008
	SOx	-889	-0.014	-1626	-0.025

Note: These values are expressed as emission reductions, such that positive values imply an emissions decrease, and negative values imply an emissions increase.

Table 12.72 Annual Emission Reductions of the MY2022-2025 Standards on Select Toxic Pollutants in Select Years

		CY2030		CY2040	
	Pollutant	Impacts (short tons)	% of US Inventory	Impacts (short tons)	% of US Inventory
Total	1,3- Butadiene	-8.7	-0.014	-20.0	-0.033
	Acetaldehyde	-5.3	-0.001	-17.2	-0.002
	Acrolein	-1.0	-0.002	-2.8	-0.006
	Benzene	311.6	0.110	539.4	0.190
	Formaldehyde	59.6	0.004	91.5	0.007
Downstream (Rebound)	1,3- Butadiene	-10.4	-0.017	-23	-0.038
	Acetaldehyde	-16.5	-0.002	-37.5	-0.005
	Acrolein	-1.8	-0.004	-4.1	-0.008
	Benzene	-58.6	-0.021	-132	-0.047
	Formaldehyde	-35.4	-0.003	-80.2	-0.006
Fuel production & distribution	1,3- Butadiene	1.7	0.003	3.0	0.005
	Acetaldehyde	11.4	0.001	20.7	0.002
	Acrolein	1.0	0.002	1.7	0.003
	Benzene	376	0.133	682	0.241
	Formaldehyde	95.1	0.007	172	0.013
Electricity	1,3- Butadiene	0	0.000	0	0.000
	Acetaldehyde	-0.2	0.000	-0.4	0.000
	Acrolein	-0.2	0.000	-0.4	-0.001
	Benzene	-5.8	-0.002	-10.6	-0.004
	Formaldehyde	-0.1	0.000	-0.3	0.000

Note: These values are expressed as emission reductions, such that positive values imply an emissions decrease, and negative values imply an emissions increase.

The fuel consumption analysis relied on the same set of fleet and activity inputs as the emission analysis. EPA modeled the entire fleet as using petroleum gasoline (consistent with OMEGA model results showing a lack of projected diesel penetration in the central analysis), and used a conversion factor of 8887 grams of CO_2 per gallon of petroleum gasoline in order to determine the quantity of fuel savings. The term petroleum gasoline is used here to mean fuel with 115,000 BTU/gallon. This is different than retail fuel, which is typically blended with ethanol and has a lower energy content as discussed earlier in Section 12.2.2.7.

[R] The total US inventory for selected pollutants (in short tons) was derived from the EPA National Emissions Inventory (NEI) 2011 (https://www.epa.gov/air-emissions-inventories/national-emissions-inventory)

Table 12.73 Annual Impacts of the MY2022-2025 Standards on Fuel and Electricity Consumption

Calendar Year	Petroleum Gasoline (billion gallons)	Petroleum Gasoline (billion barrels)	Electricity (billion kWh)
2021	-0.25	-0.01	0.11
2022	-0.77	-0.02	0.29
2023	-1.54	-0.04	0.54
2024	-2.56	-0.06	0.86
2025	-3.82	-0.09	1.26
2026	-5.05	-0.12	1.66
2027	-6.26	-0.15	2.05
2028	-7.43	-0.18	2.44
2029	-8.54	-0.20	2.81
2030	-9.59	-0.23	3.17
2031	-10.60	-0.25	3.52
2032	-11.57	-0.28	3.85
2033	-12.48	-0.30	4.17
2034	-13.34	-0.32	4.46
2035	-14.15	-0.34	4.74
2036	-14.91	-0.35	5.00
2037	-15.60	-0.37	5.23
2038	-16.25	-0.39	5.44
2039	-16.84	-0.40	5.63
2040	-17.39	-0.41	5.80
2041	-17.92	-0.43	5.96
2042	-18.41	-0.44	6.11
2043	-18.88	-0.45	6.25
2044	-19.34	-0.46	6.39
2045	-19.78	-0.47	6.53
2046	-20.21	-0.48	6.66
2047	-20.64	-0.49	6.79
2048	-21.07	-0.50	6.92
2049	-21.49	-0.51	7.04
2050	-21.92	-0.52	7.17
Sum	**-389**	**-9.26**	**129**

Note: These values are expressed as absolute inventory changes, such that negative values imply a decrease in consumption, and positive values imply an increase in consumption.

12.2.3.2 Model Year Lifetime Results

Table 12.74 MY Lifetime Emission Reductions of the MY2022-2025 Standards on GHGs (MMT CO_2e)

Model Year	Downstream (including A/C)	Fuel Production & Distribution	Electricity	**Total**
2021	27.4	7.7	-0.9	**34.2**
2022	56.9	15.9	-1.4	**71.4**
2023	85.7	24.0	-2.0	**108**
2024	114	32.0	-2.6	**144**
2025	144	40.2	-3.2	**181**
Sum	**428**	**120**	**-10.0**	**538**

Note: These values are expressed as emission reductions, such that positive values imply an emissions decrease, and negative values imply an emissions increase.

Table 12.75 MY Lifetime Emission Reductions of the MY2022-2025 Standards on Select non-GHG Criteria Pollutants (Short tons)

Model Year	VOC	CO	NOx	PM2.5	SO_2
2021	17,635	-19,775	3,977	650	2,752
2022	36,730	-37,876	8,644	1,407	5,904
2023	55,546	-52,658	13,398	2,141	8,969
2024	74,346	-64,598	18,295	2,866	12,000
2025	93,600	-73,959	23,445	3,600	15,069
Sum	**277,857**	**-248,864**	**67,760**	**10,663**	**44,693**

Note: These values are expressed as emission reductions, such that positive values imply an emissions decrease, and negative values imply an emissions increase.

Table 12.76 MY Lifetime Emission Reductions of the MY2022-2025 Standards on Select Toxic Pollutants (Short tons)

Model Year	Benzene	1,3 Butadiene	Formaldehyde	Acetaldehyde	Acrolein
2021	89	-5.3	22.0	-16.0	-0.8
2022	190	-10.4	46.8	-31.5	-1.6
2023	293	-14.7	72.4	-44.2	-2.1
2024	399	-18.4	99.1	-54.9	-2.6
2025	512	-21.6	127	-63.9	-3.0
Sum	**1,482**	**-70.4**	**368**	**-210**	**-10.1**

Note: These values are expressed as emission reductions, such that positive values imply an emissions decrease, and negative values imply an emissions increase.

Table 12.77 MY Lifetime Impacts of the MY2022-2025 Standards on Fuel and Electricity Consumption

Model Year	Retail Gasoline (billion gallons)	Retail Gasoline (billion barrels)	Electricity (billion kWh)
2021	-3.2	-0.1	1.4
2022	-6.7	-0.2	2.3
2023	-10.1	-0.2	3.2
2024	-13.4	-0.3	4.2
2025	-16.9	-0.4	5.3
Sum	**-50.3**	**-1.2**	**16.4**

Note: These values are expressed as absolute inventory changes, such that negative values imply a decrease in consumption, and positive values imply an increase in consumption.

12.2.4 Sensitivity Analysis Results

In this section, EPA presents the central case emissions impact analysis results using AEO 2015 reference fuel price cases (shown in Section 12.2.3) with two additional analyses based on the low and high fuel price cases found in the Annual Energy Outlook 2015 report (see Chapter 10 for more discussion regarding these fuel price cases). These additional analyses provide a good bracket around the uncertainty in fuel price projections and shows the magnitude of the effect of differing fuel price projections on emission impacts. Similarly to Section 12.2.3, Section 12.2.4.1 shows non-cumulative calendar year results for all three fuel price cases, and Section 12.2.4.2 shows model year lifetime and cumulative sum results for all three fuel price cases.

12.2.4.1 Calendar Year Case Comparison Results

Table 12.78 Annual Emission Reductions of the MY2022-2025 Standards and AEO Fuel Price Cases on Total GHGs (MMT CO_2e)

Calendar Year	AEO Low Fuel Price Case	**Central Case AEO Reference Fuel Price Case**	AEO High Fuel Price Case
2022	8.3	**8.2**	7.9
2025	41.8	**40.8**	39.1
2030	106	**102**	96.6
2040	193	**186**	172
2050	244	**234**	216

Note: These values are expressed as emission reductions, such that positive values imply an emissions decrease, and negative values imply an emissions increase.

Table 12.79 Annual Impacts of the MY2022-2025 Standards on Fuel Consumption

Calendar Year	AEO Low Fuel Price Case		**Central Case - AEO Reference Fuel Price Case**		AEO High Price Case	
	Petroleum Gasoline (Billon Gallons)	Electricity (Billion kWh)	**Petroleum Gasoline (Billon Gallons)**	**Electricity (Billion kWh)**	Petroleum Gasoline (Billon Gallons)	Electricity (Billion kWh)
2022	-0.78	0.28	**-0.77**	**0.29**	-0.75	0.33
2025	-3.91	1.35	**-3.82**	**1.26**	-3.67	1.53
2030	-9.91	3.44	**-9.59**	**3.17**	-9.09	3.83
2040	-18.09	6.28	**-17.39**	**5.80**	-16.22	6.90
2050	-22.87	7.81	**-21.92**	**7.17**	-20.29	8.55

Note: These values are expressed as absolute inventory changes, such that negative values imply a decrease in consumption, and positive values imply an increase in consumption.

12.2.4.1 Model Year Lifetime Case Comparison Results

Table 12.80 MY Lifetime Emission Reductions of the MY2022-2025 Standards and AEO Fuel Price Cases on Total GHGs (MMT CO_2e)

Model Year	AEO Low Fuel Price Case	**Central Case AEO Reference Fuel Price Case**	AEO High Fuel Price Case
2021	34.7	**34.2**	32.9
2022	72.7	**71.3**	69.0
2023	110	**108**	104
2024	148	**144**	137
2025	186	**181**	172
Sum	551	**538**	514

Note: The values shown in the table above are expressed as emission reductions, such that negative values imply an emissions increase while positive values imply an emissions decrease.

Table 12.81 MY Lifetime Impacts of the MY2022-2025 Standards and AEO Fuel Price Cases on Fuel Consumption

Calendar Year	AEO Low Fuel Price Case		**Central Case AEO Reference Fuel Price Case**		AEO High Fuel Price Case	
	Petroleum Gasoline (billion gallons)	Electricity (billion kWh)	**Petroleum Gasoline (billion gallons)**	**Electricity (billion kWh)**	Petroleum Gasoline (billion gallons)	Electricity (billion kWh)
2021	-3.3	1.3	**-3.2**	**1.4**	-3.1	1.5
2022	-6.8	2.3	**-6.7**	**2.3**	-6.5	2.7
2023	-10.3	3.4	**-10.1**	**3.2**	-9.7	3.9
2024	-13.8	4.6	**-13.4**	**4.2**	-12.9	5.2
2025	-17.4	5.9	**-16.9**	**5.3**	-16.1	6.6
Sum	-51.6	17.6	**-50.3**	**16.4**	-48.4	19.9

Note: These values are expressed as absolute inventory changes, such that negative values imply a decrease in consumption, and positive values imply an increase in consumption.

12.3 EPA's Benefit-Cost Analysis Results

In Section 12.3.1, EPA presents results of its model year analysis, which looks at the lifetimes of MY2021-2025 vehicles. In Section 12.3.2, EPA presents results of its calendar year analysis, which looks at annual impacts through the year 2050. The inventory inputs used to generate the monetized benefits presented here are discussed in Section 12.2. The monetary inputs used to generate the monetized benefits and costs presented here are discussed in Chapter 10 where we present \$/ton, \$/gallon and \$/mile premiums that are applied to the inventory inputs to generate the benefit cost analysis results.

12.3.1 Model Year Analysis

In our MY analysis, we look at the impacts over the lifetimes of MY2021-2025 vehicles.[S] All values are discounted at 3 percent and 7 percent discount rates with the exception of the social costs of greenhouse gases which are discounted at the discount rate used in their generation. All values are discounted back to CY 2015.

12.3.1.1 AEO 2015 Reference Fuel Price Case Using ICMs

In the central analysis, we use AEO 2015 reference fuel prices and fleet projections, and, as noted, we include our estimate of EV and PHEV sales required by the ZEV program in the reference and control case fleets. Importantly, Table 12.82 shows that technology and maintenance costs are estimated at roughly \$35 billion and benefits excluding fuel savings are estimated at roughly \$41 billion (using the 3 percent average SC-GHG value). In other words, even without fuel savings, benefits outweigh costs. Similarly, Table 12.83 shows that technology and maintenance costs are estimated at roughly \$25 billion and benefits excluding fuel savings are estimated at roughly \$30 billion (using the 3 percent average SC-GHG value). In other words, even without fuel savings, benefits outweigh costs.

[S] See Chapter 12.1.1.1.2 for details on why MY2021 is included in our Control Case.

Table 12.82 MY Lifetime Costs & Benefits Using AEO Reference Fuel Prices and ICMs (3 Percent Discount Rate, Billions of 2013$)[a, b, c]

	2021	2022	2023	2024	2025	Sum
Vehicle Program	-$2.5	-$4.7	-$6.8	-$8.8	-$10.8	-$33.6
Maintenance	$0.0	-$0.2	-$0.3	-$0.5	-$0.6	-$1.6
Pre-tax Fuel	$5.9	$12.0	$17.9	$23.7	$29.4	$88.8
Energy Security	$0.3	$0.6	$0.9	$1.3	$1.6	$4.7
Crashes, Noise, Congestion	-$0.6	-$1.2	-$1.7	-$2.2	-$2.7	-$8.3
Travel Value	$0.7	$1.4	$2.0	$2.6	$3.2	$9.8
Refueling	$0.5	$1.0	$1.4	$1.9	$2.3	$7.1
Non-GHG	$0.3 - $0.8	$0.7 - $1.6	$1.1 - $2.5	$1.4 - $3.2	$1.8 - $4.0	$5.4 - $12.1
GHG						
SC-GHG 5% Avg	$0.3	$0.6	$0.9	$1.2	$1.4	$4.4
SC-GHG 3% Avg	$1.2	$2.5	$3.8	$5.0	$6.2	$18.6
SC-GHG 2.5% Avg	$1.9	$3.9	$5.9	$7.7	$9.6	$29.0
SC-GHG 3% 95th	$3.7	$7.6	$11.3	$15.0	$18.6	$56.1
Net Benefits						
SC-GHG 5% Avg	$5.0	$10.7	$16.2	$21.5	$26.8	$80.1
SC-GHG 3% Avg	$6.0	$12.6	$19.0	$25.2	$31.5	$94.3
SC-GHG 2.5% Avg	$6.6	$14.0	$21.1	$28.0	$35.0	$104.8
SC-GHG 3% 95th	$8.4	$17.7	$26.6	$35.2	$43.9	$131.8

Notes:

[a] The non-GHG benefits presented in this table are based on PM2.5-related benefit per ton values (see Chapter 10.6 for more information); the range of benefits are derived from two premature mortality estimates - the American Cancer Society cohort study (Krewski et al., 2009) and the Harvard Six-Cities study (Lepeule et al., 2012). The range of benefits also assumes either a 3 percent or 7 percent discount rate in the valuation of PM-related premature mortality to account for a twenty-year segmented cessation lag. Benefit-per-ton values were estimated for the years 2016, 2020, 2025 and 2030. We hold values constant for intervening years (e.g., the 2016 values are assumed to apply to years 2017-2019; 2020 values for years 2021-2024; 2025 values for years 2026-2029; and 2030 values for years 2031 and beyond). See Table 10-10 for the benefit per ton values used in this analysis.

[b] GHG benefit estimates include reductions in CO_2, CH_4, and N_2O but do not include HFC reductions. Note that net present value of reduced GHG emissions is calculated differently than other benefits. The same discount rate used to discount the value of damages from future emissions (SC-CO_2, SC-CH_4, and SC-N_2O, each discounted at rates of 5, 3, 2.5 percent) is used to calculate net present value of SC-CO_2, SC-CH_4, and SC-N_2O, respectively, for internal consistency. Refer to the Chapter 10.7 for more detail.

[c] Chapter 10.7 notes that SC-GHGs increases over time. Corresponding to the years in this table (2021-2025), the SC-CO_2 estimates range as follows: for Average SC-CO_2 at 5%: $13-$15; for Average SC-CO_2 at 3%: $46-$50; for Average SC-CO_2 at 2.5%: $69-$75; and for 95th percentile SC-CO_2 at 3%: $140-$150. For the years 2021-2025, the SC-CH_4 estimates range as follows: for Average SC-CH_4 at 5%: $620-$700; for Average SC-CH_4 at 3%: $1,400-$1,500; for Average SC-CH_4 at 2.5%: $1,800-$2,000; and for 95th percentile SC-CH_4 at 3%: $3,600-$4,100. For the years 2021-2025, the SC-N_2O estimates range as follows: for Average SC-N_2O at 5%: $5,300-$6,000; for Average SC-N_2O at 3%: $17,000-$19,000; for Average SC-N_2O at 2.5%: $25,000-$26,000; and for 95th percentile SC-N_2O at 3%: $44,000-$48,000. Chapter 10.7 also presents these SC-GHG estimates.

Table 12.83 MY Lifetime Costs & Benefits Using AEO Reference Fuel Prices and ICMs, (7 Percent Discount Rate, Billions of 2013$) [a, b, c]

	2021	2022	2023	2024	2025	Sum
Vehicle Program	-$2.0	-$3.5	-$4.9	-$6.1	-$7.2	-$23.8
Maintenance	$0.0	-$0.1	-$0.2	-$0.2	-$0.3	-$0.9
Pre-tax Fuel	$3.5	$7.0	$10.1	$12.8	$15.3	$48.7
Energy Security	$0.2	$0.4	$0.5	$0.7	$0.8	$2.6
Crashes, Noise, Congestion	-$0.4	-$0.7	-$1.0	-$1.2	-$1.4	-$4.7
Travel Value	$0.4	$0.8	$1.1	$1.4	$1.6	$5.4
Refueling	$0.3	$0.6	$0.8	$1.0	$1.2	$3.9
Non-GHG	$0.2 - $0.4	$0.4 - $0.9	$0.6 - $1.3	$0.7 - $1.6	$0.9 - $1.9	$2.7 - $6.1
GHG						
SC-GHG 5% Avg	$0.3	$0.6	$0.9	$1.2	$1.4	$4.4
SC-GHG 3% Avg	$1.2	$2.5	$3.8	$5.0	$6.2	$18.6
SC-GHG 2.5% Avg	$1.9	$3.9	$5.9	$7.7	$9.6	$29.0
SC-GHG 3% 95th	$3.7	$7.6	$11.3	$15.0	$18.6	$56.1
Net Benefits						
SC-GHG 5% Avg	$2.7	$5.6	$8.2	$10.6	$12.8	$40.0
SC-GHG 3% Avg	$3.6	$7.5	$11.1	$14.4	$17.6	$54.2
SC-GHG 2.5% Avg	$4.3	$8.9	$13.2	$17.2	$21.0	$64.7
SC-GHG 3% 95th	$6.1	$12.6	$18.7	$24.4	$30.0	$91.7

Notes

[a] The non-GHG benefits presented in this table are based on PM2.5-related benefit per ton values (see Chapter 10.6 for more information); the range of benefits are derived from two premature mortality estimates - the American Cancer Society cohort study (Krewski et al., 2009) and the Harvard Six-Cities study (Lepeule et al., 2012). The range of benefits also assumes either a 3 percent or 7 percent discount rate in the valuation of PM-related premature mortality to account for a twenty-year segmented cessation lag. Benefit-per-ton values were estimated for the years 2016, 2020, 2025 and 2030. We hold values constant for intervening years (e.g., the 2016 values are assumed to apply to years 2017-2019; 2020 values for years 2021-2024; 2025 values for years 2026-2029; and 2030 values for years 2031 and beyond). See Table 10-10 for the benefit per ton values used in this analysis.

[b] GHG benefit estimates include reductions in CO_2, CH_4, and N_2O but do not include HFC reductions. Note that net present value of reduced GHG emissions is calculated differently than other benefits. The same discount rate used to discount the value of damages from future emissions (SC-CO_2, SC-CH_4, and SC-N_2O, each discounted at rates of 5, 3, 2.5 percent) is used to calculate net present value of SC-CO_2, SC-CH_4, and SC-N_2O, respectively, for internal consistency. Refer to the Chapter 10.7 for more detail.

[c] Chapter 10.7 notes that SC-GHGs increases over time. Corresponding to the years in this table (2021-2025), the SC-CO_2 estimates range as follows: for Average SC-CO_2 at 5%: $13-$15; for Average SC-CO_2 at 3%: $46-$50; for Average SC-CO_2 at 2.5%: $69-$75; and for 95th percentile SC-CO_2 at 3%: $140-$150. For the years 2021-2025, the SC-CH_4 estimates range as follows: for Average SC-CH_4 at 5%: $620-$700; for Average SC-CH_4 at 3%: $1,400-$1,500; for Average SC-CH_4 at 2.5%: $1,800-$2,000; and for 95th percentile SC-CH_4 at 3%: $3,600-$4,100. For the years 2021-2025, the SC-N_2O estimates range as follows: for Average SC-N_2O at 5%: $5,300-$6,000; for Average SC-N_2O at 3%: $17,000-$19,000; for Average SC-N_2O at 2.5%: $25,000-$26,000; and for 95th percentile SC-N_2O at 3%: $44,000-$48,000. Chapter 10.7 also presents these SC-GHG estimates.

12.3.1.2 AEO 2015 Reference Fuel Price Case Using RPEs

In the central analysis, we use AEO 2015 reference fuel prices and fleet projections, and we include our estimate of EV and PHEV sales required by the ZEV program in the reference and control case fleets. Importantly, Table 12.84 shows that technology and maintenance costs are estimated at roughly $39 billion and benefits excluding fuel savings are estimated at roughly $40 billion (using the 3 percent average SC-GHG value). In other words, even without fuel savings, benefits outweigh costs. Similarly, Table 12.85 shows that technology and maintenance costs are estimated at roughly $28 billion and benefits excluding fuel savings are estimated at roughly $30 billion (using the 3 percent average SC-GHG value). In other words, even without fuel savings, benefits outweigh costs.

Table 12.84 MY Lifetime Costs & Benefits Using AEO Reference Fuel Prices and RPEs (3 Percent Discount Rate, Billions of 2013$) [a, b, c]

	2021	2022	2023	2024	2025	Sum
Vehicle Program	-$2.6	-$5.2	-$7.6	-$10.0	-$12.2	-$37.6
Maintenance	$0.0	-$0.2	-$0.3	-$0.5	-$0.6	-$1.6
Pre-tax Fuel	$5.9	$12.0	$17.9	$23.7	$29.4	$88.8
Energy Security	$0.3	$0.6	$0.9	$1.3	$1.6	$4.7
Crashes, Noise, Congestion	-$0.6	-$1.2	-$1.7	-$2.2	-$2.7	-$8.3
Travel Value	$0.7	$1.4	$2.0	$2.6	$3.1	$9.8
Refueling	$0.5	$1.0	$1.4	$1.9	$2.3	$7.1
Non-GHG	$0.3 - $0.7	$0.7 - $1.6	$1.1 - $2.4	$1.4 - $3.2	$1.8 - $3.9	$5.3 - $11.8
GHG						
SC-GHG 5% Avg	$0.3	$0.6	$0.9	$1.2	$1.4	$4.4
SC-GHG 3% Avg	$1.2	$2.5	$3.7	$4.9	$6.1	$18.5
SC-GHG 2.5% Avg	$1.9	$3.9	$5.8	$7.7	$9.6	$28.9
SC-GHG 3% 95th	$3.6	$7.5	$11.3	$14.9	$18.5	$55.8
Net Benefits						
SC-GHG 5% Avg	$4.9	$10.2	$15.3	$20.2	$25.2	$75.9
SC-GHG 3% Avg	$5.8	$12.1	$18.1	$24.0	$29.9	$90.1
SC-GHG 2.5% Avg	$6.5	$13.5	$20.2	$26.8	$33.4	$100.4
SC-GHG 3% 95th	$8.3	$17.1	$25.7	$34.0	$42.3	$127.4

Notes:

[a] The non-GHG benefits presented in this table are based on PM2.5-related benefit per ton values (see Chapter 10.6 for more information); the range of benefits are derived from two premature mortality estimates - the American Cancer Society cohort study (Krewski et al., 2009) and the Harvard Six-Cities study (Lepeule et al., 2012). The range of benefits also assumes either a 3 percent or 7 percent discount rate in the valuation of PM-related premature mortality to account for a twenty-year segmented cessation lag. Benefit-per-ton values were estimated for the years 2016, 2020, 2025 and 2030. We hold values constant for intervening years (e.g., the 2016 values are assumed to apply to years 2017-2019; 2020 values for years 2021-2024; 2025 values for years 2026-2029; and 2030 values for years 2031 and beyond). See Table 10-10 for the benefit per ton values used in this analysis.

[b] GHG benefit estimates include reductions in CO_2, CH_4, and N_2O but do not include HFC reductions. Note that net present value of reduced GHG emissions is calculated differently than other benefits. The same discount rate used to discount the value of damages from future emissions (SC-CO_2, SC-CH_4, and SC-N_2O, each discounted at rates of 5, 3, 2.5 percent) is used to calculate net present value of SC-CO_2, SC-CH_4, and SC-N_2O, respectively, for internal consistency. Refer to the Chapter 10.7 for more detail.

[c] Chapter 10.7 notes that SC-GHGs increases over time. Corresponding to the years in this table (2021-2025), the SC-CO_2 estimates range as follows: for Average SC-CO_2 at 5%: $13-$15; for Average SC-CO_2 at 3%: $46-$50; for Average SC-CO_2 at 2.5%: $69-$75; and for 95th percentile SC-CO_2 at 3%: $140-$150. For the years 2021-2025, the SC-CH_4 estimates range as follows: for Average SC-CH_4 at 5%: $620-$700; for Average SC-CH_4 at 3%: $1,400-$1,500; for Average SC-CH_4 at 2.5%: $1,800-$2,000; and for 95th percentile SC-CH_4 at 3%: $3,600-$4,100. For the

years 2021-2025, the SC-N_2O estimates range as follows: for Average SC-N_2O at 5%: $5,300-$6,000; for Average SC-N_2O at 3%: $17,000-$19,000; for Average SC-N_2O at 2.5%: $25,000-$26,000; and for 95th percentile SC-N_2O at 3%: $44,000-$48,000. Chapter 10.7 also presents these SC-GHG estimates.

Table 12.85 MY Lifetime Costs & Benefits Using AEO Reference Fuel Prices and RPEs, (7 Percent Discount Rate, Billions of 2013$) [a, b, c]

	2021	2022	2023	2024	2025	Sum
Vehicle Program	-$2.0	-$3.9	-$5.5	-$6.9	-$8.2	-$26.6
Maintenance	$0.0	-$0.1	-$0.2	-$0.3	-$0.3	-$0.9
Pre-tax Fuel	$3.5	$7.0	$10.1	$12.8	$15.3	$48.7
Energy Security	$0.2	$0.4	$0.5	$0.7	$0.8	$2.6
Crashes, Noise, Congestion	-$0.4	-$0.7	-$1.0	-$1.2	-$1.4	-$4.6
Travel Value	$0.4	$0.8	$1.1	$1.4	$1.6	$5.4
Refueling	$0.3	$0.6	$0.8	$1.0	$1.2	$3.9
Non-GHG	$0.2 - $0.4	$0.4 - $0.8	$0.5 - $1.2	$0.7 - $1.6	$0.8 - $1.9	$2.6 - $5.9
GHG						
SC-GHG 5% Avg	$0.3	$0.6	$0.9	$1.2	$1.4	$4.4
SC-GHG 3% Avg	$1.2	$2.5	$3.7	$4.9	$6.1	$18.5
SC-GHG 2.5% Avg	$1.9	$3.9	$5.8	$7.7	$9.6	$28.9
SC-GHG 3% 95th	$3.6	$7.5	$11.3	$14.9	$18.5	$55.8
Net Benefits						
SC-GHG 5% Avg	$2.6	$5.3	$7.6	$9.8	$11.8	$37.1
SC-GHG 3% Avg	$3.5	$7.2	$10.5	$13.6	$16.5	$51.3
SC-GHG 2.5% Avg	$4.2	$8.5	$12.6	$16.4	$20.0	$61.7
SC-GHG 3% 95th	$5.9	$12.2	$18.0	$23.5	$28.9	$88.6

Notes:

[a] The non-GHG benefits presented in this table are based on PM2.5-related benefit per ton values (see Chapter 10.6 for more information); the range of benefits are derived from two premature mortality estimates - the American Cancer Society cohort study (Krewski et al., 2009) and the Harvard Six-Cities study (Lepeule et al., 2012). The range of benefits also assumes either a 3 percent or 7 percent discount rate in the valuation of PM-related premature mortality to account for a twenty-year segmented cessation lag. Benefit-per-ton values were estimated for the years 2016, 2020, 2025 and 2030. We hold values constant for intervening years (e.g., the 2016 values are assumed to apply to years 2017-2019; 2020 values for years 2021-2024; 2025 values for years 2026-2029; and 2030 values for years 2031 and beyond). See Table 10-10 for the benefit per ton values used in this analysis.

[b] GHG benefit estimates include reductions in CO_2, CH_4, and N_2O but do not include HFC reductions. Note that net present value of reduced GHG emissions is calculated differently than other benefits. The same discount rate used to discount the value of damages from future emissions (SC-CO_2, SC-CH_4, and SC-N_2O, each discounted at rates of 5, 3, 2.5 percent) is used to calculate net present value of SC-CO_2, SC-CH_4, and SC-N_2O, respectively, for internal consistency. Refer to the Chapter 10.7 for more detail.

[c] Chapter 10.7 notes that SC-GHGs increases over time. Corresponding to the years in this table (2021-2025), the SC-CO_2 estimates range as follows: for Average SC-CO_2 at 5%: $13-$15; for Average SC-CO_2 at 3%: $46-$50; for Average SC-CO_2 at 2.5%: $69-$75; and for 95th percentile SC-CO_2 at 3%: $140-$150. For the years 2021-2025, the SC-CH_4 estimates range as follows: for Average SC-CH_4 at 5%: $620-$700; for Average SC-CH_4 at 3%: $1,400-$1,500; for Average SC-CH_4 at 2.5%: $1,800-$2,000; and for 95th percentile SC-CH_4 at 3%: $3,600-$4,100. For the years 2021-2025, the SC-N_2O estimates range as follows: for Average SC-N_2O at 5%: $5,300-$6,000; for Average SC-N_2O at 3%: $17,000-$19,000; for Average SC-N_2O at 2.5%: $25,000-$26,000; and for 95th percentile SC-N_2O at 3%: $44,000-$48,000. Chapter 10.7 also presents these SC-GHG estimates.

12.3.1.3 AEO 2015 High Fuel Price Case Using ICMs

In the AEO high fuel price analysis, we use AEO 2015 high fuel prices and fleet projections, and we include our estimate of EV and PHEV sales required by the ZEV program in the reference and control case fleets. Importantly, Table 12.86 shows that technology and maintenance costs are estimated at roughly $32 billion and benefits excluding fuel savings are estimated at roughly $36 billion (using the 3 percent average SC-GHG value). In other words, even without fuel savings, benefits outweigh costs. Similarly, Table 12.87 shows that technology and maintenance costs are estimated at roughly $22 billion and benefits excluding fuel savings are estimated at roughly $27 billion (using the 3 percent average SC-GHG value). In other words, even without fuel savings, benefits outweigh costs.

Table 12.86 MY Lifetime Costs & Benefits Using AEO High Fuel Prices and ICMs (3 Percent Discount Rate, Billions of 2013$) [a, b, c]

	2021	2022	2023	2024	2025	Sum
Vehicle Program	-$2.4	-$4.6	-$6.7	-$8.7	-$10.6	-$30.6
Maintenance	$0.0	-$0.1	-$0.2	-$0.4	-$0.5	-$1.2
Pre-tax Fuel	$5.6	$11.7	$17.3	$22.7	$28.1	$79.8
Energy Security	$0.3	$0.6	$0.9	$1.2	$1.5	$4.2
Crashes, Noise, Congestion	-$0.6	-$1.2	-$1.7	-$2.2	-$2.6	-$7.7
Travel Value	$0.7	$1.3	$1.9	$2.5	$3.0	$8.8
Refueling	$0.5	$0.9	$1.4	$1.8	$2.2	$6.4
Non-GHG	$0.3 - $0.7	$0.7 - $1.6	$1.0 - $2.3	$1.3 - $3.0	$1.7 - $3.7	$4.7 - $10.6
GHG						
SC-GHG 5% Avg	$0.3	$0.6	$0.9	$1.1	$1.4	$3.9
SC-GHG 3% Avg	$1.2	$2.4	$3.6	$4.7	$5.8	$16.6
SC-GHG 2.5% Avg	$1.8	$3.8	$5.6	$7.4	$9.2	$26.0
SC-GHG 3% 95th	$3.5	$7.3	$10.9	$14.3	$17.7	$50.1
Net Benefits						
SC-GHG 5% Avg	$4.9	$10.4	$15.4	$20.3	$25.2	$71.3
SC-GHG 3% Avg	$5.8	$12.2	$18.2	$23.9	$29.6	$84.0
SC-GHG 2.5% Avg	$6.5	$13.6	$20.2	$26.6	$32.9	$93.3
SC-GHG 3% 95th	$8.2	$17.1	$25.5	$33.5	$41.5	$117.5

Notes:

[a] The non-GHG benefits presented in this table are based on PM2.5-related benefit per ton values (see Chapter 10.6 for more information); the range of benefits are derived from two premature mortality estimates - the American Cancer Society cohort study (Krewski et al., 2009) and the Harvard Six-Cities study (Lepeule et al., 2012). The range of benefits also assumes either a 3 percent or 7 percent discount rate in the valuation of PM-related premature mortality to account for a twenty-year segmented cessation lag. Benefit-per-ton values were estimated for the years 2016, 2020, 2025 and 2030. We hold values constant for intervening years (e.g., the 2016 values are assumed to apply to years 2017-2019; 2020 values for years 2021-2024; 2025 values for years 2026-2029; and 2030 values for years 2031 and beyond). See Table 10-10 for the benefit per ton values used in this analysis.

[b] GHG benefit estimates include reductions in CO_2, CH_4, and N_2O but do not include HFC reductions. Note that net present value of reduced GHG emissions is calculated differently than other benefits. The same discount rate used to discount the value of damages from future emissions (SC-CO_2, SC-CH_4, and SC-N_2O, each discounted at rates of 5, 3, 2.5 percent) is used to calculate net present value of SC-CO_2, SC-CH_4, and SC-N_2O, respectively, for internal consistency. Refer to the Chapter 10.7 for more detail.

[c] Chapter 10.7 notes that SC-GHGs increases over time. Corresponding to the years in this table (2021-2025), the SC-CO_2 estimates range as follows: for Average SC-CO_2 at 5%: $13-$15; for Average SC-CO_2 at 3%: $46-$50; for Average SC-CO_2 at 2.5%: $69-$75; and for 95th percentile SC-CO_2 at 3%: $140-$150. For the years 2021-2025, the SC-CH_4 estimates range as follows: for Average SC-CH_4 at 5%: $620-$700; for Average SC-CH_4 at 3%: $1,400-$1,500; for Average SC-CH_4 at 2.5%: $1,800-$2,000; and for 95th percentile SC-CH_4 at 3%: $3,600-$4,100. For the years 2021-2025, the SC-N_2O estimates range as follows: for Average SC-N_2O at 5%: $5,300-$6,000; for Average SC-N_2O at 3%: $17,000-$19,000; for Average SC-N_2O at 2.5%: $25,000-$26,000; and for 95th percentile SC-N_2O at 3%: $44,000-$48,000. Chapter 10.7 also presents these SC-GHG estimates.

Table 12.87 MY Lifetime Costs & Benefits Using AEO High Fuel Prices and ICMs (7 Percent Discount Rate, Billions of 2013$) [a, b, c]

	2021	2022	2023	2024	2025	Sum
Vehicle Program	-$1.9	-$3.5	-$4.9	-$6.0	-$7.1	-$21.5
Maintenance	$0.0	-$0.1	-$0.1	-$0.2	-$0.3	-$0.7
Pre-tax Fuel	$3.4	$6.8	$9.7	$12.3	$14.6	$43.5
Energy Security	$0.2	$0.4	$0.5	$0.6	$0.8	$2.3
Crashes, Noise, Congestion	-$0.4	-$0.7	-$1.0	-$1.2	-$1.4	-$4.3
Travel Value	$0.4	$0.8	$1.1	$1.4	$1.6	$4.8
Refueling	$0.3	$0.6	$0.8	$1.0	$1.2	$3.5
Non-GHG	$0.2 - $0.4	$0.4 - $0.8	$0.5 - $1.2	$0.7 - $1.5	$0.8 - $1.8	$2.3 - $5.3
GHG						
SC-GHG 5% Avg	$0.3	$0.6	$0.9	$1.1	$1.4	$3.9
SC-GHG 3% Avg	$1.2	$2.4	$3.6	$4.7	$5.8	$16.6
SC-GHG 2.5% Avg	$1.8	$3.8	$5.6	$7.4	$9.2	$26.0
SC-GHG 3% 95th	$3.5	$7.3	$10.9	$14.3	$17.7	$50.1
Net Benefits						
SC-GHG 5% Avg	$2.7	$5.4	$7.9	$10.0	$12.0	$35.4
SC-GHG 3% Avg	$3.5	$7.3	$10.6	$13.7	$16.5	$48.1
SC-GHG 2.5% Avg	$4.2	$8.6	$12.6	$16.3	$19.8	$57.5
SC-GHG 3% 95th	$5.9	$12.2	$17.9	$23.2	$28.3	$81.6

Notes:
[a] The non-GHG benefits presented in this table are based on PM2.5-related benefit per ton values (see Chapter 10.6 for more information); the range of benefits are derived from two premature mortality estimates - the American Cancer Society cohort study (Krewski et al., 2009) and the Harvard Six-Cities study (Lepeule et al., 2012). The range of benefits also assumes either a 3 percent or 7 percent discount rate in the valuation of PM-related premature mortality to account for a twenty-year segmented cessation lag. Benefit-per-ton values were estimated for the years 2016, 2020, 2025 and 2030. We hold values constant for intervening years (e.g., the 2016 values are assumed to apply to years 2017-2019; 2020 values for years 2021-2024; 2025 values for years 2026-2029; and 2030 values for years 2031 and beyond). See Table 10-10 for the benefit per ton values used in this analysis.
[b] GHG benefit estimates include reductions in CO_2, CH_4, and N_2O but do not include HFC reductions. Note that net present value of reduced GHG emissions is calculated differently than other benefits. The same discount rate used to discount the value of damages from future emissions (SC-CO_2, SC-CH_4, and SC-N_2O, each discounted at rates of 5, 3, 2.5 percent) is used to calculate net present value of SC-CO_2, SC-CH_4, and SC-N_2O, respectively, for internal consistency. Refer to the Chapter 10.7 for more detail.
[c] Chapter 10.7 notes that SC-GHGs increases over time. Corresponding to the years in this table (2021-2025), the SC-CO_2 estimates range as follows: for Average SC-CO_2 at 5%: $13-$15; for Average SC-CO_2 at 3%: $46-$50; for Average SC-CO_2 at 2.5%: $69-$75; and for 95th percentile SC-CO_2 at 3%: $140-$150. For the years 2021-2025, the SC-CH_4 estimates range as follows: for Average SC-CH_4 at 5%: $620-$700; for Average SC-CH_4 at 3%: $1,400-$1,500; for Average SC-CH_4 at 2.5%: $1,800-$2,000; and for 95th percentile SC-CH_4 at 3%: $3,600-$4,100. For the years 2021-2025, the SC-N_2O estimates range as follows: for Average SC-N_2O at 5%: $5,300-$6,000; for Average SC-N_2O at 3%: $17,000-$19,000; for Average SC-N_2O at 2.5%: $25,000-$26,000; and for 95th percentile SC-N_2O at 3%: $44,000-$48,000. Chapter 10.7 also presents these SC-GHG estimates.

12.3.1.4 AEO 2015 Low Fuel Price Case Using ICMs

In the AEO low fuel price analysis, we use AEO 2015 low fuel prices and fleet projections, and we include our estimate of EV and PHEV sales required by the ZEV program in the reference and control case fleets. Importantly, Table 12.88 shows that technology and maintenance costs are estimated at roughly $33 billion and benefits excluding fuel savings are estimated at roughly $39 billion (using the 3 percent average SC-GHG value). In other words, even without fuel savings, benefits outweigh costs. Similarly, Table 12.89 shows that technology and maintenance costs are estimated at roughly $23 billion and benefits excluding fuel savings are estimated at roughly $29 billion (using the 3 percent average SC-GHG value). In other words, even without fuel savings, benefits outweigh costs.

Table 12.88 MY Lifetime Costs & Benefits Using AEO Low Fuel Prices and ICMs (3 Percent Discount Rate, Billions of 2013$) [a, b, c]

	2021	2022	2023	2024	2025	Sum
Vehicle Program	-$2.4	-$4.6	-$6.8	-$8.9	-$10.9	-$31.2
Maintenance	-$0.1	-$0.2	-$0.3	-$0.5	-$0.6	-$1.5
Pre-tax Fuel	$5.9	$12.2	$18.3	$24.3	$30.3	$85.2
Energy Security	$0.3	$0.6	$1.0	$1.3	$1.6	$4.5
Crashes, Noise, Congestion	-$0.6	-$1.2	-$1.7	-$2.2	-$2.7	-$7.8
Travel Value	$0.7	$1.4	$2.1	$2.7	$3.2	$9.4
Refueling	$0.5	$1.0	$1.5	$1.9	$2.4	$6.8
Non-GHG	$0.4 - $0.8	$0.7 - $1.7	$1.1 - $2.5	$1.5 - $3.3	$1.8 - $4.1	$5.2 - $11.6
GHG						
SC-GHG 5% Avg	$0.3	$0.6	$0.9	$1.2	$1.5	$4.2
SC-GHG 3% Avg	$1.2	$2.6	$3.8	$5.1	$6.3	$17.8
SC-GHG 2.5% Avg	$1.9	$4.0	$6.0	$8.0	$9.9	$27.8
SC-GHG 3% 95th	$3.7	$7.7	$11.6	$15.4	$19.1	$53.8
Net Benefits						
SC-GHG 5% Avg	$5.3	$11.1	$16.7	$22.3	$27.8	$77.9
SC-GHG 3% Avg	$6.2	$13.1	$19.7	$26.2	$32.7	$91.6
SC-GHG 2.5% Avg	$6.9	$14.5	$21.8	$29.0	$36.3	$101.6
SC-GHG 3% 95th	$8.7	$18.2	$27.4	$36.4	$45.5	$127.5

Note: [a] The non-GHG benefits presented in this table are based on PM2.5-related benefit per ton values (see Chapter 10.6 for more information); the range of benefits are derived from two premature mortality estimates - the American Cancer Society cohort study (Krewski et al., 2009) and the Harvard Six-Cities study (Lepeule et al., 2012). The range of benefits also assumes either a 3 percent or 7 percent discount rate in the valuation of PM-related premature mortality to account for a twenty-year segmented cessation lag. Benefit-per-ton values were estimated for the years 2016, 2020, 2025 and 2030. We hold values constant for intervening years (e.g., the 2016 values are assumed to apply to years 2017-2019; 2020 values for years 2021-2024; 2025 values for years 2026-2029; and 2030 values for years 2031 and beyond). See Table 10-10 for the benefit per ton values used in this analysis.

[b] GHG benefit estimates include reductions in CO_2, CH_4, and N_2O but do not include HFC reductions. Note that net present value of reduced GHG emissions is calculated differently than other benefits. The same discount rate used to discount the value of damages from future emissions (SC-CO_2, SC-CH_4, and SC-N_2O, each discounted at rates of 5, 3, 2.5 percent) is used to calculate net present value of SC-CO_2, SC-CH_4, and SC-N_2O, respectively, for internal consistency. Refer to the Chapter 10.7 for more detail.

[c] Chapter 10.7 notes that SC-GHGs increases over time. Corresponding to the years in this table (2021-2025), the SC-CO_2 estimates range as follows: for Average SC-CO_2 at 5%: $13-$15; for Average SC-CO_2 at 3%: $46-$50; for Average SC-CO_2 at 2.5%: $69-$75; and for 95th percentile SC-CO_2 at 3%: $140-$150. For the years 2021-2025, the SC-CH_4 estimates range as follows: for Average SC-CH_4 at 5%: $620-$700; for Average SC-CH_4 at 3%: $1,400-$1,500; for Average SC-CH_4 at 2.5%: $1,800-$2,000; and for 95th percentile SC-CH_4 at 3%: $3,600-$4,100. For the years 2021-2025, the SC-N_2O estimates range as follows: for Average SC-N_2O at 5%: $5,300-$6,000; for Average SC-N_2O at 3%: $17,000-$19,000; for Average SC-N_2O at 2.5%: $25,000-$26,000; and for 95th percentile SC-N_2O at 3%: $44,000-$48,000. Chapter 10.7 also presents these SC-GHG estimates.

Table 12.89 MY Lifetime Costs & Benefits Using AEO Low Fuel Prices and ICMs (7 Percent Discount Rate, Billions of 2013$) [a, b, c]

	2021	2022	2023	2024	2025	Sum
Vehicle Program	-$1.9	-$3.5	-$4.9	-$6.2	-$7.3	-$21.8
Maintenance	$0.0	-$0.1	-$0.2	-$0.2	-$0.3	-$0.9
Pre-tax Fuel	$3.6	$7.1	$10.3	$13.1	$15.8	$46.3
Energy Security	$0.2	$0.4	$0.5	$0.7	$0.8	$2.4
Crashes, Noise, Congestion	-$0.4	-$0.7	-$1.0	-$1.2	-$1.4	-$4.4
Travel Value	$0.4	$0.8	$1.2	$1.4	$1.7	$5.1
Refueling	$0.3	$0.6	$0.8	$1.1	$1.3	$3.7
Non-GHG	$0.2 - $0.4	$0.4 - $0.9	$0.6 - $1.3	$0.7 - $1.6	$0.9 - $2.0	$2.6 - $5.8
GHG						
SC-GHG 5% Avg	$0.3	$0.6	$0.9	$1.2	$1.5	$4.2
SC-GHG 3% Avg	$1.2	$2.6	$3.8	$5.1	$6.3	$17.8
SC-GHG 2.5% Avg	$1.9	$4.0	$6.0	$8.0	$9.9	$27.8
SC-GHG 3% 95th	$3.7	$7.7	$11.6	$15.4	$19.1	$53.8
Net Benefits						
SC-GHG 5% Avg	$2.9	$5.9	$8.6	$11.1	$13.4	$38.9
SC-GHG 3% Avg	$3.8	$7.8	$11.5	$15.0	$18.2	$52.5
SC-GHG 2.5% Avg	$4.5	$9.2	$13.6	$17.8	$21.8	$62.5
SC-GHG 3% 95th	$6.3	$13.0	$19.2	$25.2	$31.0	$88.4

Notes:

[a] The non-GHG benefits presented in this table are based on PM2.5-related benefit per ton values (see Chapter 10.6 for more information); the range of benefits are derived from two premature mortality estimates - the American Cancer Society cohort study (Krewski et al., 2009) and the Harvard Six-Cities study (Lepeule et al., 2012). The range of benefits also assumes either a 3 percent or 7 percent discount rate in the valuation of PM-related premature mortality to account for a twenty-year segmented cessation lag. Benefit-per-ton values were estimated for the years 2016, 2020, 2025 and 2030. We hold values constant for intervening years (e.g., the 2016 values are assumed to apply to years 2017-2019; 2020 values for years 2021-2024; 2025 values for years 2026-2029; and 2030 values for years 2031 and beyond). See Table 10-10 for the benefit per ton values used in this analysis.

[b] GHG benefit estimates include reductions in CO_2, CH_4, and N_2O but do not include HFC reductions. Note that net present value of reduced GHG emissions is calculated differently than other benefits. The same discount rate used to discount the value of damages from future emissions (SC-CO_2, SC-CH_4, and SC-N_2O, each discounted at rates of 5, 3, 2.5 percent) is used to calculate net present value of SC-CO_2, SC-CH_4, and SC-N_2O, respectively, for internal consistency. Refer to the Chapter 10.7 for more detail.

[c] Chapter 10.7 notes that SC-GHGs increases over time. Corresponding to the years in this table (2021-2025), the SC-CO_2 estimates range as follows: for Average SC-CO_2 at 5%: $13-$15; for Average SC-CO_2 at 3%: $46-$50; for Average SC-CO_2 at 2.5%: $69-$75; and for 95th percentile SC-CO_2 at 3%: $140-$150. For the years 2021-2025, the SC-CH_4 estimates range as follows: for Average SC-CH_4 at 5%: $620-$700; for Average SC-CH_4 at 3%: $1,400-$1,500; for Average SC-CH_4 at 2.5%: $1,800-$2,000; and for 95th percentile SC-CH_4 at 3%: $3,600-$4,100. For the years 2021-2025, the SC-N_2O estimates range as follows: for Average SC-N_2O at 5%: $5,300-$6,000; for Average SC-N_2O at 3%: $17,000-$19,000; for Average SC-N_2O at 2.5%: $25,000-$26,000; and for 95th percentile SC-N_2O at 3%: $44,000-$48,000. Chapter 10.7 also presents these SC-GHG estimates.

12.3.1.5 Summary of MY Lifetime Benefit-Cost Analysis Results

The table below summarizes EPA's MY lifetime BCA results. Importantly, the fuel savings do not vary in the AEO 2015 reference fuel price case regardless of choice of ICM or RPE since these metrics are tied directly to standard level targets (rather than achieved) values. The slight variations that do exist in the benefits category in the AEO 2015 reference fuel price case is the result of slightly different projected EV/PHEV penetration above and beyond the ZEV program. The different penetrations result in different electricity demands and, therefore, different upstream emission impacts. The differences in all categories when comparing across fuel price cases are the result of the different fleet makeups across fuel prices, different ZEV program sales projections across fuel prices cases, and the different fuel prices themselves.

Table 12.90 MY Lifetime Costs & Benefits in the Central & Sensitivity Cases (Billions of 2013$)

	3 Percent Discount Rate			7 Percent Discount Rate		
	AEO Low (ICMs)	AEO Ref (ICMs & RPEs)	AEO High (ICMs)	AEO Low (ICMs)	AEO Ref (ICMs & RPEs)	AEO High (ICMs)
Vehicle Program	-$31.2	-$37.6 to -$33.6	-$30.6	-$21.8	-$26.6 to -$23.8	-$21.5
Maintenance	-$1.5	-$1.6 to -$1.6	-$1.2	-$0.9	-$0.9 to -$0.9	-$0.7
Fuel	$85.2	$88.8 to $88.8	$79.8	$46.3	$48.7 to $48.7	$43.5
Benefits	$39.1	$40.4 to $40.7	$36.0	$28.9	$30.0 to $30.2	$26.8
Net Benefits	$91.6	$90.1 to $94.3	$84.0	$52.5	$51.3 to $54.2	$48.1

Note: AEO Reference fuel price case shows ranges generated using both ICMs and RPEs in calculating indirect technology costs; Benefits and Net Benefits values presented here use the mid-point value of the non-GHG range for the applicable discount rate and the central SC-GHG values (average SC-CO_2, average SC-CH_4, average SC-N_2O, each at 3 percent) discounted at 3 percent in all cases.

Importantly, Table 12.90 shows that, in all cases, the net benefits are greater than the fuel savings. In other words, even excluding fuel savings, the benefits of the standards outweigh the costs. It is also important to note in the table above that the net benefits are actually lowest in the high fuel price case. This is counterintuitive. This result is driven by the lower share of trucks projected in the high fuel price case whereas the low fuel price case has a higher share of trucks. Trucks drive more miles so, in general, more trucks in the fleet results in more GHG and fuel reductions (and associated fuel savings) and, thus, more net benefits. Fewer trucks, as in the high fuel price case, results in fewer net benefits. Importantly, EPA would not suggest that to maximize net benefits we should all buy trucks. Instead, the analysis projects those relatively higher net benefits in a world consisting of such a high share of trucks. If the car/truck mix is not so dependent upon fuel price as estimated in AEO 2015 (i.e., if the low fuel price case had a fleet mix like that of the reference or high fuel price case), then the net benefits of the low fuel price case would be lower, as one might initially expect.

12.3.2 Calendar Year Analysis

In our calendar year (CY) analysis, EPA looks at the impacts year-over-year through the year 2050. All annual values are presented without discounting and the stream of values for the years 2021 through 2050 are then discounted back to the year 2015 at both 3 and 7 percent discount rates, with the exception that all social costs of greenhouse gases are discounted at the discount rate used in their generation.

12.3.2.1 AEO 2015 Reference Fuel Price Case Using ICMs

In the central analysis, we use AEO 2015 reference fuel prices and fleet projections, and we include our estimate of EV and PHEV sales required by the ZEV program in the reference case fleet.

Table 12.91 Annual Costs & Benefits Using AEO Reference Fuel Prices and ICMs (Billions of 2013$) [a, b, c]

	2025	2030	2040	2050	NPV, 3%	NPV, 7%
Vehicle Program	-$14.7	-$14.8	-$16.8	-$18.8	-$240.5	-$114.8
Maintenance	-$0.2	-$0.5	-$1.0	-$1.3	-$10.7	-$4.4
Pre-tax Fuel	$9.8	$27.0	$61.6	$77.6	$611.3	$248.0
Energy Security	$0.5	$1.4	$3.4	$4.3	$33.5	$13.5
Crashes, Noise, Congestion	-$1.0	-$2.6	-$4.7	-$5.9	-$50.3	-$21.0
Travel Value	$1.1	$2.9	$6.5	$8.1	$64.9	$26.5
Refueling	$0.8	$2.2	$4.4	$6.2	$46.9	$19.2
Non-GHG	$0.6 - $1.5	$1.6 - $4.0	$2.9 - $7.2	$3.6 - $9.0	$34.2 - $76.4	$12.7 - $28.5
GHG						
SC-GHG 5% Avg	$0.4	$0.9	$1.3	$1.2	$27.9	$27.9
SC-GHG 3% Avg	$1.5	$3.6	$5.8	$6.3	$128.9	$128.9
SC-GHG 2.5% Avg	$2.4	$5.6	$9.2	$10.2	$204.7	$204.7
SC-GHG 3% 95th	$4.5	$10.8	$17.7	$19.2	$392.4	$392.4
Net Benefits						
SC-GHG 5% Avg	-$2.3	$19.3	$59.6	$77.7	$538.3	$215.5
SC-GHG 3% Avg	-$1.1	$22.0	$64.2	$82.8	$639.2	$316.4
SC-GHG 2.5% Avg	-$0.3	$24.0	$67.5	$86.7	$715.1	$392.3
SC-GHG 3% 95th	$1.9	$29.2	$76.0	$95.7	$902.8	$580.0

Notes:

[a] The non-GHG benefits presented in this table are based on PM2.5-related benefit per ton values (see Chapter 10.6 for more information); the range of benefits are derived from two premature mortality estimates - the American Cancer Society cohort study (Krewski et al., 2009) and the Harvard Six-Cities study (Lepeule et al., 2012). The range of benefits also assumes either a 3 percent or 7 percent discount rate in the valuation of PM-related premature mortality to account for a twenty-year segmented cessation lag. Benefit-per-ton values were estimated for the years 2016, 2020, 2025 and 2030. We hold values constant for intervening years (e.g., the 2016 values are assumed to apply to years 2017-2019; 2020 values for years 2021-2024; 2025 values for years 2026-2029; and 2030 values for years 2031 and beyond). See Table 10-10 for the benefit per ton values used in this analysis.

[b] GHG benefit estimates include reductions in CO_2, CH_4, and N2O but do not include HFC reductions. Note that net present value of reduced GHG emissions is calculated differently than other benefits. The same discount rate used to discount the value of damages from future emissions (SC-CO_2, SC-CH_4, and SC-N_2O, each discounted at rates of 5, 3, 2.5 percent) is used to calculate net present value of SC-CO_2, SC-CH_4, and SC-N_2O, respectively, for internal consistency. Refer to the Chapter 10.7 for more detail.

[c] Chapter 10.7 notes that SC-GHGs increases over time. Corresponding to the years in this table (2025-2050), the SC-CO_2 estimates range as follows: for Average SC-CO_2 at 5%: $15-$26; for Average SC-CO_2 at 3%: $50-$69; for Average SC-CO_2 at 2.5%: $75-$95; and for 95th percentile SC-CO_2 at 3%: $150-$210. For the years 2025-2050, the SC-CH_4 estimates range as follows: for Average SC-CH_4 at 5%: $710-$1400; for Average SC-CH_4 at 3%: $1,500-$2,700; for Average SC-CH_4 at 2.5%: $2,000-$3,400; and for 95th percentile SC-CH_4 at 3%: $4,100-$7,300. For the years 2025-2050, the SC-N_2O estimates range as follows: for Average SC-N_2O at 5%: $6,000-$12,000; for Average SC-N_2O at 3%: $19,000-$30,000; for Average SC-N_2O at 2.5%: $26,000-$41,000; and for 95th percentile SC-N_2O at 3%: $48,000-$79,000. Chapter 10.7 also presents these SC-GHG estimates.

12.3.2.2 *AEO 2015 Reference Fuel Price Case Using RPEs*

Table 12.92 Annual Costs & Benefits Using AEO Reference Fuel Prices and RPEs (Billions of 2013$) [a, b, c]

	2025	2030	2040	2050	NPV, 3%	NPV, 7%
Vehicle Program	-$16.7	-$16.9	-$19.0	-$21.4	-$272.8	-$130.0
Maintenance	-$0.2	-$0.6	-$1.0	-$1.3	-$11.0	-$4.5
Pre-tax Fuel	$9.8	$27.1	$61.6	$77.6	$611.4	$248.1
Energy Security	$0.5	$1.4	$3.4	$4.3	$33.5	$13.5
Crashes, Noise, Congestion	-$1.0	-$2.6	-$4.7	-$5.9	-$50.2	-$20.9
Travel Value	$1.1	$2.9	$6.5	$8.1	$64.8	$26.4
Refueling	$0.8	$2.2	$4.4	$6.2	$46.9	$19.2
Non-GHG	$0.6 - $1.4	$1.6 - $3.9	$2.8 - $7.0	$3.6 - $8.9	$33.5 - $74.9	$12.5 - $27.9
GHG						
SC-GHG 5% Avg	$0.4	$0.9	$1.3	$1.2	$27.8	$27.8
SC-GHG 3% Avg	$1.5	$3.6	$5.8	$6.3	$128.4	$128.4
SC-GHG 2.5% Avg	$2.3	$5.6	$9.2	$10.2	$204.1	$204.1
SC-GHG 3% 95th	$4.5	$10.8	$17.6	$19.2	$391.2	$391.2
Net Benefits						
SC-GHG 5% Avg	-$4.3	$17.2	$57.2	$75.0	$504.7	$199.7
SC-GHG 3% Avg	-$3.2	$19.9	$61.7	$80.0	$605.3	$300.3
SC-GHG 2.5% Avg	-$2.3	$21.9	$65.1	$84.0	$681.0	$376.0
SC-GHG 3% 95th	-$0.2	$27.1	$73.6	$92.9	$868.0	$563.0

Notes:

[a] The non-GHG benefits presented in this table are based on PM2.5-related benefit per ton values (see Chapter 10.6 for more information); the range of benefits are derived from two premature mortality estimates - the American Cancer Society cohort study (Krewski et al., 2009) and the Harvard Six-Cities study (Lepeule et al., 2012). The range of benefits also assumes either a 3 percent or 7 percent discount rate in the valuation of PM-related premature mortality to account for a twenty-year segmented cessation lag. Benefit-per-ton values were estimated for the years 2016, 2020, 2025 and 2030. We hold values constant for intervening years (e.g., the 2016 values are assumed to apply to years 2017-2019; 2020 values for years 2021-2024; 2025 values for years 2026-2029; and 2030 values for years 2031 and beyond). See Table 10-10 for the benefit per ton values used in this analysis.

[b] GHG benefit estimates include reductions in CO_2, CH_4, and N_2O but do not include HFC reductions. Note that net present value of reduced GHG emissions is calculated differently than other benefits. The same discount rate used to discount the value of damages from future emissions (SC-CO_2, SC-CH_4, and SC-N_2O, each discounted at rates of 5, 3, 2.5 percent) is used to calculate net present value of SC-CO_2, SC-CH_4, and SC-N_2O, respectively, for internal consistency. Refer to the Chapter 10.7 for more detail.

[c] Chapter 10.7 notes that SC-GHGs increases over time. Corresponding to the years in this table (2025-2050), the SC-CO2 estimates range as follows: for Average SC-CO_2 at 5%: $15-$26; for Average SC-CO_2 at 3%: $50-$69; for Average SC-CO_2 at 2.5%: $75-$95; and for 95th percentile SC-CO_2 at 3%: $150-$210. For the years 2025-2050, the SC-CH_4 estimates range as follows: for Average SC-CH_4 at 5%: $710-$1400; for Average SC-CH_4 at 3%: $1,500-$2,700; for Average SC-CH_4 at 2.5%: $2,000-$3,400; and for 95th percentile SC-CH_4 at 3%: $4,100-$7,300. For the years 2025-2050, the SC-N_2O estimates range as follows: for Average SC-N_2O at 5%: $6,000-$12,000; for Average SC-N_2O at 3%: $19,000-$30,000; for Average SC-N_2O at 2.5%: $26,000-$41,000; and for 95th percentile SC-N_2O at 3%: $48,000-$79,000. Chapter 10.7 also presents these SC-GHG estimates.

12.3.2.3 *AEO 2015 High Fuel Price Case Using ICMs*

In the AEO high fuel price analysis, we use AEO 2015 high fuel prices and fleet projections, and we include our estimate of EV and PHEV sales required by the ZEV program in the reference case fleet.

Table 12.93 Annual Costs & Benefits Using AEO High Fuel Prices and ICMs (Billions of 2013$) [a, b, c]

	2025	2030	2040	2050	NPV, 3%	NPV, 7%
Vehicle Program	-$14.4	-$14.1	-$15.9	-$17.9	-$230.4	-$110.2
Maintenance	-$0.2	-$0.4	-$0.8	-$1.1	-$8.8	-$3.6
Pre-tax Fuel	$9.4	$25.6	$57.4	$71.8	$572.0	$232.7
Energy Security	$0.5	$1.4	$3.2	$4.0	$31.4	$12.7
Crashes, Noise, Congestion	-$1.0	-$2.5	-$4.5	-$5.6	-$48.7	-$20.4
Travel Value	$1.1	$2.8	$6.0	$7.5	$60.6	$24.8
Refueling	$0.8	$2.1	$4.1	$5.8	$43.9	$18.0
Non-GHG	$0.6 - $1.4	$1.5 - $3.7	$2.6 - $6.5	$3.2 - $8.1	$31.0 - $69.3	$11.6 - $25.9
GHG						
SC-GHG 5% Avg	$0.4	$0.8	$1.2	$1.1	$26.0	$26.0
SC-GHG 3% Avg	$1.5	$3.4	$5.4	$5.8	$119.9	$119.9
SC-GHG 2.5% Avg	$2.3	$5.3	$8.5	$9.4	$190.5	$190.5
SC-GHG 3% 95th	$4.4	$10.2	$16.4	$17.7	$365.1	$365.1
Net Benefits						
SC-GHG 5% Avg	-$2.2	$19.2	$58.2	$76.7	$536.4	$213.6
SC-GHG 3% Avg	-$0.9	$22.8	$65.6	$86.9	$630.3	$307.5
SC-GHG 2.5% Avg	$0.1	$25.2	$70.1	$93.0	$700.9	$378.1
SC-GHG 3% 95th	$3.1	$33.6	$88.9	$120.9	$875.5	$552.7

Notes:
[a] The non-GHG benefits presented in this table are based on PM2.5-related benefit per ton values (see Chapter 10.6 for more information); the range of benefits are derived from two premature mortality estimates - the American Cancer Society cohort study (Krewski et al., 2009) and the Harvard Six-Cities study (Lepeule et al., 2012). The range of benefits also assumes either a 3 percent or 7 percent discount rate in the valuation of PM-related premature mortality to account for a twenty-year segmented cessation lag. Benefit-per-ton values were estimated for the years 2016, 2020, 2025 and 2030. We hold values constant for intervening years (e.g., the 2016 values are assumed to apply to years 2017-2019; 2020 values for years 2021-2024; 2025 values for years 2026-2029; and 2030 values for years 2031 and beyond). See Table 10-10 for the benefit per ton values used in this analysis.
[b] GHG benefit estimates include reductions in CO_2, CH_4, and N_2O but do not include HFC reductions. Note that net present value of reduced GHG emissions is calculated differently than other benefits. The same discount rate used to discount the value of damages from future emissions (SC-CO_2, SC-CH_4, and SC-N_2O, each discounted at rates of 5, 3, 2.5 percent) is used to calculate net present value of SC-CO_2, SC-CH_4, and SC-N_2O, respectively, for internal consistency. Refer to the Chapter 10.7 for more detail.
[c] Chapter 10.7 notes that SC-GHGs increases over time. Corresponding to the years in this table (2025-2050), the SC-CO_2 estimates range as follows: for Average SC-CO_2 at 5%: $15-$26; for Average SC-CO_2 at 3%: $50-$69; for Average SC-CO_2 at 2.5%: $75-$95; and for 95th percentile SC-CO_2 at 3%: $150-$210. For the years 2025-2050, the SC-CH_4 estimates range as follows: for Average SC-CH_4 at 5%: $710-$1400; for Average SC-CH_4 at 3%: $1,500-$2,700; for Average SC-CH_4 at 2.5%: $2,000-$3,400; and for 95th percentile SC-CH_4 at 3%: $4,100-$7,300. For the years 2025-2050, the SC-N_2O estimates range as follows: for Average SC-N_2O at 5%: $6,000-$12,000; for Average SC-N_2O at 3%: $19,000-$30,000; for Average SC-N_2O at 2.5%: $26,000-$41,000; and for 95th percentile SC-N_2O at 3%: $48,000-$79,000. Chapter 10.7 also presents these SC-GHG estimates.

12.3.2.4 AEO 2015 Low Fuel Price Case Using ICMs

In the AEO low fuel price analysis, we use AEO 2015 low fuel prices and fleet projections, and we include our estimate of EV and PHEV sales required by the ZEV program in the reference case fleet.

Table 12.94 Annual Costs & Benefits Using AEO Low Fuel Prices and RPEs (Billions of 2013$) [a, b, c]

	2025	2030	2040	2050	NPV, 3%	NPV, 7%
Vehicle Program	-$14.9	-$15.2	-$17.2	-$19.3	-$245.2	-$116.8
Maintenance	-$0.2	-$0.5	-$1.0	-$1.3	-$10.7	-$4.4
Pre-tax Fuel	$10.1	$28.0	$64.0	$80.9	$634.8	$257.3
Energy Security	$0.5	$1.5	$3.6	$4.5	$34.8	$14.0
Crashes, Noise, Congestion	-$1.0	-$2.6	-$4.8	-$6.0	-$51.3	-$21.4
Travel Value	$1.1	$3.0	$6.7	$8.5	$67.3	$27.4
Refueling	$0.8	$2.3	$4.6	$6.5	$48.7	$19.9
Non-GHG	$0.6 - $1.5	$1.6 - $4.1	$3.0 - $7.4	$3.8 - $9.4	$35.3 - $79.0	$13.2 - $29.4
GHG						
SC-GHG 5% Avg	$0.4	$0.9	$1.3	$1.3	$29.0	$29.0
SC-GHG 3% Avg	$1.6	$3.7	$6.0	$6.5	$133.7	$133.7
SC-GHG 2.5% Avg	$2.4	$5.8	$9.5	$10.7	$212.5	$212.5
SC-GHG 3% 95th	$4.7	$11.2	$18.4	$20.0	$407.2	$407.2
Net Benefits						
SC-GHG 5% Avg	-$1.8	$21.3	$65.9	$87.8	$539.4	$216.5
SC-GHG 3% Avg	-$0.4	$25.2	$74.1	$99.3	$644.1	$321.3
SC-GHG 2.5% Avg	$0.6	$27.9	$79.2	$106.3	$722.9	$400.1
SC-GHG 3% 95th	$3.9	$37.1	$100.3	$137.8	$917.6	$594.8

Notes:
[a] The non-GHG benefits presented in this table are based on PM2.5-related benefit per ton values (see Chapter 10.6 for more information); the range of benefits are derived from two premature mortality estimates - the American Cancer Society cohort study (Krewski et al., 2009) and the Harvard Six-Cities study (Lepeule et al., 2012). The range of benefits also assumes either a 3 percent or 7 percent discount rate in the valuation of PM-related premature mortality to account for a twenty-year segmented cessation lag. Benefit-per-ton values were estimated for the years 2016, 2020, 2025 and 2030. We hold values constant for intervening years (e.g., the 2016 values are assumed to apply to years 2017-2019; 2020 values for years 2021-2024; 2025 values for years 2026-2029; and 2030 values for years 2031 and beyond). See Table 10-10 for the benefit per ton values used in this analysis.
[b] GHG benefit estimates include reductions in CO_2, CH_4, and N_2O but do not include HFC reductions. Note that net present value of reduced GHG emissions is calculated differently than other benefits. The same discount rate used to discount the value of damages from future emissions (SC-CO_2, SC-CH_4, and SC-N_2O, each discounted at rates of 5, 3, 2.5 percent) is used to calculate net present value of SC-CO_2, SC-CH_4, and SC-N_2O, respectively, for internal consistency. Refer to the Chapter 10.7 for more detail.
[c] Chapter 10.7 notes that SC-GHGs increases over time. Corresponding to the years in this table (2025-2050), the SC-CO_2 estimates range as follows: for Average SC-CO_2 at 5%: $15-$26; for Average SC-CO_2 at 3%: $50-$69; for Average SC-CO_2 at 2.5%: $75-$95; and for 95th percentile SC-CO_2 at 3%: $150-$210. For the years 2025-2050, the SC-CH_4 estimates range as follows: for Average SC-CH_4 at 5%: $710-$1400; for Average SC-CH_4 at 3%: $1,500-$2,700; for Average SC-CH_4 at 2.5%: $2,000-$3,400; and for 95th percentile SC-CH_4 at 3%: $4,100-$7,300. For the years 2025-2050, the SC-N_2O estimates range as follows: for Average SC-N_2O at 5%: $6,000-$12,000; for Average SC-N_2O at 3%: $19,000-$30,000; for Average SC-N_2O at 2.5%: $26,000-$41,000; and for 95th percentile SC-N_2O at 3%: $48,000-$79,000. Chapter 10.7 also presents these SC-GHG estimates.

12.3.2.5 Summary of CY Benefit-Cost Analysis Results

In our CY analysis, EPA looks at the impacts year-over-year through the year 2050. All annual values are discounted back to the year 2015 at both 3 and 7 percent discount rates with the exception that all social costs of greenhouse gases are discounted at the discount rate used in their generation. The table below simply summarizes the net present values presented in the calendar year analysis tables above.

Table 12.95 CY Net Present Value Costs & Benefits in the Central & Sensitivity Cases (Billions of 2013$)

	3 Percent Discount Rate			7 Percent Discount Rate		
	AEO Low (ICMs)	AEO Ref (ICMs & RPEs)	AEO High (ICMs)	AEO Low (ICMs)	AEO Ref (ICMs & RPEs)	AEO High (ICMs)
Vehicle Program	-$245.2	-$272.8 to -$240.5	-$230.4	-$116.8	-$130.0 to -$114.8	-$110.2
Maintenance	-$10.7	-$11.0 to -$10.7	-$8.8	-$4.4	-$4.5 to -$4.4	-$3.6
Fuel	$634.8	$611.3 to $611.4	$572.0	$257.3	$248.0 to $248.1	$232.7
Benefits	$265.2	$277.7 to $279.2	$297.4	$185.2	$186.8 to $187.6	$188.6
Net Benefits	$644.1	$605.3 to $639.2	$630.3	$321.3	$300.3 to $316.4	$307.5

Note: AEO Reference fuel price case shows ranges generated using both ICMs and RPEs in calculating indirect technology costs; Benefits and Net Benefits values presented here use the mid-point value of the non-GHG range for the applicable discount rate and the central SC-GHG values (average SC-CO_2, average SC-CH_4, average SC-N_2O, each at 3 percent) discounted at 3 percent in all cases.

As noted above in our MY analysis summary, it is important to note in the table above that the net benefits are actually lowest in the high fuel price case. This is counterintuitive. This result is driven by the lower share of trucks projected in the high fuel price case whereas the low fuel price case has a higher share of trucks.

12.4 Additional OMEGA Cost Analyses

12.4.1 Cost per Vehicle Tables - Absolute and Incremental Costs

EPA presents absolute costs for MY2025 vehicles meeting the 2021 standards (i.e., the reference case) in Table 12.96, and for MY2025 vehicles meeting the 2025 standards (i.e., the central analysis control case), for cars, trucks and the fleet in Table 12.97. These costs are then compared and shown as the delta, or the incremental costs of the 2025 standards relative to the 2021 standards in MY2025. In these two tables, the absolute costs shown represent costs to bring the projected MY2021 and MY2025 fleets into compliance with the indicated standard. In other words, the costs include costs that will be incurred to comply with 2015 and later MY standards.[T] Of primary interest for this analysis are the incremental costs shown in Table 12.96 and Table 12.97. These tables present the incremental costs to comply with the control case standards relative to meeting the reference case standards (i.e., the MY2021 standards).

[T] Interestingly, the absolute costs include roughly $50 to bring the projected MY2025 fleet into compliance with the 2014 standards; in other words, the standards in place for the fleet upon which our baseline fleet is derived. This $50 is the result of market shifts projected to take place between MY2014 and MY2025 -- those projections, based on AEO2015, are for a higher percentage of trucks in MY2025. The point being that, while our baseline fleet is derived from the MY2014 fleet, the absolute costs in our analysis include future costs just to ensure that the projected fleet complies with the 2014 standards.

Table 12.96 MY2021 Absolute and Incremental Costs per Vehicle in the Central Analysis Using AEO Reference Case Fuel Prices and Fleet Projections and Using both ICMs and RPEs (2013$)

	Reference Case in MY2021			Control Case in MY2021			Delta in MY2021		
Manufacturer	Car	Truck	Combined	Car	Truck	Combined	Car	Truck	Combined
BMW	$814-$888	$1147-$1283	$904-$994	$1237-$1290	$1270-$1304	$1246-$1294	$402-$423	$21-$123	$299-$342
FCA	$1015-$1182	$1221-$1458	$1160-$1376	$1079-$1307	$1615-$1840	$1456-$1682	$64-$126	$382-$394	$296-$306
Ford	$501-$575	$703-$887	$621-$760	$606-$764	$863-$1015	$758-$913	$105-$188	$128-$159	$137-$153
GM	$654-$773	$800-$915	$730-$847	$869-$958	$937-$1078	$905-$1021	$185-$215	$137-$163	$173-$174
Honda	$363-$452	$543-$609	$450-$528	$431-$527	$692-$778	$558-$649	$68-$75	$150-$169	$108-$120
Hyundai/Kia	$813-$887	$927-$1234	$827-$930	$957-$1042	$1418-$1760	$1015-$1132	$144-$155	$491-$526	$187-$202
JLR	$3048-$2973	$2321-$2465	$2459-$2561	$3989-$4237	$2998-$3043	$3186-$3269	$941-$1264	$578-$677	$708-$727
Mazda	$303-$409	$552-$534	$378-$447	$429-$489	$552-$649	$466-$537	$80-$126	$0-$115	$88-$90
Mercedes-Benz	$1567-$1858	$1702-$1735	$1623-$1807	$2020-$2210	$2035-$2236	$2026-$2221	$351-$453	$332-$501	$403-$413
Mitsubishi	$541-$640	$745-$726	$619-$673	$639-$700	$922-$999	$747-$815	$60-$98	$177-$273	$128-$142
Nissan	$526-$619	$774-$948	$630-$758	$615-$711	$970-$1139	$765-$892	$90-$92	$191-$196	$134-$135
Subaru	$307-$359	$192-$282	$218-$299	$340-$425	$277-$367	$291-$380	$33-$66	$84-$85	$73-$81
Tesla	$155-$155	$0-$0	$155-$155	$155-$155	$0-$0	$155-$155	$0-$0	$0-$0	$0-$0
Toyota	$418-$491	$741-$912	$571-$691	$462-$541	$930-$1151	$684-$831	$45-$50	$189-$238	$113-$140
Volkswagen	$1807-$1980	$1606-$1611	$1728-$1834	$2240-$2411	$2073-$2047	$2174-$2267	$432-$433	$437-$468	$434-$447
Volvo	$1288-$1543	$1899-$2023	$1614-$1799	$1912-$1988	$2094-$2479	$2009-$2250	$445-$624	$194-$455	$395-$450
Fleet	$697-$800	$869-$1019	$782-$908	$850-$962	$1094-$1253	$971-$1106	$154-$162	$225-$234	$189-$197

Note: In the Reference and Control cases, lower values use ICMs while higher values use RPEs; in the Delta columns, the minimum delta forms the lower value while the maximum delta forms the higher value.

Table 12.97 MY2025 Absolute and Incremental Costs per Vehicle in the Central Analysis Using AEO Reference Case Fuel Prices and Fleet Projections and Using both ICMs and RPEs (2013$)

	Reference Case in MY2025			Control Case in MY2025			Delta in MY2025		
Manufacturer	Car	Truck	Combined	Car	Truck	Combined	Car	Truck	Combined
BMW	$644-$741	$872-$965	$698-$794	$1724-$1921	$1942-$2153	$1776-$1977	$1080-$1181	$1070-$1188	$1078-$1183
FCA	$911-$1085	$1051-$1308	$1009-$1242	$1789-$2149	$2451-$2809	$2254-$2613	$879-$1063	$1400-$1501	$1245-$1371
Ford	$434-$538	$630-$800	$548-$690	$969-$1144	$1777-$2073	$1438-$1684	$535-$606	$1147-$1273	$890-$993
GM	$575-$674	$728-$900	$652-$787	$1169-$1384	$2248-$2534	$1707-$1957	$593-$710	$1520-$1633	$1055-$1170
Honda	$298-$327	$474-$578	$380-$444	$842-$896	$967-$1349	$901-$1107	$544-$569	$493-$771	$520-$663
Hyundai/Kia	$716-$804	$845-$1056	$732-$834	$1447-$1705	$2128-$2335	$1529-$1780	$731-$901	$1279-$1284	$797-$946
JLR	$1727-$2123	$2044-$2229	$1978-$2207	$5090-$5489	$3436-$3821	$3782-$4170	$3363-$3366	$1391-$1592	$1804-$1963
Mazda	$302-$341	$429-$501	$341-$390	$772-$880	$1081-$1250	$866-$993	$469-$539	$652-$748	$525-$603
Mercedes-Benz	$1099-$1442	$1479-$1534	$1244-$1477	$2482-$2843	$2732-$3061	$2577-$2926	$1383-$1401	$1253-$1528	$1334-$1449
Mitsubishi	$505-$601	$614-$666	$544-$624	$1178-$1325	$1333-$1532	$1234-$1399	$673-$724	$719-$866	$689-$775
Nissan	$468-$549	$710-$862	$564-$673	$1148-$1184	$1526-$2080	$1298-$1539	$635-$680	$816-$1218	$734-$866
Subaru	$225-$315	$160-$226	$174-$246	$686-$766	$691-$873	$690-$849	$451-$461	$531-$647	$515-$603
Tesla	$140-$140	$0-$0	$140-$140	$140-$140	$0-$0	$140-$140	$0-$0	$0-$0	$0-$0
Toyota	$336-$449	$676-$759	$490-$589	$884-$1004	$1547-$1900	$1184-$1409	$548-$555	$871-$1140	$694-$820
Volkswagen	$1418-$1633	$1359-$1405	$1396-$1547	$2751-$3178	$2560-$2721	$2679-$3005	$1333-$1544	$1202-$1316	$1284-$1458
Volvo	$1104-$1327	$1595-$1821	$1360-$1584	$2351-$2902	$3170-$3078	$2777-$2994	$1247-$1575	$1257-$1575	$1410-$1417
Fleet	$586-$695	$765-$918	$671-$801	$1293-$1483	$1864-$2184	$1565-$1818	$707-$789	$1099-$1267	$894-$1017

Note: In the Reference and Control cases, lower values use ICMs while higher values use RPEs; in the Delta columns, the minimum delta forms the lower value while the maximum delta forms the higher value.

The vehicle costs used as inputs to the OMEGA Inventory, Cost and Benefit Tool (ICBT) are shown in the tables below.

Table 12.98 Reference Case Absolute Cost/Vehicle Used as Inputs to the OMEGA Inventory, Cost and Benefit Tool (2013$)

	AEO Reference Fuel Price Case, ICMs		AEO High Fuel Price Case, ICMs		AEO Low Fuel Price Case, ICMs		AEO Reference Fuel Price Case, RPEs	
MY	Car	Truck	Car	Truck	Car	Truck	Car	Truck
2021	$696	$868	$721	$912	$675	$866	$799	$1,019
2022	$669	$843	$696	$885	$649	$841	$774	$994
2023	$636	$812	$664	$852	$617	$809	$742	$964
2024	$601	$778	$630	$816	$582	$775	$708	$930
2025	$586	$765	$617	$801	$569	$762	$695	$918
2026	$586	$765	$617	$801	$569	$762	$695	$917
2027	$586	$766	$617	$802	$568	$763	$694	$919
2028	$585	$766	$617	$802	$568	$763	$694	$919
2029	$585	$765	$616	$801	$568	$762	$694	$918
2030	$585	$765	$616	$800	$568	$762	$694	$917

Table 12.99 Control Case Absolute Cost/Vehicle Used as Inputs to the OMEGA Inventory, Cost and Benefit Tool (2013$)

	AEO Reference Fuel Price Case, ICMs		AEO High Fuel Price Case, ICMs		AEO Low Fuel Price Case, ICMs		AEO Reference Fuel Price Case, RPEs	
MY	Car	Truck	Car	Truck	Car	Truck	Car	Truck
2021	$850	$1,094	$861	$1,140	$835	$1,064	$961	$1,253
2022	$961	$1,287	$976	$1,342	$946	$1,259	$1,092	$1,486
2023	$1,067	$1,474	$1,085	$1,538	$1,051	$1,447	$1,218	$1,714
2024	$1,170	$1,658	$1,191	$1,731	$1,153	$1,633	$1,340	$1,939
2025	$1,293	$1,864	$1,319	$1,945	$1,276	$1,839	$1,483	$2,184
2026	$1,293	$1,863	$1,318	$1,945	$1,276	$1,839	$1,483	$2,184
2027	$1,292	$1,866	$1,318	$1,948	$1,275	$1,842	$1,483	$2,187
2028	$1,292	$1,866	$1,317	$1,947	$1,275	$1,842	$1,482	$2,187
2029	$1,292	$1,864	$1,317	$1,944	$1,274	$1,840	$1,482	$2,184
2030	$1,292	$1,863	$1,317	$1,943	$1,274	$1,839	$1,482	$2,184

12.4.2 Cost per Percentage Improvement in CO_2

Each manufacturer's starting and ending CO_2 levels are shown in the tables below by car, truck and combined fleet. Also included are EPA's estimated costs per vehicle. Using these data, we can calculate the costs per percentage reduction in CO_2 emissions from the baseline case (i.e., the MY2025 fleet meeting the MY2014 standards) to the central analysis control case (i.e., the MY2025 fleet meeting the MY2025 standards) and using ICMs only here.

The results shown in these tables represent the CO_2 impacts and cost impacts (using ICMs) of taking the MY2014 baseline fleet, projecting it to a MY2025 fleet meeting the MY2014 standards, and bringing that fleet into compliance with the MY2025 standards. Note that the costs presented here fall slightly short of the costs presented in earlier tables. For example, Table 12.102 shows a delta cost of $1,512 while Table 12.97 shows a cost of $1,565 (using ICMs). This difference between $1,565 and $1,512 represents the costs to bring the baseline fleet in MY2025 into compliance with the MY2014 standards. That cost is reflected in Table 12.97 but is not reflected below since the tables below use the 2014 standards as their reference case (i.e., costs below are relative to meeting the 2014 standards).

Table 12.100 CO_2 and Cost Changes in MY2025 using the 2014 Standards as the Reference Case and the 2025 Standards as the Control Case for Cars (CO_2 in g/mi, dollar values in 2013$)

Manufacturer	Base CO2	Final CO2	Delta CO2	% Delta CO2	Cost delta	$/%CO2
BMW	236	146	-90	-38%	$1,664	-$44
FCA	271	160	-111	-41%	$1,729	-$42
Ford	245	166	-80	-32%	$908	-$28
GM	257	169	-89	-35%	$1,109	-$32
Honda	206	142	-63	-31%	$782	-$25
Hyundai/Kia	242	149	-92	-38%	$1,387	-$36
JLR	271	102	-168	-62%	$5,030	-$81
Mazda	205	149	-56	-27%	$712	-$26
Mercedes-Benz	263	142	-121	-46%	$2,422	-$53
Mitsubishi	220	148	-72	-33%	$1,118	-$34
Nissan	219	146	-73	-33%	$1,088	-$33
Subaru	234	174	-61	-26%	$626	-$24
Tesla	0	0	0	0	$0	$0
Toyota	205	143	-62	-30%	$824	-$27
Volkswagen	248	134	-114	-46%	$2,691	-$58
Volvo	265	154	-110	-42%	$2,291	-$55
All	232	150	-82	-35%	$1,233	-$35

Note: Values include use of A/C and off-cycle credits described in Table 12.6 and their costs.

Table 12.101 CO_2 and Cost Changes in MY2025 using the 2014 Standards as the Reference Case and the 2025 Standards as the Control Case for Trucks (CO_2 in g/mi, dollar values in 2013$)

Manufacturer	Base CO2	Final CO2	Delta CO2	% Delta CO2	Cost delta	$/%CO2
BMW	306	197	-109	-35%	$1,896	-$53
FCA	350	199	-150	-43%	$2,404	-$56
Ford	364	219	-145	-40%	$1,730	-$43
GM	359	209	-150	-42%	$2,202	-$53
Honda	295	192	-103	-35%	$921	-$26
Hyundai/Kia	313	171	-142	-45%	$2,082	-$46
JLR	344	205	-140	-41%	$3,389	-$84
Mazda	274	175	-99	-36%	$1,035	-$29
Mercedes-Benz	348	203	-145	-42%	$2,686	-$65
Mitsubishi	244	151	-93	-38%	$1,286	-$34
Nissan	322	197	-125	-39%	$1,480	-$38
Subaru	239	164	-75	-32%	$644	-$20
Tesla						
Toyota	336	203	-133	-39%	$1,501	-$38
Volkswagen	321	204	-117	-36%	$2,514	-$69
Volvo	336	183	-152	-45%	$3,124	-$69
All	333	201	-133	-40%	$1,817	-$46

Note: Values include use of A/C and off-cycle credits described in Table 12.6 and their costs.

Table 12.102 CO_2 and Cost Changes in MY2025 using the 2014 Standards as the Reference Case and the 2025 Standards as the Control Case for the Combined Fleet (CO_2 in g/mi, dollar values in 2013$)

Manufacturer	Base CO2	Final CO2	Delta CO2	% Delta CO2	Cost delta	$/%CO2
BMW	252	157	-96	-38%	$1,723	-$46
FCA	326	189	-138	-42%	$2,200	-$52
Ford	314	197	-117	-37%	$1,385	-$37
GM	308	189	-119	-39%	$1,653	-$43
Honda	247	165	-82	-33%	$847	-$26
Hyundai/Kia	250	150	-100	-40%	$1,475	-$37
JLR	329	185	-144	-44%	$3,728	-$85
Mazda	226	156	-70	-31%	$813	-$26
Mercedes-Benz	295	165	-131	-44%	$2,524	-$57
Mitsubishi	228	148	-80	-35%	$1,180	-$34
Nissan	260	165	-94	-36%	$1,244	-$34
Subaru	238	168	-71	-30%	$636	-$21
Tesla	0	0	0	0	$0	$0
Toyota	264	170	-94	-36%	$1,130	-$32
Volkswagen	276	160	-116	-42%	$2,626	-$63
Volvo	302	170	-132	-44%	$2,723	-$62
All	281	174	-106	-38%	$1,512	-$40

Note: Values include use of A/C and off-cycle credits described in Table 12.6 and their costs.

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[1] A DVD has been placed in the docket with the name "OMEGA_TAR2016."
[2] Previous OMEGA documentation for versions used in MYs 2012-2016 Final Rule (EPA-420-B-09-035), Interim Joint Draft TAR (EPA-420-B-10-042). Docket Nos. EPA-HQ-OAR-2010-0799-1108 and EPA-HQ-OAR-2010-0799-1109.
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[7] EPA. Regulatory Impact Analysis: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards, Chapter 4.2, 4.6, EPA-420-R-12-016, August 2012.
[8] EPA. Regulatory Impact Analysis: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards, Chapter 4.6.3., EPA-420-R-12-016, August 2012, Chapter 4.6.3.
[9] 77 FR 62821, October 15, 2012.
[10] See EPA's final RIA in support of the 2012 FRM (EPA-420-R-12-016) at page 4-131.
[11] Argonne National Laboratory's The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8c.0, available at http://www.transportation.anl.gov/modeling_simulation/GREET/). EPA Docket EPA-HQ-OAR-2009-0472. (Docket No. EPA-HQ-OAR-2010-0799-1105).
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[13] 40 CFR 86.1866-12(a).

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Chapter 13:Analysis of Augural CAFE Standards

The purpose of this chapter is to describe the inputs, assumptions, and tools that form the foundation of NHTSA's analysis in the Draft TAR. The results of the analysis that uses all of these assumptions and tools are summarized in Section 13.3. While many of the inputs to this analysis have been summarized elsewhere in the Draft TAR, this chapter provides more detailed descriptions of assumptions that either differ in important ways from the last Final Rule (covering MYs 2017-2021) or have the ability to significantly impact the evaluation of program impacts. The chapter takes a close look at a range of important factors that influence the impact of CAFE standards, such as variations in fuel price and the ways that consumer demand influence technology integration on the supply side.

NHTSA's analysis illustrates the impact of these and other technical assumptions by modeling the Augural Standards for 2022-2025 as a point of comparison relative to NHTSA's final CAFE standards through 2021. As noted in the executive summary, the Draft TAR does not present alternatives to the Augural Standards because, as the first stage of the Midterm Evaluation process, the TAR is principally an exploration of technical issues – including assumptions about the effectiveness and cost of specific technologies, as well as other inputs, methodologies and approaches for accounting for these issues. The agencies seek comment from stakeholders to further inform the analyses, which will inform subsequent development of stringency alternatives.

To conduct today's analysis, NHTSA has made use of NHTSA's Corporate Average Fuel Economy (CAFE) Modeling System (sometimes referred to as "the CAFE model" or "the Volpe model"), which DOT's Volpe National Transportation Systems Center (Volpe Center) continuously develops, maintains, and applies to support NHTSA CAFE analyses and rulemakings. The Volpe Center has supported the CAFE program since USDOT first established fuel economy rules beginning with MY 1978, following the initial authorization of the CAFE program in the Energy Policy and Conservation Act of 1975. NHTSA developed the first version of the model in 2002 to support the 2003 issuance of CAFE standards for MYs 2005-2007 light trucks. NHTSA has since significantly expanded and refined the model, and has applied the model to support every ensuing CAFE rulemaking, including:

2006: MYs 2008-2011 light trucks

2008: MYs 2011-2015 passenger cars and light trucks

2009: MY 2011 passenger cars and light trucks

2010: MYs 2012-2016 passenger cars and light trucks

2012: MYs 2017-2021 passenger cars and light trucks

2015: MYs 2021-2027 heavy-duty pickups and vans (NPRM)

Past analyses conducted using the CAFE model have been subjected to extensive and detailed review and comment, much of which has informed the model's expansion and refinement. NHTSA's use of the model was considered and supported in 2007 litigation (CBD v. NHTSA), and the model has been subjected to formal peer review and review by the General Accounting Office (GAO) and National Research Council (NRC). NHTSA makes public the model, source code, and—except insofar as doing so will compromise confidential business information (CBI) manufacturers have provided to NHTSA—all model inputs and outputs underlying published rulemaking analyses.[1]

Although the CAFE model can also be used for more aggregated analysis (e.g., involving "representative vehicles," single-year snapshots, etc.), NHTSA designed the model with a view toward (a) detailed simulation of manufacturers' potential actions given a defined set of standards, followed by (b) calculation of resultant impacts and economic costs and benefits. The model is intended to describe actions manufacturers could take in light of defined standards, estimated production constraints, and other input assumptions and estimates, not to predict actions manufacturers will take. While a more detailed description of the model appears in the model documentation, Section 13.2 of this chapter provides an overview of important model logic and new developments since the last public release accompanying the 2012 Final Rule.

13.1 Significant Assumptions and Inputs to the NHTSA Analysis

13.1.1 MY2015 Analysis Fleet

For the CAFE model, the "analysis fleet" is the foundation of the analysis. The characteristics of the analysis fleet have important implications both for the simulation of what standard manufacturers are required to meet, and for what technologies are applicable within the compliance simulation. The 2017-2021 Final Rule used all MY2010 vehicles available for sale in the U.S. market as its analysis fleet, holding vehicle characteristics constant at MY2010 levels but using other information sources to estimate future production volumes. As discussed above in Chapter 4, for the Draft TAR we have opted to use the MY2015 fleet, being the most current available at the time of the analysis. The sales volumes, which determine achieved CAFE levels, are based on projections submitted by manufacturers and may differ from final end-of-year compliance submissions.

The standards are calculated from the sales-weighted, harmonic average of individual vehicle targets and these targets are determined from the footprint and regulatory class of a vehicle. For this reason, changes to an individual vehicle which alter either of these characteristics may result in different standards for the manufacturer fleet of that vehicle. The CAFE model currently does not attempt to estimate changes in vehicle footprint or changes in characteristics which would shift a given light-duty vehicle's fuel economy targets or even regulatory class, though the model does provide means to estimate the impact of mass reduction on fuel consumption targets for heavy-duty pickups and vans regulated separately from light-duty vehicles, and future analyses may consider allowing the footprint of individual vehicle models to change and thereby alter a given light-duty vehicle model's fuel economy target under the standards (although doing so would likely also entail a fuel economy change to be balanced against the change in the target).

A manufacturer's individual average requirement under the standard may also change based on its decision to introduce or discontinue vehicles from a fleet, or through shifts in production vehicles among existing vehicles, especially insomuch as such shifts affect the relative shares represented by passenger cars and light trucks, respectively. Although the CAFE model can accommodate inputs that account for exogenously estimated shifts in product offerings, there is no way within the CAFE model to endogenously estimate the entrance or exiting of a model

[1] Analyses can be found at http://www.nhtsa.gov/fuel-economy

from a manufacturer's fleet, so, from the perspective of this analysis, the set of vehicles that exists in the analysis fleet (MY2015, in this case) is the set of vehicles to which technology may be added to achieve compliance.

The calculation of manufacturers' estimated actual requirements in 2015, relative to earlier predictions for that year, demonstrate how evolving production trends can impact the standards on a year-by-year basis. For example, Figure 13.1 compares the 2015 requirements simulated using the 2017-2021 Final Rule Analysis, based on the 2010 fleet (dotted-lines) and the calculated 2015 requirements (solid lines). As noted above, the patterns reflected in the chart demonstrate the impact of, among other things, changes in the ratio between passenger cars and light trucks – responsive to the latter comprising a greater share of production than anticipated in at the time of the Final Rule, which assumed passenger cars would represent 65 percent of the new vehicle market (and growing). The actual value for MY2015 is closer to 58 percent, which is reflected in the combined requirement for each manufacturer. When passenger cars and light trucks are separated by class, the gaps between previously-forecast and currently-estimated actual requirements are narrower.

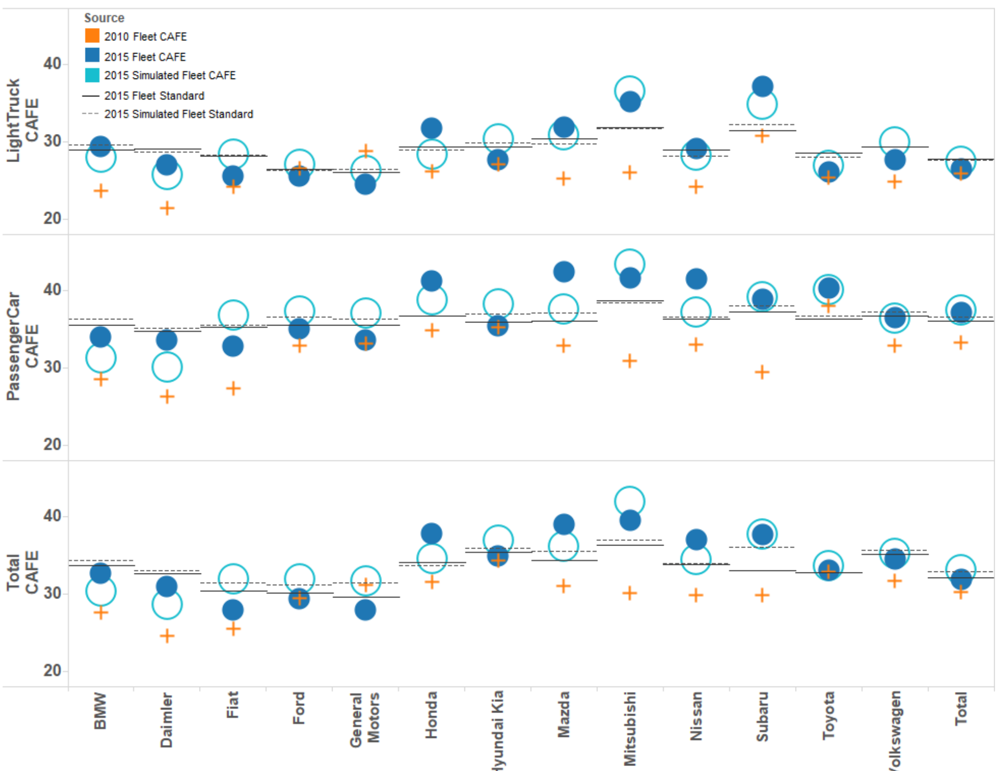

Figure 13.1 CAFE and Standard from 2010 Fleet Simulations vs. 2015 Observed Fleet

Figure 13.1 also shows how CAFE levels in the MY2010 fleet compared to the MY2015 fleet. Even with shifts in the relative market shares of passenger cars and light trucks, the CAFE level for most manufacturers' combined fleets is higher in MY2015 than it was in 2010. Exceptions tend to reflect especially pronounced car-to-light-truck shifts. For example, Ford, which is currently estimated to have produced a 48 percent PC fleet in MY2015 rather than the 56 percent forecast in the 2012 analysis, had a CAFE level of 29.48 in their 2010 fleet, and 29.33 in their 2015 fleet. For fleets where a manufacturer was well below their 2015 requirement in 2010, there is the most movement in the CAFE level (BMW, Daimler, Mitsubishi, Nissan, and Subaru, while Fiat seems to be an exception to this trend). For manufacturers that were close to their 2015 requirement in 2010 (Ford, Hyundai Kia, and Toyota, while Honda seems to be an exception, here), there is less movement in their fleets. Some manufacturers have made choices to rely on banked credits or pay fines. Of manufacturers that did not meet their 2015 standard, BMW, Ford, GM, Hyundai-Kia, and Volkswagen all had credits built up, while Daimler and Fiat already had a negative credit balance, but have historically been fine-payers. In total, the CAFE level has increased from 30.2 to 31.8, close to the industry standard of 32.1.

Another trend reflected in Figure 13.1 is that while the simulated and actual 2015 CAFE requirements differ somewhat, the delta between achieved levels and requirements is narrow, and comparable, across both. The Final Rule simulation of MY2015 showed the industry-level CAFE at 33.2 and the requirement at 32.9; the simulation showed the industry exceeding the 2015 average requirement by the same amount that the actual fleet was short of the requirement (.3 MPG). For most manufacturer's combined fleet, the simulated gap between the requirement and CAFE level achieved was fairly close to the observed gap. For BMW, Daimler, Honda, Mazda, Nissan, and Subaru, the Final Rule simulation underestimated their CAFE levels in 2015 relative to their observed CAFE: all of these manufacturers performed better in reality than their simulated fleets. And this is true even accounting for differences between the expected 2015 requirement and the actual requirement. For example, Nissan's requirement is very close to the simulated requirement, but they performed much better than the simulated fleet; possibly due to the entrance of the Leaf in 2014 to their passenger car fleet, which was not present in the MY2010 fleet. Daimler, BMW and Honda all had slightly lower requirements, but the majority of their improvement against their requirements can be attributed to their CAFE levels being higher than predicted with the 2010 fleet. The Subaru simulated CAFE level is the same as their achieved level, but their requirement is significantly less stringent than the simulated requirement (this is likely attributable to the redesigns of two of their popular light truck models—which made their footprints larger and their targets lower—the Forester and Outback in 2014 and 2015, respectively).

Figure 13.2 shows the sales for all manufacturers by regulatory class in 2010, 2015, and simulated 2015 sales from the 2010 fleet. The simulated 2015 fleet was fairly indicative of how many vehicles were sold in each manufacturer's fleet. Sales for the Big 3 (Ford, Fiat, and GM) were not predicted as well, possibly due to the time of the U.S. automobile industry volatility (2008-2009) or the assumption that passenger cars would gain share for manufacturers that sell large volumes of pickup trucks. Fiat sold slightly more passenger cars and significantly more light trucks than shown in the 2015 simulated fleet, Ford sold slightly fewer light trucks and significantly fewer passenger cars, and General Motors sold more light trucks and fewer passenger cars. Only Nissan sold more passenger cars than predicted, though they sold more trucks as well. The total sales were not included because they would significantly skew the scale of the figure, but the 2015 industry fleet was made up of 1 million more light trucks and 800 thousand fewer passenger cars than the simulated industry fleet.

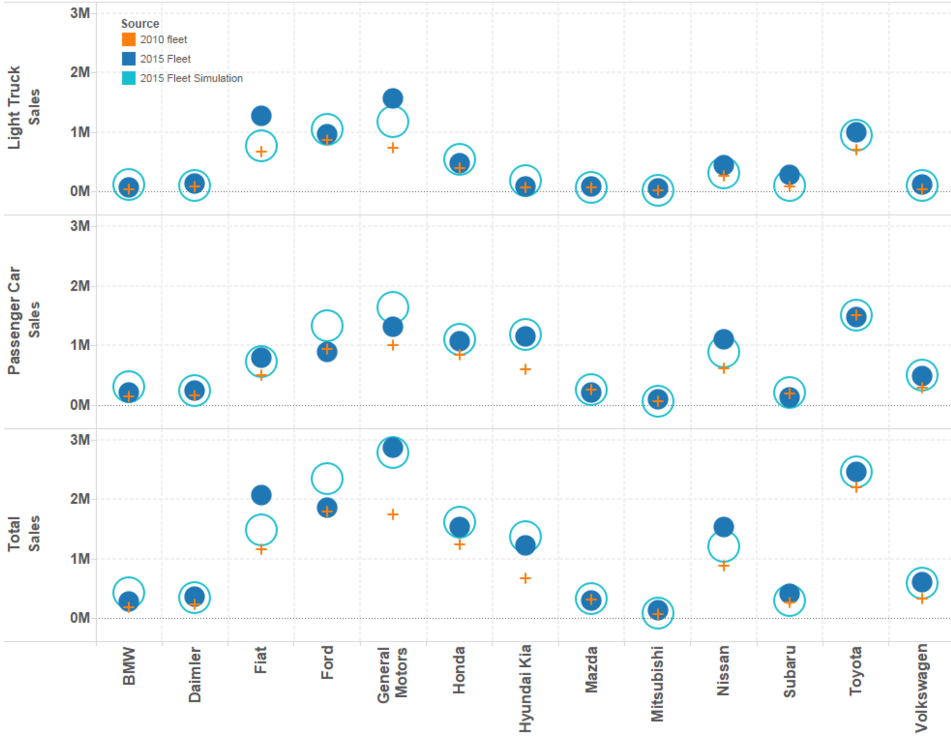

Figure 13.2 Sales from 2010 Fleet Simulations vs. 2015 Observed Fleet

The preceding discussion illustrates that compliance simulations with the CAFE model can do a reasonably good job of estimating future CAFE levels and requirements, but that dynamic economic trends, including consumer choice, can affect production trends over time and affect actual requirements. Predictive modeling will consistently reflect the best available forecasts of macro-economic trends like energy prices and overall growth, which in turn tend to inform consumer choices and trends in driving habits.

13.1.2 Assumptions about Product Cadence

Past comments on the CAFE model have stressed the importance of product cadence—i.e., the development and periodic redesign and freshening of vehicles—in terms of involving technical, financial, and other practical constraints on applying new technologies, and NHTSA has steadily made changes to both the CAFE model and its inputs with a view toward accounting for these considerations. For example, early versions of the model added explicit "carrying forward" of applied technologies between model years, subsequent versions applied assumptions that most technologies will be applied when vehicles are freshened or redesigned, and more recent versions applied assumptions that manufacturers would sometimes apply technology earlier than "necessary" in order to facilitate compliance with standards in ensuing model years. Thus, for example, if a manufacturer is expected to redesign many of its products in model years 2018 and 2023, and the standard's stringency increases significantly in model year 2021, the CAFE model will estimate the potential that the manufacturer will add more technology than necessary for compliance in MY 2018, in order to carry those product changes forward through the next redesign and contribute to compliance with the MY 2021 standard. This explicit simulation of multiyear planning plays an important role in determining year-by-year analytical results.

As in previous iterations of CAFE rulemaking analysis, the NHTSA's simulation of compliance actions that manufacturers might take is constrained by the pace at which new technologies can be applied in the new vehicle market. Operating at the Make/Model level (e.g., Toyota Camry) allows NHTSA to explicitly account for the fact that individual vehicle models undergo significant redesigns relatively infrequently. Many popular models are only redesigned every six years or so, with some larger/legacy platforms (the old Ford Econoline Vans, for example) stretching more than a decade between significant redesigns. Engines, which are often shared among many different models and platforms for a single manufacturer, can last even longer – eight to ten years in most cases.

Understanding manufacturers' redesign schedules, albeit subject to change, is valuable for planning purposes, including anticipating redesign schedules, as well as predicting when and how manufacturers may make use of crediting options. However, while manufacturers' characterizations of product cadence are important to any evaluation of the impacts of CAFE standards, they are not known with certainty – even by the manufacturers themselves over time horizons as long as those covered by this analysis. For example, the Honda Civic, which was typically redesigned on a 4-6 year cycle, underwent a significant, and unprecedented, change for the 2013 model year to address feedback from the MY2012 redesign. Even in that case, the engines and transmissions offered on the Civic did not change between MY2012 and MY2013, suggesting that either Honda considered the feedback was entirely due to other characteristics of the vehicle or that changing the powertrains so quickly was too costly.

Indeed, when NHTSA staff meets with manufacturers to discuss manufacturers' plans vis-à-vis CAFE requirements, manufacturers' staff typically present specific and detailed year-by-year information that explicitly accounts for anticipated redesigns. Such year-by-year analysis is also essential to manufacturers' plans to make use of statutory provisions allowing CAFE credits to be carried forward to future model years, carried back from future model years, transferred between regulated fleets, and traded with other manufacturers. Manufacturers are never certain about future plans, but they spend considerable effort developing them. For every model that appears in the MY2015 analysis fleet, NHTSA has estimated the model years in which future redesigns (and less significant "freshening." which offer manufacturers the opportunity to make less significant changes to models) will occur. These appear in the market data file for each model. Figure 13.3 gives a summary of the share of each manufacturer's sales expected to be redesigned in a given model year. It is worth noting that every manufacturer has at least one model year in which no significant portion of its models (by sales) is redesigned. Mid-cycle freshening may provide additional opportunities to add some technologies in these cases. In addition, NHTSA's analysis accounts for multiyear planning--that is, the potential that manufacturers may apply "extra" technology in an early model year with many planned redesigns in order to carry technology forward to facilitate compliance in a later model year with fewer planned redesigns. So, for example, Figure 13.3 suggests FCA might be expected to apply more technology than required in MY2018 in order to carry that technology forward to MY2019. Further, NHTSA's analysis accounts for the potential that manufacturers could earn CAFE credits in some model years and use those credits in later model years, thereby providing another compliance option in years with few planned redesigns. Finally, it should be noted that neither Figure 13.3 nor today's analysis account for future new products (or discontinued products) –

past trends suggest that some years in which an OEM had few redesigns may have been years when that OEM introduced significant new products. Such changes in product offerings can obviously be important to manufacturers' compliance positions, but cannot be systematically and transparently accounted for with a fleet forecast extrapolated forward ten or more years from a largely-known fleet.

Manufacturer	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
BMW	7%	1%	27%	37%	11%	10%	13%	10%	37%	16%	9%	11%	17%	26%	20%
Daimler	11%	7%	28%	10%	0%	27%	32%	19%	20%	0%	24%	9%	43%	10%	8%
FCA	0%	24%	48%	5%	19%	12%	7%	4%	0%	11%	39%	18%	3%	4%	4%
Ford	10%	0%	3%	31%	17%	42%	6%	0%	2%	16%	54%	20%	0%	1%	7%
General Motors	2%	22%	19%	27%	24%	20%	2%	29%	19%	32%	9%	34%	17%	24%	3%
Honda	27%	36%	21%	5%	3%	27%	44%	21%	11%	19%	9%	59%	6%	25%	6%
Hyundai Kia	25%	26%	14%	9%	19%	17%	49%	6%	8%	26%	28%	32%	3%	15%	33%
JLR	13%	9%	0%	30%	19%	27%	13%	12%	1%	22%	18%	30%	17%	13%	0%
Mazda	15%	0%	58%	0%	30%	0%	15%	55%	4%	0%	44%	0%	44%	0%	11%
Mitsubishi	16%	0%	0%	11%	75%	0%	23%	0%	0%	0%	26%	21%	0%	48%	0%
Nissan	4%	4%	33%	21%	0%	30%	14%	25%	14%	9%	13%	20%	28%	23%	13%
Subaru	3%	26%	0%	0%	3%	69%	28%	1%	2%	0%	33%	63%	3%	0%	0%
Toyota	22%	5%	31%	16%	23%	16%	4%	15%	14%	20%	34%	14%	14%	3%	28%
Volvo	0%	5%	0%	96%	0%	0%	0%	0%	0%	4%	0%	95%	0%	0%	0%
VWA	8%	15%	43%	4%	18%	4%	18%	15%	21%	7%	20%	19%	32%	1%	9%

Figure 13.3 Share of Manufacturer Sales Redesigned In Each Model Year 2016 - 2030

Additionally, each technology considered for application by the CAFE model is assigned to either a "refresh" or "redesign" that dictates when it can be applied to a vehicle. Technologies that are assigned to "refresh" can be applied at either a refresh or redesign, while technologies that are assigned to "redesign" can only be applied during a significant vehicle redesign. Table 13.3 and Table 13.4 (in the Technology section of the CAFE model, below) show the technologies available to manufacturers in the compliance simulation, the level at which they are applied (described in greater detail in both the CAFE model documentation and in Section 13.2 below), whether they available outside of a vehicle redesign, and a short description of each. A brief examination of the tables shows that most technologies are only assumed to be available during a vehicle redesign – and nearly all engine and transmission improvements are assumed to be available only during redesign. While there are past and recent examples of mid-cycle product changes, NHTSA expects that manufacturers will tend to attempt to keep engineering and other costs down by applying most major changes mainly during vehicle redesigns, and some mostly modest changes during product freshening. As mentioned below, NHTSA seeks comment on its approach to accounting for product cadence.

The assumptions about product cadence determine the extent to which manufacturers can respond to increasingly stringent standards in a given a model year. When a sufficiently small percentage of a manufacturer's sales volume is redesigned in a given model year, the opportunities to increase its CAFE level may not be sufficient to achieve compliance. In these situations, of which there are many (based on Figure 13.3), actions taken in earlier model years and carried forward will have a much greater impact than actions taken in that single year. In order to account for both the constraint of infrequent vehicle redesigns, and the accumulation and depletion of CAFE credits resulting from these multi-year planning decisions, it is critical that

NHTSA simulate CAFE compliance on a year-by-year basis. NHTSA seeks comment on its approach to accounting for product cadence in CAFE analysis.

13.1.3 Assumptions about Consumer Behavior

While all previous CAFE analyses, including the present one supporting the Draft TAR, focus on manufacturer actions in response to the standards, there are important considerations regarding the impact of evaluated standards on consumer demand for new vehicles. One limitation of all CAFE analyses up to this point is a lack of dynamic demand response to the simulated changes in vehicle attributes – importantly, fuel economy, price, electrification level, and perhaps curb weight – that occur as manufacturers add technology to new vehicles to comply with standards. Currently, sales volumes at the model/variant level, for all future model years, are an input to the CAFE model and do not respond to simulated changes in vehicle attributes. The result of this implementation is that when a range of regulatory alternatives is examined, all alternatives are assumed to have the same total number and sales mix of vehicle models, regardless of the stringency of the alternative considered.

To support the Draft TAR, NHTSA purchased a commercial forecast from IHS/Polk that necessarily includes their assumptions about decisions manufacturers will have to make in order to comply with standards through MY2021, as does the AEO 2015, which also informed the production volumes used in this analysis. So any changes in market share, within a manufacturer/segment that seems likely to occur between MY2015, which forms the basis for Draft TAR analysis, and MY2021, when NHTSA's final standards stop increasing in stringency, should already be present in the static volume projections at the model/variant level. However, any volume changes that would occur as a result of post-2021 standards would not be captured by the current approach.

NHTSA has experimented with discrete consumer choice models, fully integrated into the CAFE model that revise up or down the model/variant sales, based on the changing attributes of the vehicle and the availability of other vehicles in the market with more attractive features. A developmental version of the CAFE model used a discrete choice model that contained a representation of households in the U.S. and explicitly considered the way demand for given vehicle attributes differs by household type – and the sales implications of modifying those vehicle attributes through a program like CAFE. While testing showed promise, the current version of the model relies on the static approach described above, for a number of reasons.

One important implication of relying on a discrete choice model to dynamically adjust vehicle sales is that the concept of price becomes a driving factor. While it is also an obviously important factor in real-world decisions about new vehicle purchases, there is no obvious definition of price that fits all purchases. For example, the CAFE model does not consider the value of optional vehicle content (e.g., navigation or sound systems, luxury interior options like heated/cooled seats, or exterior options like roof racks), yet some of these options can influence sales price to a greater degree than NHTSA's estimates for many new powertrain technologies. It is also true that sales price, which can vary considerably by geographic location, is rarely equal to the vehicle's Manufacturer's Suggested Retail Price (MSRP) – which is all NHTSA currently observes in the analysis fleet, and on which most consumer choice models are estimated. While the analysis fleet has some resolution at the make/model/variant level (e.g., each engine variant of the Honda Civic), bundled packages and model editions that do not vary by fuel economy, footprint, or both are unlikely to be represented in the analysis fleet. As such, even the MSRP values in the analysis fleet represent an average across model variants that, while identical for the purposes of CAFE compliance, vary in other consumer-facing attributes in ways that strongly influence MSRP.

Other considerations are the pricing strategies that manufacturers employ that also influence MSRP – often cross subsidizing vehicles in one class, or at a particular stage of design life, with more popular vehicle models or models serving market segments with less price sensitivity. NHTSA has considered multiple technology cost allocation (i.e. pricing) models over the last several years, but for reporting purposes, currently implements a pay-as-you-go model where the change in price of each vehicle model reflects the amount of additional technology content it acquires in response to the standards. NHTSA seeks comment on these and other aspects of consumer behavior and how to account for them.

Still another consideration involves how manufacturers apply technology that improves energy efficiency. Manufacturers may prefer to apply technology to improve other vehicle attributes that consumers value if their compliance position is favorable and if that affordable technology is available. Historical evidence is sufficient to justify the existence of consumer preferences for vehicle size, power, or both. Yet, the CAFE model does not currently attempt to estimate the potential that manufacturers would seek to apply fuel-saving technologies with a view toward also improving vehicle performance or utility.[2] In other words, while technology-related inputs to the CAFE model can reflect underlying assumptions about manufacturers' likely balancing of the potential to improve fuel economy and/or performance, the model itself does not attempt to endogenously optimize this balance when considering the potential to apply specific technologies to specific vehicles. With inputs that assume manufacturers would apply technologies such that most or all of the technical potential is used to improve fuel economy, this could lead to a consumer choice model showing a manufacturer of already-efficient vehicles losing market share to a rival who improves fuel economy in a cost effective manner, while preserving already-superior levels of performance.

One interpretation of the current approach is that NHTSA assumes manufacturers will price vehicle models in a way that both covers the increase in technology cost attributable to the CAFE standards and allows them to sell the mix of vehicles that makes them the most profitable. In that context, NHTSA need not account for prices explicitly. This characterization implicitly assumes that manufacturers are able to cross-subsidize the sale of less profitable models with more profitable ones – to fully recover the cost increase without affecting the mix of vehicles sold. While this is already current practice, NHTSA recognizes the importance of considering the impact of potential standards on the ability to cross-subsidize without affecting fleet mix and other factors.

In the absence of satisfying resolutions to these issues, NHTSA continues to us the static volume approach it has used in the past while it continues to refine an approach to modeling the demand response to changing prices and attributes in the new vehicle market. However, there is

[2] The current CAFE analysis, which assumes manufacturers are unlikely to reduce powertrain output except at relatively significant levels of mass reduction, effectively assumes that some vehicles could improve in performance or utility, depending in part on how technologies are shared among different vehicles. This approach helps to preserve the size of the initial set of engines in the MY2015 fleet. The approach does not generate unique engines for each variant, based on NHTSA's analysis of observed trends for managing platform and powertrain complexity given resource and cost considerations.

an area where NHTSA has attempted to capture some market behavior and its interaction with the supply of new vehicles.

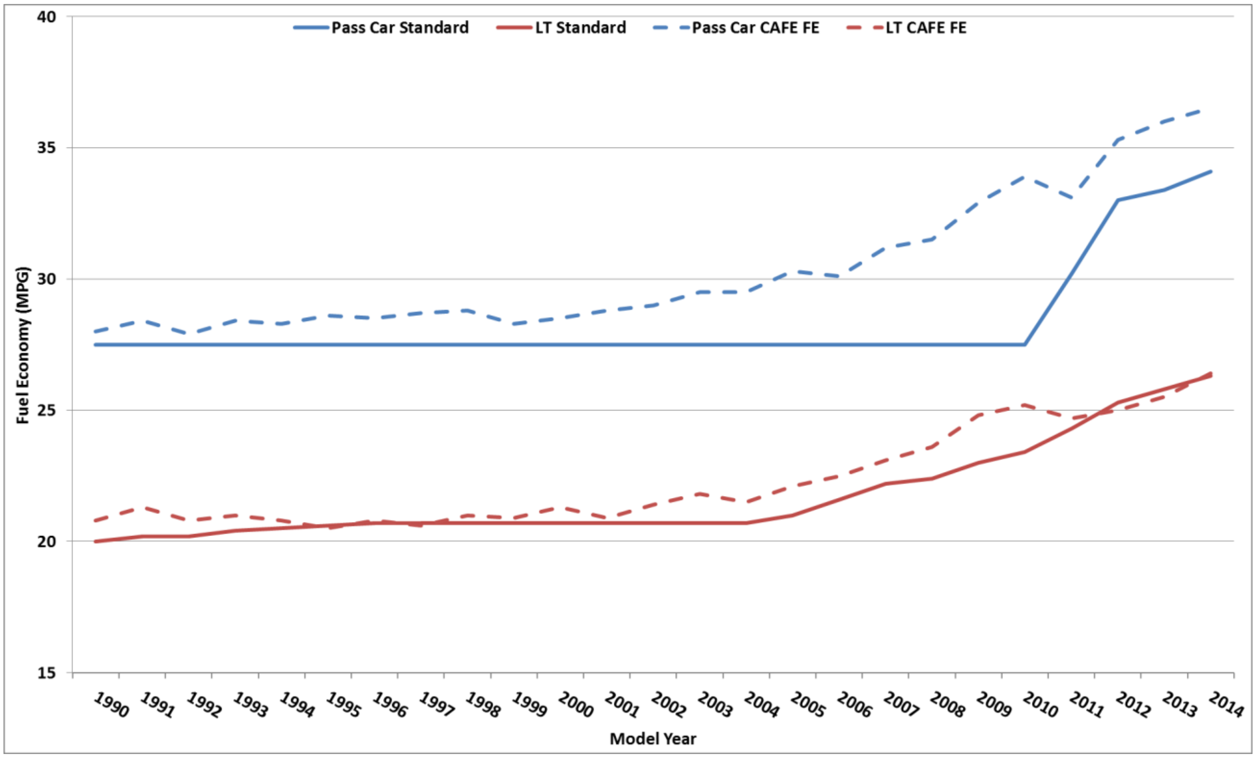

Figure 13.4 Industry Average CAFE and Standard 1990 - 2014

As Figure 13.4 illustrates, the industry (though not all individual manufacturers) has exceeded the required CAFE level for both classes in the past, though by almost 5 MPG during the fuel price spikes of the 2000s. Worth noting is that the industry average in Figure 13.4 includes a number of manufacturers that traditionally paid CAFE fines – some of whom reached compliance during years with high oil prices. NHTSA attempts to account for this observed consumer preference for fuel economy, above and beyond that required by the CAFE standard, by allowing fuel price to influence the ranking of technologies when the model applies technology to vehicles in order to achieve compliance. In particular, the model ranks available technology not by cost, but by "effective cost."

While described in greater detail in the CAFE model documentation, the effective costs contains an assumption not about consumers' actual willingness to pay for additional fuel economy, but about what manufacturers believe consumers are willing to pay. The default assumption in the model is that manufacturers will treat all technologies that pay for themselves within the first three years of ownership (through reduced expenditures on fuel) as if the cost of that technology were negative. This holds true up to the point at which the manufacturer achieves compliance with the standard – after which the manufacturer treats all technologies that pay for themselves within the first year of ownership as having a negative effective cost. This change in the pre- and post-compliance effective valuate of fuel economy is intended to serve as proxy for manufacturers' differential willingness to risk providing "too much" fuel economy.[3]

One implication of this assumption is that futures with higher, or lower, fuel prices produce different sets of attractive technologies (and at different times). In the extreme cases, where fuel prices are above $7 or $8/gallon, many of the technologies in this analysis could pay for themselves within a year and appear in the baseline. Similarly, at the other extreme, almost no additional fuel economy would be observed.

While these assumptions about desired payback period and consumer preferences for fuel economy may not affect the eventual level of achieved CAFE in the later years of the program, they will affect the amount of additional technology cost and fuel savings that are attributable to the standard. NHTSA seeks comment on the approach described above, the current values it ascribes to manufacturers' belief about consumer willingness-to-pay for fuel economy, and suggestions for future improvements and refinements.

13.1.4 Updated Mileage Accumulation Schedules for the Draft TAR

In order to develop new mileage accumulation schedules for vehicles regulated under the CAFE program (classes 1-3), NHTSA purchased a data set of vehicle odometer readings from IHS/Polk (Polk). Polk collects odometer readings from registered vehicles when they encounter maintenance facilities, state inspection programs, or interactions with dealerships and OEMs. The (average) odometer readings in the data set NHTSA purchased are based on over 74 million unique odometer readings across 16 model years (2000-2015) and vehicle classes present in the data purchase (all registered vehicles less than 14,000 lbs. GVW).

The Polk data provide a measure of the cumulative lifetime vehicle miles traveled (VMT) for vehicles, at the time of measurement, aggregated by the following parameters: make, model, model year, fuel type, drive type, door count, and ownership type (commercial or personal). Within each of these subcategories they provide the average odometer reading, the number of odometer readings in the sample from which Polk calculated the averages, and the total number of that subcategory of vehicles in operation.

13.1.4.1 Updated Schedules

Figure 13.5 shows the predicted total VMT by age for the sample of passenger cars. It also shows the previous and current schedules together. The previous schedule was developed using self-reported odometer data in the 2009 National Household Travel Survey (NHTS), and was the basis for estimated travel demand in the 2012 final rule. The current schedule predicts lower annual VMT for all ages—except the first year—but the difference increases for vehicles older than 8 years. The resulting difference in VMT over a 30-year life of a passenger car is a decrease of 96,882 miles under the new schedule, a 32 percent decrease from the previous schedule. A notable trend in the new passenger car schedule is a higher annual VMT for the first year,

[3] NHTSA does not endogenously model the purchase choices of individual new vehicle buyers, nor do we attempt to estimate the usage profiles of individual new vehicle buyers. NHTSA's analysis currently vehicle survival and mileage accumulation in terms of the nationwide average of vehicles—based on millions of odometer readings spanning both high and low usage owners—that varies by vehicle class. It is possible that the difference between the total estimated benefits derived from the average usage and the sum of the true individual usage could be either higher or lower depending upon the fleet mix and the extent to which lower and higher fuel economy models are driven differently than the average.

followed by a relatively constant annual VMT until age 6 (MY 2014 to MY 2008, for our sample). This trend is likely a byproduct of the patterns of commercial and personal vehicle ownership over the age of vehicles, although other factors (e.g., fuel prices, employment levels, GDP, typical length of a new car loan) could underlie the steep decline in average annual mileage accumulation after vehicles have been in operation for 6 years.

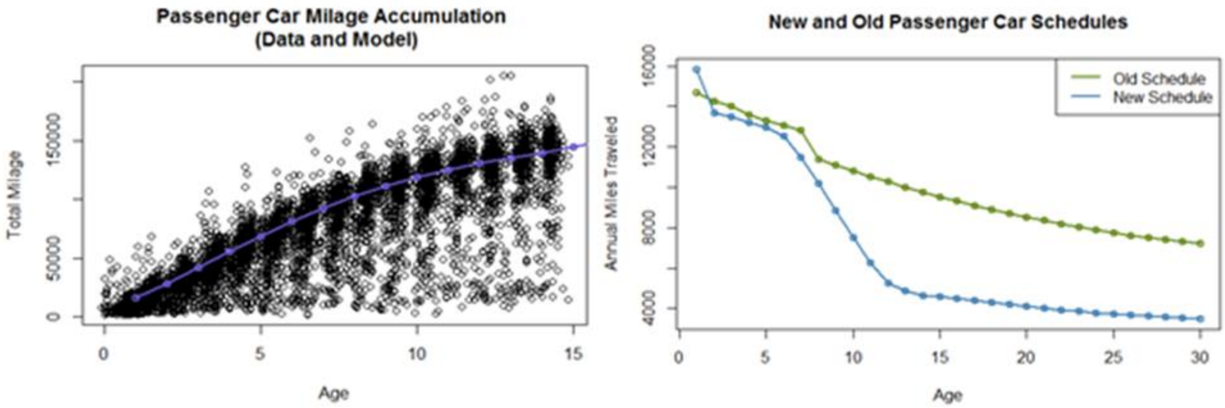

Figure 13.5 A Comparison of the Current and Previous Passenger Car Schedules

Figure 13.6 shows the share of passenger cars registered between commercial and personal fleets, and the population-weighted average odometer reading by ownership type. Commercial vehicles are driven more than personally-owned vehicles, and make up the largest share of one-year-old vehicles, relative to other ages. Since a model year of vehicles is sold starting in the fall of the previous calendar year, throughout the matching calendar year, and into the succeeding one, this initial proportion suggests that (in proportion to fleet share) more commercially-owned vehicles are bought early. Another partial explanation is likely that commercial vehicles are sold into the personal fleet after a short time. Regardless of the cause, this pattern of ownership likely explains why the first year annual VMT is higher than other years: the share of more heavily-driven commercial vehicles is highest for age one vehicles, and we weight the models by the proportion each makes up of the total population of registered vehicles. The SUV/Van and light-duty truck class fleets show similar patterns of more-heavily driven commercial vehicles, and the highest share of commercial vehicles occurring for one-year-old vehicles. Unsurprisingly, the initial peak of annual VMT occurs for these classes as well.

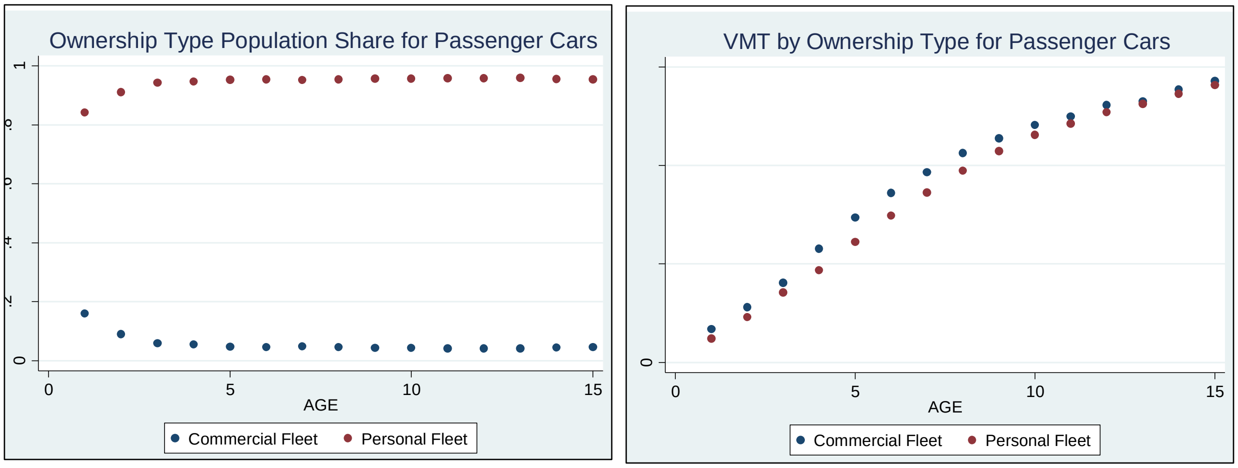

Figure 13.6 Total VMT and Share of Population by Ownership Type for Passenger Cars

The old SUV and van schedules are very similar (Figure 13.7). Since the Polk data is already aggregated to the model-level, there are 38 categories of vans in 2014. For all other classes there are at least three times as many model-level classifications. For these reasons, we determined that vans and SUVs were sufficiently similar, and merged them into a single class for VMT purposes. The new SUV/Van schedule shows a peak average annual VMT (16,035) occurring at age one. It predicts lower annual VMT for all ages (except the first year, which is slightly higher than the old SUV schedule, though still predicts lower annual VMT than the old van schedule). The new schedule predicts a total of 101,023 (30 percent) fewer miles driven over a 30-year lifespan than the old SUV schedule, and a total of 124,859 (34 percent) fewer miles driven over a 30-year lifespan than the old van schedule.

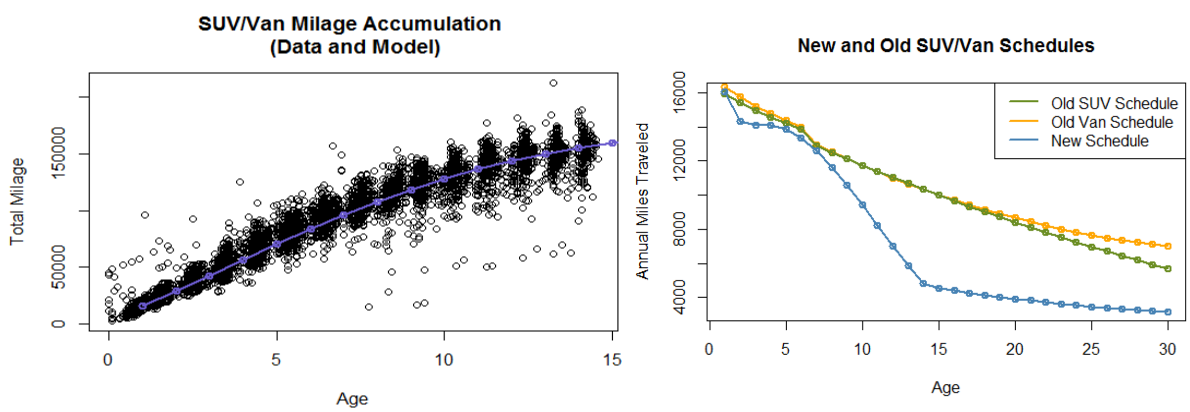

Figure 13.7 A Comparison of the Current and Previous SUV/Van Schedules

The new light-duty pickup schedule predicts a peak annual VMT of 17,436 miles at age one. Figure 13.8 shows that the new light-duty pickup VMT schedule predicts higher annual VMT for ages one through five, and lower annual VMT for all other ages. Even considering this, the new schedule for light pickups predicts a total 30-year lifetime decrease of 95,133 (26 percent) from the old schedule for light trucks.

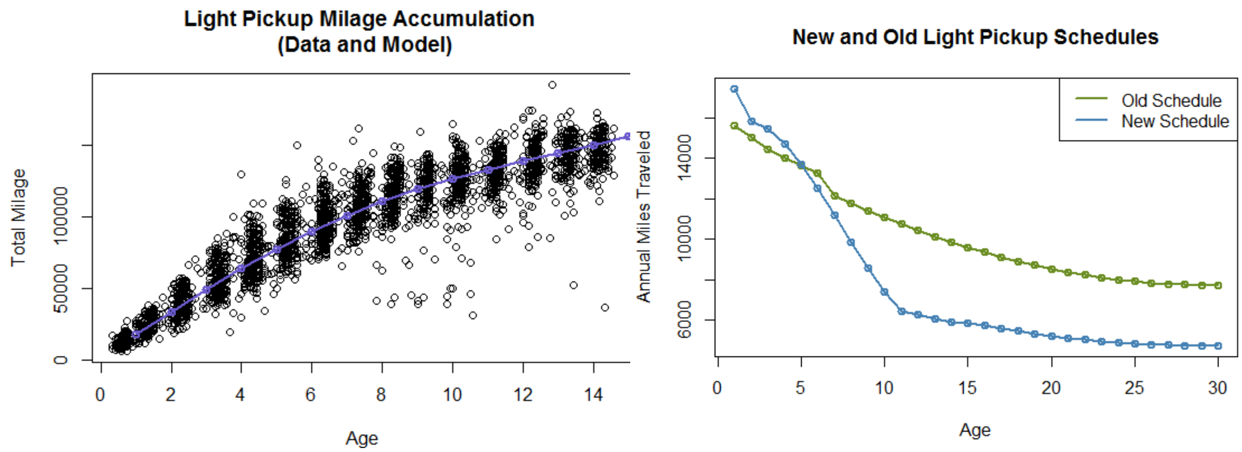

Figure 13.8 A Comparison of the Current and Previous Pickup Truck Schedules

The new medium-duty van/pickup schedule in Figure 13.9 predicts higher annual VMT for vehicles between ages one through five years, and lower annual VMT for all other vehicle ages, than the old schedule. Over the first 30-year span, the new schedule predicts that medium-duty vans/pickups drive 24,249 (9 percent) fewer miles than the old schedule. We predict the maximum average annual VMT for medium-duty vehicles (23,307 miles) at age two. The pattern of the share of commercially and personally owned vehicles (see Figure 6) is qualitatively different than the other classes, and offers a potential explanation for the maximum annual VMT occurring at age two.

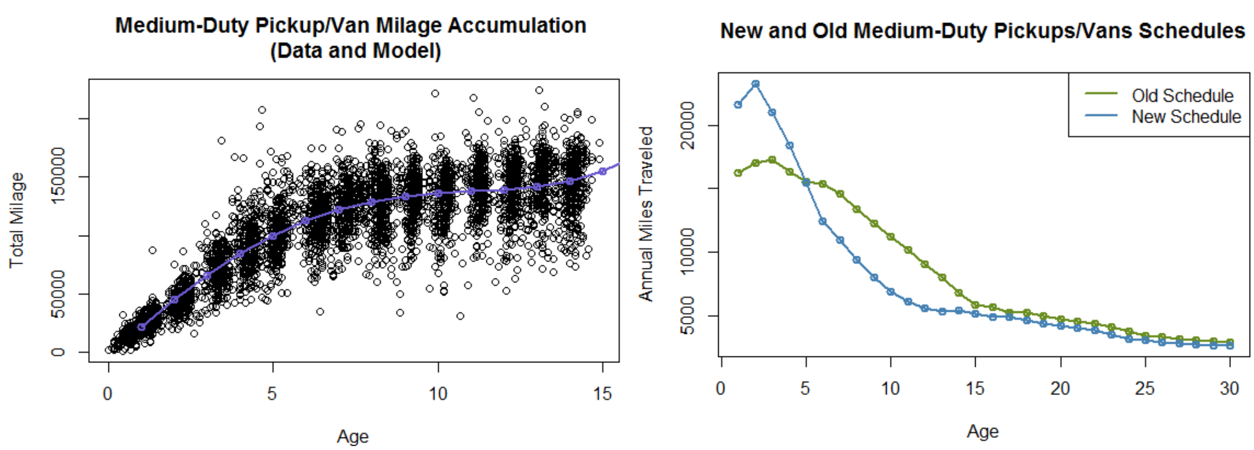

Figure 13.9 A Comparison of the Current and Previous MD Pickup/Van Schedules

Figure 13.10 shows that while the maximum share of commercially-owned vehicles occurs at age one, the registration population-weighted average odometer reading for personally and commercially owned vehicles are almost identical for this age. However, the share of commercially-owned vehicles is higher for age two vehicles than all older ages, and there is a larger spread between the average odometer readings of the two ownership types for this age of vehicle (while the spread between the average odometer readings for age three is even larger, the share of commercially-owned vehicles is smaller, and likely counteracts this effect in the registration population-weighted models). This increase in the difference between the average odometer reading of the ownership types can explain the peak annual VMT at age two.

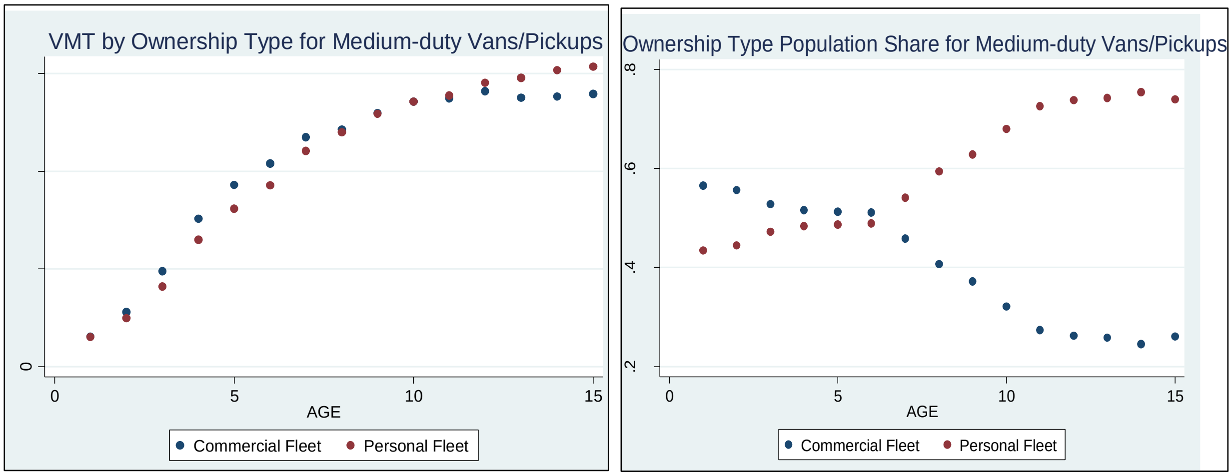

Figure 13.10 Total VMT and Share of Population by Ownership Type for MD Pickups/Vans

Table 13.1 Summary Comparison of Lifetime VMT for Current and Previous Schedules offers a summary of the comparison of lifetime VMT (by class) under the new schedule, compared with lifetime VMT under the old schedule. In addition to the total lifetime VMT expected under each schedule for vehicles that survive to their full expected life, Table 13.1 also shows the survival-weighted lifetime VMT for both schedules. This represents the average lifetime VMT for all vehicles, not only those that survive to their full expected life. The percentage difference between the two schedules is not as stark for the survival-weighted schedules: the percentage decrease of survival-weighted lifetime VMT under the new schedules range from 6.5 percent (for medium-duty trucks and vans) to 21.2 percent (for passenger vans).

Table 13.1 Summary Comparison of Lifetime VMT for Current and Previous Schedules

	Lifetime VMT			Survival-Weighted Lifetime VMT		
	Current	Previous	% difference	Current	Previous	% difference
Car	204,233	301,115	32.2%	142,119	179,399	20.8%
Van	237,623	362,482	34.4%	155,115	196,725	21.2%
SUV	237,623	338,646	29.8%	155,115	193,115	19.7%
Pickup	265,849	360,982	26.4%	157,991	188,634	16.2%
2b/3	246,413	270,662	9.0%	176,807	189,020	6.5%

13.1.4.2 Data Description

While the Polk data set contains model-level average odometer readings, the CAFE model assigns lifetime VMT schedules at a lower resolution based on vehicle body style. For the purposes of VMT accounting, the CAFE model classifies every vehicle in the analysis fleet as being one of the following: passenger car, SUV, pickup truck, passenger van, or medium-duty pickup/van. In order to use the Polk data to develop VMT schedules for each of the (VMT) classes in the CAFE model, we constructed a mapping between the classification of each model in the Polk data and the classes in the CAFE model. The only difference between the mapping for the VMT schedules and the rest of the CAFE model is that we merged the SUV and van body styles into one class (for reasons described in our discussion of the SUV/van schedule above). This mapping allowed us to predict the lifetime miles traveled, by the age of a vehicle, for the categories in the CAFE model.

In estimating the VMT models, we weighted each data point (make/model classification) by the share of each make/model in the total population of the corresponding CAFE class. This weighting ensures that the predicted odometer readings, by class and model year, represent each of vehicle classification among observed vehicles (i.e., the vehicles for which Polk has odometer readings), based on each vehicles' representation in the registered vehicle population of its class. Implicit in this weighting scheme, is the assumption that the samples used to calculate each average odometer reading by make, model, and model year are representative of the total population of vehicles of that type. Several indicators suggest that this is a reasonable assumption.

First, the majority of each vehicle make/model is well-represented in the sample. Histograms and empirical cumulative distribution functions (CDF's) of the ratio of the number of odometer readings to the total population of those makes/models by each class (Figure 13.11, below), show that for more than 85 percent of make/model combinations, the average odometer readings are collected for 20 percent or more of the total population. Most make/model observations have sufficient sample sizes, relative to their representation in the vehicle population, to produce meaningful average odometer totals at that level[4].

[4] We developed similar figures, stratified by each vehicle class, but these were no more revealing than the figures for all vehicles.

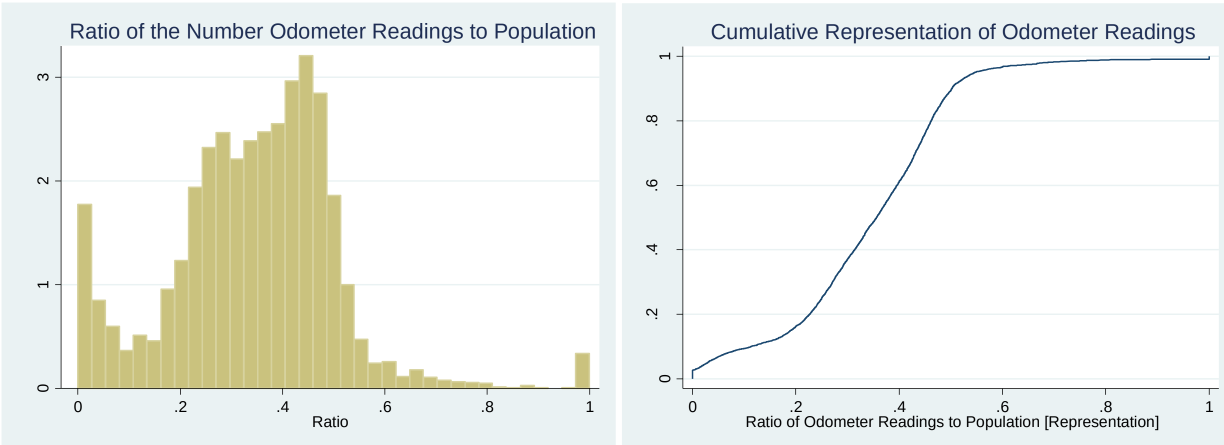

Figure 13.11 Distribution of the Ratio of Sample Size to Population Size (by Make/Model/MY)

We also considered whether the representativeness of the odometer sample varies by vehicle age, since VMT schedules in the CAFE model are specific to each age. To investigate, we calculated the percentage of vehicle types (by make, model, and model year) that did not have odometer readings. Figure 13.12 shows that all model years, apart from 2015, have odometer readings for 96 percent or more of the total types of vehicles observed in the fleet.

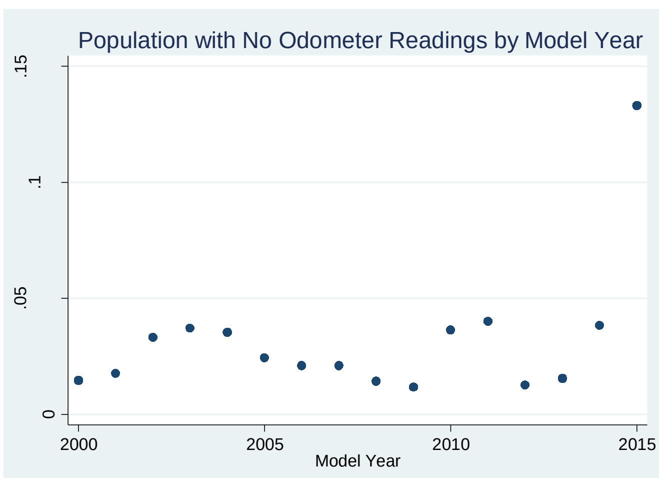

Figure 13.12 Percentage of Total Vehicle Population with No Odometer Readings across Model Years

While the preceding discussion supports the *coverage* of the odometer sample across makes/models by each model year, it is possible that, for some of those models, an insufficient number of odometer readings is recorded to create an average that is likely to be representative of all of those models in operation for a given year. Figure 13.13 below shows the percentage of all vehicle types for which the number of odometer readings is less than 5 of the total population (for that model). Again, for all model years other than 2015, about 95 percent or more of vehicles types are represented by at least 5 percent of their population. For this reason, we included observations from all model years, other than 2015, in the estimation of the new VMT schedules.

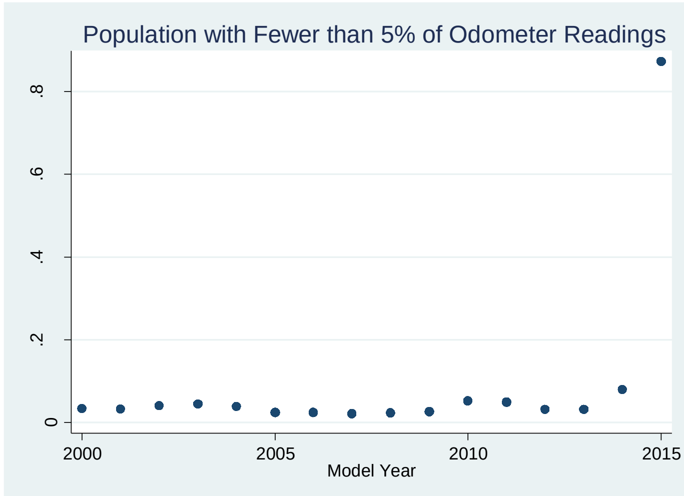

Figure 13.13 Percentage of Vehicle Models with Fewer than 5% of the Population in Odometer Readings Data (by Class)

It is possible that the odometer sample is biased. If certain vehicles are over-represented in the sample of odometer readings relative to the registered vehicle population, a simple average, or even one weighted by the number of odometer observations will be biased. However, while weighting by the share of each vehicle in the population will account for this bias, it would not correct for a sample that entirely omits a large number of makes/models within a model year. We tested for this by computing the proportion of the count of odometer readings for each individual vehicle type—within a class and model year—to the total count of readings for that class and model year. We also compared the population of each make/model—within each class and model year—to the population of the corresponding class and model year. The difference of these two ratios shows the difference of the representation of a vehicle type—in its respective class and model year—in the sample versus the population (summarized in Figure 13.14, below). All vehicle types are represented in the sample within 10 percent of their representation in the population, and the variance between the two representations is normally distributed. This suggests that, on average, the likelihood that a vehicle is in the sample is comparable to its proportion in the relevant population, and that there is little under or over sampling of certain vehicle makes/models.[5]

[5] We produced similar figures, stratified by class, but these were no more revealing; the only difference being that cars are represented in the sample within 5% of their representation in the population (with a distribution range of .05 on either side).

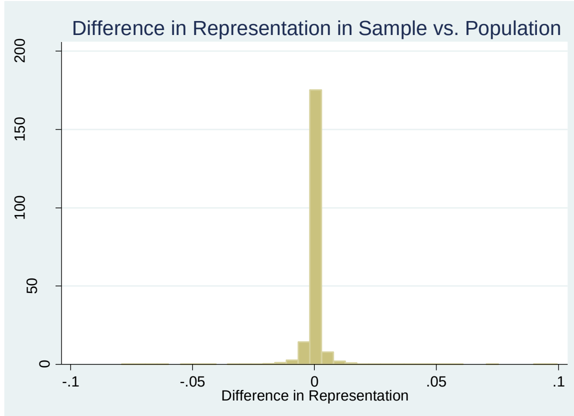

Figure 13.14 Difference in Share of Each Vehicle Model in Population vs. Odometer Sample (by Class)

13.1.4.3 Estimation

Since model years are sold in the fall of the previous calendar year, throughout the same calendar year, and even into the following calendar year—not all registered vehicles of a make/model/model year will have been registered for at least a year (or more) until age 3. The result is that some MY2014 vehicles may have been driven for longer than one year, and some less, at the time the odometer was observed. In order to consider this in our definition of age, we assign the age of a vehicle to be the difference between the average reading date of a make/model and the average first registration date of that make/model. The result is that the continuous age variable reflects the amount of time that a car has been registered at the time of odometer reading, and presumably the time span that the car has accumulated the miles.

After creating the "Age" variable, we fit the make/model lifetime VMT data points to a weighted quartic polynomial regression of the age of the vehicle (stratified by class). The predicted values of the quartic regressions are used to calculate the marginal annual VMT by age for each class by calculating differences in estimated lifetime mileage accumulation by age. However, the Polk data acquired by NHTSA only contains observations for vehicles newer than 16 years of age. In order to estimate the schedule for vehicles older than the age 15 vehicles in the Polk data, we combined information about that portion of the schedule from the VMT schedules used in both the 2017-2021 Final Light Duty Rule and 2019-2025 Medium-Duty NPRM. The light-duty schedules were derived from the survey data contained in the 2009 National Household Travel Survey (NHTS) and the 2001 Vehicle In Use Survey (VIUS), for medium-duty trucks.

Based on the vehicle ages for which we have data (from the Polk purchase), the newly estimated annual schedules differ from the previous version in important ways. Perhaps most significantly, the annual mileage associated with ages beyond age 8 begin to, and continue to, trend much lower. The approach taken here attempts to preserve the results obtained through estimation on the Polk observations, while leveraging the existing (NHTS-based) schedules to support estimation of the higher ages (age 16 and beyond). Since the two schedules are so far apart, simply splicing them together would have created not only a discontinuity, but also precluded the possibility of a monotonically decreasing scale with age (which is consistent with previous schedules, the data acquired from Polk, and common sense).

In the 2009 NHTS survey, VMT per vehicle decreases steadily as household vehicles age, though with declining samples sizes for the oldest vehicles. The Polk data show an annual VMT increase for the oldest vehicles. In order to force the expected monotonicity, we perform a triangular smoothing algorithm until the schedule is monotonic. This performs a weighted average which weights the observations close to the observation more than those farther from it. The result is a monotonic function, which predicts similar lifetime VMT for the sample span as the original function. Since the Polk data does not show vehicles greater than15 years of age, we are not able to correctly capture that part of the annual VMT curve using only the new dataset. For this reason, we use trends in the old data to extrapolate the new schedule for ages beyond the sample range.

In order to use the VMT information from the newer data source for ages outside of the sample, we use the final in-sample age (15 years) as a seed and then apply the annual VMT decline from the old schedules to extrapolate the new schedules out to age 30. To do this, we calculated the annual percentage difference in VMT of the old schedule for ages 15-30. The same annual percentage difference in VMT is applied to the new schedule to extend beyond the final in-sample value. This assumes that the overall proportional trend in the outer years is correctly modeled in the old VMT schedule, and imposes this same trend for the outer years of the new schedule. The extrapolated schedules are the final input for the VMT schedules in the CAFE model.

Older vehicles are not well represented, even in the NHTS, where sample sizes for these vehicles are very small. This is an area that would benefit from further research.

13.1.4.4 Comparison to previous schedules

New VMT data suggest lower lifetime mileage accumulation rates than the VMT schedule used in the last Light-Duty CAFE Final Rule, particularly for higher vehicle ages. The previous schedules are based on self-reported odometer readings that were acquired during a period of economic and fuel price volatility, while the observations from Polk are between 5 and 7 years newer than those in the NHTS and represent observed odometer readings (rather than self-reported information).

Additionally, NHTSA finds the Polk data, which provides a much larger representative sample of some 70 million vehicles preferable to the previous schedule, which relied on the NHTS's representative sample of about 200,000 households. However, by properly accounting for vehicle population weights in the new averages and models, we corrected for this issue in the derivation of the new schedules.

Sample surveys have inherent limitations. While the NHTS is carefully designed to be a representative sample of *households*, it may not be a representative sample of *vehicles*. Since the NHTS only samples households, it does not detect the differing driving patterns of commercially registered vehicles, which turn out to be particularly important for new vehicles and for medium pick-ups. It seems likely that there is another previously undetected phenomenon: there may be many older light duty vehicles that retain their registration but are little driven from one year to the next. These vehicles, if they exist, were not detected by the NHTS survey. This is an uncertainty that could be clarified by further research.

Both the previous and current schedules are limited by the nature of the data on which they are based. Each schedule relies upon a single snapshot in time, then treats the cross-section of vehicle ages as if it were a panel – observations about the same set of vehicles as they age. This is done out of necessity, but can clearly bias estimates of mileage accumulation. In the case of the NHTS, older vehicles would have experienced nearly a decade of strong economic growth and historically low fuel prices –perhaps inflating VMT relative to today. In the case of the Polk sample, vehicles would have experienced prolonged periods of both fuel price instability and economic distress (the years from 2007 - 2010, though continuing longer for certain age cohorts that remained chronically underemployed for a longer period of time) - perhaps depressing VMT relative to today. These biases cannot even be detected with a single year of data, and NHTSA intends to take steps in the future to improve the resources on which the schedules are estimated.

13.1.4.5 Future direction

In consultation with other agencies closely involved with VMT estimation (e.g., FHWA), NHTSA will continue to seek means to further refine estimated mileage accumulation schedules. For example, one option under consideration would be to obtain odometer reading data from successive calendar years, thus providing a more robust basis to consider, for example, the influence of changing fuel prices or economic conditions on the accumulation of miles by vehicles of a given age.

NHTSA seeks comment on the information and methods used to develop today's odometer-based estimates of annual mileage accumulation schedules, recommendations regarding any other methods to estimate such schedules, and information that could be used to refine these schedules or develop and implement alternative methods.

13.1.5 Other Assumptions of Note

There are a number of additional assumptions that influence both the simulation of manufacturers' compliance decisions and the estimated benefits and costs resulting from the standards – among them are technology cost and effectiveness, both discussed in greater detail in chapter 5 of the Draft TAR. One assumption that warrants additional discussion are fuel prices.

Few inputs touch as many aspects of the analysis as fuel prices; they are a primary driver of the value of fuel savings (which is the largest single benefit of the program), they influence the projected share of light trucks in the new vehicle market, the ranking of technologies by manufacturers in the compliance simulation (discussed more later), the amount of additional fuel economy demanded by the market in the absence of regulatory pressure, and the magnitude of the rebound effect that generates additional vehicle miles traveled when fleet fuel economy improves. Yet, over the increasingly long time horizons of recent CAFE analyses (the Draft TAR analysis covers the full useful lives of vehicles produced between model years 2015 and 2032, and the Final Rule analysis covered the full useful lives of vehicles produced between model years 2011 and 2025 – necessitating fuel price estimates out as far as 2060), the uncertainty in fuel price projections becomes increasingly important. In Figure 13.15, we see a comparison of oil price projections from the Annual Energy Outlook compared to the actual average price observed in a given year. The green cells represent underestimates, while the blue cells highlight overestimates.

Projected vs. Actual
(percent difference)

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
AEO 1994	5.9	10.8	5.8	-7.0	9.1	76.9	30.7	-13.2	16.8	14.9	4.3	-14.6	-33.6	-41.7	-45.9	-59.1	-33.8	-46.8			
AEO 1995		-1.9	-0.2	-13.1	1.7	63.2	19.0	-21.7	3.5	0.1	-10.6	-27.6	-44.0	-51.1	-54.9	-66.0	-45.0	-55.5			
AEO 1996			0.1	-14.5	-0.9	59.6	17.0	-22.8	2.8	-0.5	-11.1	-28.0	-44.2	-51.6	-55.5	-66.7	-46.5	-57.1	-67.1	-65.5	-63.4
AEO 1997				-3.7	3.6	58.4	12.2	-28.6	-5.8	-9.6	-19.9	-35.7	-50.7	-57.6	-61.4	-71.4	-54.5	-63.9	-72.6	-71.4	-70.0
AEO 1998					-0.3	53.6	12.3	-26.4	-3.9	-8.8	-19.2	-35.3	-50.4	-57.6	-61.4	-71.4	-54.5	-63.8	-72.5	-71.4	-69.9
AEO 1999						3.9	-21.2	-47.1	-25.8	-25.3	-29.9	-41.4	-53.5	-58.5	-61.1	-71.1	-54.1	-63.6	-72.3	-71.2	-69.7
AEO 2000							0.8	-20.6	-3.2	-8.2	-19.5	-35.8	-51.1	-58.1	-61.9	-71.8	-55.2	-64.5	-73.1	-72.0	-70.6
AEO 2001								1.9	13.2	-3.9	-19.6	-35.7	-51.0	-58.0	-61.8	-71.8	-55.1	-64.4	-73.0	-72.0	-70.6
AEO 2002									4.5	-7.5	-14.4	-31.5	-47.7	-55.2	-59.2	-69.8	-52.0	-61.9	-71.1	-70.0	-68.5
AEO 2003										-0.1	-3.5	-28.7	-47.7	-55.1	-59.1	-69.7	-51.9	-61.8	-71.0	-69.8	-68.3
AEO 2004											0.3	-30.4	-48.4	-55.7	-59.6	-70.0	-52.3	-62.1	-71.2	-70.0	-68.4
AEO 2005												0.2	-26.2	-44.4	-54.2	-67.7	-50.7	-61.5	-70.6	-69.2	-67.3
AEO 2006													5.0	-2.7	-16.2	-41.2	-11.8	-34.1	-50.5	-49.1	-47.0
AEO 2007														7.8	-6.1	-33.4	-0.4	-25.7	-46.9	-47.7	-46.8
AEO 2008															-4.9	-17.9	21.8	-8.3	-33.5	-34.1	-34.2
AEO 2009																6.0	-32.7	-32.8	-35.9	-22.9	-9.5
AEO 2010																	-3.8	-9.4	-32.4	-23.5	-13.3
AEO 2011																		-0.1	-19.1	-16.1	-9.8
AEO 2012																			-0.6	1.8	14.6
AEO 2013																				2.0	1.1
AEO 2014																					5.1
Average Absolute Percent Difference	5.9	6.3	2.0	9.6	3.1	52.6	16.2	22.8	8.8	7.9	13.8	28.7	42.6	46.8	48.2	57.8	39.8	46.5	54.9	52.8	47.9

Sources: Projections: *Annual Energy Outlook* , Reference Case Projections, Various Editions, "Imported Crude Oil Price" (average imported refiners' acquisition cost for crude oil, "IRAC").

Historical Data: U.S. Energy Information Administration, September 2014 Monthly Energy Review, DOE/EIA-0035(2013/08) (Washington, DC, September 25, 2014), Table 9.1. Bureau of Economic Analysis, US Dept. of Commerce, September 2014.

Figure 13.15 Retrospective Analysis of EIA Fuel Price Projections

As Figure 13.15 shows, projections of years farther in the future tended to be significantly different from observed prices. Also of note is the fact that long-term underestimation continued for a number of years after observed price increases – suggesting that the forecasting model is slow to adapt to regime changes. In general, this stability may be advantageous; a model that is too reactionary could produce large swings between iterations of the AEO and present projections that are too "noisy" for planning purposes. However, if longer-term prices are significantly different from prices over the last 8 – 10 years, current forecasts could overstate or understate future oil prices. There is inherent uncertainty in future fuel prices, and updates to forecasts will continue to integrate current information as it becomes available, which will continue to impact future CAFE analysis.

As discussed elsewhere in this document, the global oil market has experienced a period of rapid and dramatic change since the final rule was published in 2012. The fuel price estimates in the AEO reflect these changes. As Figure 13.16 illustrates, the recent decline in fuel prices represents a deviation from the projections used in the 2012 final rule analysis. However, as discussed above, the long term trend is roughly consistent with the older forecast but starts from a lower point. And while these lower prices are likely to increase demand relative to a higher price scenario, each gallon saved results in a lower value of fuel savings to consumers as a result of the drop in per-gallon price relative to the 2012 FR analysis.

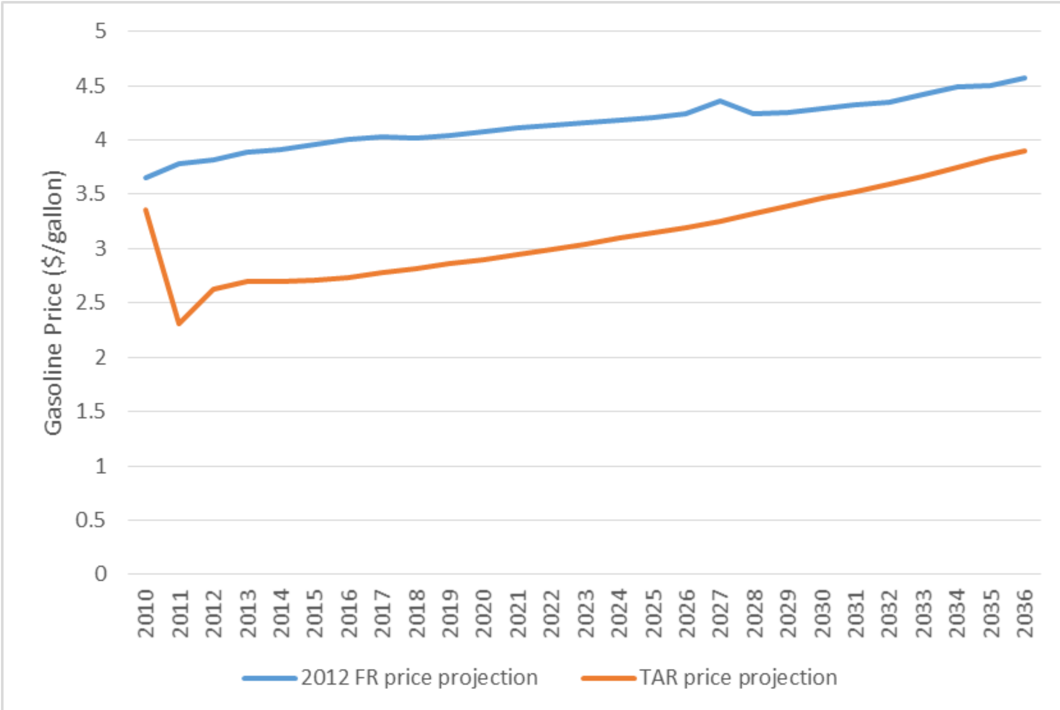

Figure 13.16 Comparison of Fuel Price Estimates in Draft TAR and 2012 Final Rule Analysis

13.2 CAFE Model (aka "Volpe Model") Overview and Updates Since the 2012 Final Rule

This analysis reflects several changes made to the model since 2012, when NHTSA used the model to estimate the effects, costs, and benefits of final CAFE standards for light-duty vehicles produced during MYs 2017-2021, and Augural Standards for MYs 2022-2025. Some of these changes specifically enable analysis of potential fuel consumption standards (and, hence, related CO_2 emissions standards harmonized with fuel consumption standards) for heavy-duty pickups and vans; other changes implement more general improvements to the model. Key changes relevant to today's analysis include the following:

- Expansion of model inputs, procedures, and outputs to accommodate technologies not included in prior analyses.
- Changes to the algorithm used to apply technologies, enabling more explicit accounting for shared vehicle platforms and adoption and "inheritance" of major engine changes.
- Expanded accounting for CAFE credits carried over from years prior to those included in the analysis fleet (a.k.a. "banked" credits).
- Changes to the model's approach to estimating the effect of combinations of fuel-saving technologies.

13.2.1 Updates to 2012 Final Rule Version of the CAFE Model

After the light-duty rulemaking analysis accompanying the 2012 final rule that finalized NHTSA's standards through MY2021, NHTSA staff began work on changes to the CAFE model with the intention of better reflecting constraints of product planning and cadence for which previous analyses did not account. These changes, summarized below, interact with preexisting model characteristics discussed above. Additionally, NHTSA fully integrated the results of a simulation database constructed by Argonne National Laboratory and described in Chapter 5 (Section 5.4.2.4). While the technologies, assumptions, and experimental design are discussed in chapter 5, the integration into the CAFE model is discussed below.

Engine and Transmission Sharing and Inheritance

In practice, manufacturers are limited in the number of engines and transmissions that they produce. Typically a manufacturer produces a number of engines—perhaps six or eight engines for a large manufacturer—and tunes them for slight variants in output for a variety of car and truck applications. Manufacturers limit complexity in their engine portfolio for much the same reason as they limit complexity in vehicle variants: they face engineering manpower limitations, and supplier, production and service costs that scale with the number of parts produced.

In previous analyses that used the CAFE model, engines and transmissions in individual models were allowed relative freedom in technology application, potentially leading to solutions that would, if followed, create many more unique engines and transmissions that exist in the analysis fleet (or in the market) for a given model year. This multiplicity likely failed to sufficiently account for costs associated with such increased complexity in the product portfolio, and may have represented an unrealistic diffusion of products for manufacturers that are consolidating global production to increasingly smaller numbers of shared engines and platforms (cite NAS here). The lack of a constraint in this area allowed the model to apply different levels of technology to the engine in each vehicle at the time of redesign or refresh, independent of what was done to other vehicles using a previously identical engine.

In the current version of the CAFE model, engines and transmissions that are shared between vehicles must apply the same levels of technology, in all technologies, dictated by engine or transmission inheritance. This forced adoption is referred to as "engine inheritance" in the model documentation.

In practice, the model first chooses an "engine leader" among vehicles sharing the same engine. The leader is selected first by the vehicle with the lowest average sales across all available model years. If there is a tie, the vehicle with the highest average MSRP across model years is chosen. The model applies the same logic with respect to the application of transmission changes. The model follows this formulation due to previous market trends suggesting that many technologies begin deployment at the high-end, low-volume end of the market as manufacturers build their confidence and capability in a technology, and later expand the technology across more mainstream product lines.

NHTSA received comments specific to its approach to accounting for shared engines and transmissions, although comments from some environmental organizations cited examples of sharing between light- and heavy-duty products. NHTSA has continued to refine its implementation of its approach to accounting for shared engines and transmissions, and again seeks comment on the approach, recommendations regarding any other approaches, and any information that would facilitate implementation of the agency's current approach or any alternative approaches.

Platforms, Sharing, and Technology

The term "platform" is used loosely in industry, but generally refers to a common structure shared by a group of vehicle variants. The degree of commonality varies, with some platform variants exhibiting traditional "badge engineering" where two products are differentiated by little more than insignias, while other platforms be used to produce a broad suite of vehicles that bear little outer resemblance to one another.

Given the degree of commonality between variants of a single platform, manufacturers do not have complete freedom to apply technology to a vehicle: while some technologies (e.g. low rolling resistance tires) are very nearly "bolt-on" technologies, others involve substantial changes to the structure and design of the vehicle, and therefore necessarily are constant among vehicles that share a common platform. NHTSA staff has, therefore, modified the CAFE model such that all levels of mass reduction and aerodynamic improvement are forced, over time, to be constant among variants of a platform. However, because these levels are not concretely defined in terms of specific engineering changes, and the vehicle models in the analysis fleet are not defined in terms of specific engineering content, this aspect of the CAFE model does not mean that every vehicle model on a platform necessarily receives identical engineering changes to attain the same level of aerodynamic improvement or mass reduction. Also, with the application of these improvements tied to vehicle redesign or freshening, some vehicle models on a shared platform may inherit them from platform "leaders."

Within the analysis fleet, each vehicle is associated with a specific platform. Similar to the application of engine and transmission technologies, the CAFE model defines a platform "leader" as the vehicle variant of a given platform that has the highest level of observed mass reduction and aerodynamic technologies present in the analysis fleet. If there is a tie, the CAFE model begins applying aerodynamic and mass reduction technology to the vehicle with the lowest average sales across all available model years. If there remains a tie, the model begins by choosing the vehicle with the highest average MSRP across all available model years. As the model applies technologies, it effectively levels up all variants on a platform to the highest level of (mass and aerodynamic) technology on the platform.

In the 2015 NPRM proposing new fuel consumption and GHG standards for heavy-duty pickups and vans, NHTSA specifically requested comment on the general use of platforms within CAFE rulemakings. While the agency received no responses to this specific request, comments from some environmental organizations cited examples of technology sharing between light- and heavy-duty products. NHTSA has continued to refine its implementation of an approach accounting for shared platforms, and again seeks comment on the approach, recommendations regarding any other approaches, and any information that would facilitate implementation of the agency's current approach or any alternative approaches.

Interactions between Regulatory Classes

Like earlier versions, the current CAFE model provides for integrated analysis spanning different regulatory classes, accounting both for standards that apply separately to different classes and for interactions between regulatory classes. Light vehicle CAFE standards are specified separately for passenger cars and light trucks. However, there is considerable sharing between these two regulatory classes – where a single engine, transmission, or platform can appear in both the passenger car and light truck regulatory class. For example, some sport-utility vehicles are offered in 2WD versions classified as passenger cars and 4WD versions classified as light trucks. Integrated analysis of manufacturers' passenger car and light truck fleets provides the ability to account for such sharing and reduce the likelihood of finding solutions that could involve introducing impractical levels of complexity in manufacturers' product lines. Additionally, integrated analysis provides the ability to simulate the potential that manufacturers could earn CAFE credits by over complying with one standard and use those credits toward compliance with the other standard (i.e., to simulate credit transfers between regulatory classes). This is discussed further below.

HD pickups and vans are regulated separately from light-duty vehicles. While manufacturers cannot transfer credits between light-duty and MDHD classes, there is some sharing of engineering and technology between light-duty vehicles and HD pickups and vans. For example, some passenger vans with GVWR over 8,500 pounds are classified as medium-duty passenger vehicles (MDPVs) and are thus included in manufacturers' light-duty truck fleets, while cargo vans sharing the same nameplate are classified as HD vans. NHTSA has also identified several engines (across all manufacturers) that are shared between the light-truck and HD pickup and van classes.

Today's analysis uses an overall analysis fleet spanning both the light-duty and HD pickup and van fleets. As discussed below, doing so shows some technology "spilling over" to HD pickups and vans due, for example, to the application of technology in response to current light-duty standards. For most manufacturers, these interactions appear relatively small. For Nissan, however, they appear considerable, because Nissan's heavy-duty vans use engines also used in Nissan's light-duty SUVs. Daimler also exhibits significant levels of component sharing between its MDHD and light-duty fleets, but is not sufficiently constrained by the upcoming MDHD CAFE standards to expect technology migration into the light-duty fleet as a result of the regulations.

In the NPRM proposing new standards for heavy-duty pickups and vans NHTSA and EPA commented on the expansion of the analysis fleet such that the impacts of new HD pickup and van standards can be estimated within the context of an integrated analysis of light-duty vehicles and HD pickups and vans, accounting for interactions between the fleets. As mentioned above, some environmental organizations specifically cited commonalities and overlap between light- and heavy-duty products. NHTSA seeks comment on the approach it has developed to account for such sharing, recommendations regarding any other approaches, and any information that would facilitate implementation of the agency's current approach or any alternative approaches.

Phase-In Caps

The CAFE model retains the ability to use phase-in caps (specified in model inputs) as proxies for a variety of practical restrictions on technology application, including the improvements described above. Unlike vehicle-specific restrictions related to redesign, refreshes or platforms/engines, phase-in caps constrain technology application at the vehicle manufacturer level for a given model year. Introduced in the 2006 version of the CAFE model, they were intended to reflect a manufacturer's overall resource capacity available for implementing new technologies (such as engineering research and development personnel and financial resources), thereby ensuring that resource capacity is accounted for in the modeling process.

Compared to prior analyses of light-duty standards, these model changes result in some changes in the broad characteristics of the model's application of technology to manufacturers' fleets. Since the use of phase-in caps has been de-emphasized and manufacturer technology deployment remains tied strongly to estimated product redesign and freshening schedules, technology penetration rates may jump more quickly as manufacturers apply technology to high-volume products in their portfolio.

In previous CAFE rulemakings, redesign/refresh schedules and phase-in caps were the primary mechanisms to reflect a manufacturer's limited pool of available resources during the rulemaking time frame and the years preceding it, especially in years where many models may be scheduled for refresh or redesign. The newly-introduced representation of platform-, engine-, and transmission-related considerations discussed above augment the model's preexisting representation of redesign cycles, and eliminate the need to rely on phase-in caps. By design, restrictions that enforce commonality of mass reduction and aerodynamic technologies on variants of a platform, and those that enforce engine inheritance, will result in fewer vehicle-technology combinations in a manufacturer's future modeled fleet. NHTSA seeks comment regarding this shift away from relying on phase-in caps and, if greater reliance on phase-in caps is recommended, what approach and information can be used to define and apply these caps.

Accounting for CAFE Credits

The changes discussed above relate specifically to the model's approach to simulating manufacturers' potential addition of fuel-saving technology in response to CAFE standards and fuel prices within an explicit product planning context. The model's approach to simulating compliance decisions also accounts for the potential to earn and use CAFE credits, as provided by EPCA/EISA. Like past versions, the current CAFE model can be used to simulate credit carry-forward (a.k.a. banking) between model years and transfers between the passenger car and light truck fleets, but not credit carry-back (a.k.a. borrowing) between model years or trading between manufacturers. Unlike past versions, the current CAFE model provides a basis to specify (in model inputs) CAFE credits available from model years earlier than those being simulated explicitly. For example, with today's analysis representing model years 2015-2032 explicitly, credits specified as being available from model year 2014 are made available for use through model year 2019 (given the 5-year limit on carry-forward of credits).

As discussed in the CAFE model documentation[6], the model's default logic attempts to maximize credit carry-forward—that is to "hold on" to credits for as long as possible. Although the model uses credits before they expire if a manufacturer needs to cover a shortfall that occurs when insufficient opportunities exist to add technology in order to achieve compliance with a standard, the model will otherwise carry forward credits until they are within 2 years of expiration, at which point it will use them before adding technology. The model always applies expiring credits before applying technology in a given model year, but attempts to use credits that will expire within the next three years as a means to smooth out technology application over time to avoid both shortfalls and high levels of over-compliance that can result in a surplus of

[6] Available at: http://www.nhtsa.gov/fuel-economy

credits. As further discussed in the CAFE model documentation, model inputs can be used to adjust this logic to shift the use of credits ahead by one or more model years.

NHTSA recently introduced the CAFE Public Information Center (at http://www.nhtsa.gov/CAFE_PIC/CAFE_PIC_Home.htm) to provide public access to a range of information regarding the CAFE program, including manufacturers' credit balances. Having reviewed credit balances (as of January 23, 2016) and estimated the potential that some manufacturers could trade credits, NHTSA developed inputs for today's analysis that make carried-forward credit available as summarized below, after subtracting credits assumed to be traded to other manufacturers, and adding credits assumed to be acquired from other manufacturers through such trades. NHTSA seeks comment regarding the model's representation of the CAFE credit provisions, recommendations regarding any other options, and any information that could help to refine the current approach or develop and implement an alternative approach.

Table 13.2 CAFE Credits Estimated to be Available from 2010-2014 (1 vehicle x 0.1 mpg = 1 credit)

	Passenger Car					Light Truck				
	2010	2011	2012	2013	2014	2010	2011	2012	2013	2014
BMW	1,867,281	5,484,006	6,487,815	8,653,773	13,678,596	-	39,458	24,674	163,927	749,703
Daimler	-	3,565,752	3,959,432	4,897,035	458,100	-	160,528	120,002	404,128	-
FCA	2,876,264	42,336,994	51,750,678	64,726,258	4,182,307	-	5,553,261	5,088,698	1,461,785	-
Ford	36,375,648	33,608,823	42,075,418	72,048,358	64,729,568	7,587,839	6,551,119	1,158,854	5,747,065	4,634,359
General Motors	27,631,650	48,958,466	27,741,179	42,650,469	47,350,779	23,344,950	4,983,427	570,140	1,988,083	15,118,329
Honda	64,652,589	18	2,045,973	9,826,880	1,290,074	16,271,310	-	-	-	-
Hyundai Kia	47,621,472	12,088,388	24,961,094	45,456,981	30,988,589	6,256,961	3,566,052	1,192,473	616,827	1,129,148
JLR	-	731,304	867,378	1,380,529	847,794	-	148,329	108,544	395,626	844,612
Mazda	13,387,185	504,080	1,062,098	1,380,624	180,964	3,150,208	-	-	-	-
Mitsubishi	1,925,910	1,100,080	1,602,650	2,401,174	4,281,902	783,180	-	-	508,898	1,282,604
Nissan	-	-	4,917,773	9,551,573	618,917	4,247,124	194,670	88,218	-	-
Subaru	2,198,848	118,040	1,579,019	4,967,329	4,740,723	11,317,086	145,270	-	1,839,959	5,211,684
Tesla	-	-	1,039,207	159,008	514,937	-	-	-	-	-
Toyota	169,026,869	18,459,036	33,398,277	32,011,519	3,306,679	22,424,142	7,817,895	574,879	1,742,995	-
Volvo	-	316,089	45,579	818,184	-	-	62,876	-	-	235,285
VWA	15,911,604	18,824,971	18,193,147	32,795,905	34,158,829	719,074	994,291	294,668	1,672,648	2,783,619

13.2.1.1 Integrating Vehicle Simulation Results into the CAFE Model

In previous versions of the CAFE Model, technology effectiveness values entered into the model as a single number for each technology (for each of several classes), intended to represent the incremental improvement in fuel consumption achieved by applying that technology to a vehicle in a particular class. At a basic level, this implied that successive application of new vehicle technologies resulted in an improvement in fuel consumption (as a percentage) that was the product of the individual incremental effectiveness of each technology applied. Since this construction fails to capture interactive effects – cases where a given technology either improves or degrades the impact of subsequently applied technologies – the CAFE Model applied "synergy factors." The synergy factors were defined for a relatively small number of technology pairs, and were intended to represent the result of physical interactions among pairs of technologies – attempting to account for situations where $2 \times 2 \neq 4$.

For this analysis, the CAFE Model has been modified to accommodate the results of the large-scale vehicle simulation study conducted by Argonne National Laboratory (and described above). While Autonomie, Argonne's vehicle simulation model, produces absolute fuel consumption values for each simulation record, the results have been modified in a way that preserves much of the existing structure of the CAFE Model's compliance logic, but still faithfully reproduces the totality of the simulation outcomes present in the database. Fundamentally, the implementation represents a translation of the absolute values in the simulation database into incremental improvements and a substantially expanded set of synergy factors.

Incremental Effectiveness or Absolute Improvement?

As it always has, the CAFE Model applies a given technology, to a given vehicle and estimates the incremental improvement in fuel consumption from the new combination of technologies – with the ultimate goal of estimating a manufacturer's compliance position relative to a set of fuel economy standards. However, unlike previous versions, the notion of *incremental* has more nuance. As one sees from an examination of the Argonne database, each technology applied results in a different level of fuel consumption depending upon the existing technology content (and mass) of the vehicle to which it is applied. In the past, the *incremental* effectiveness of a given technology was represented by a single point but, as the database illustrates, the true incremental effectiveness of a given technology is a distribution across all of the technology combinations to which it can be applied, rather than a single point.

For example, as Figure 13.17 shows, it is possible to apply level 1 turbocharging to vehicles of widely varying initial fuel economies, though the bulk of the observations in the database are between 45 and 60 MPG. There are nearly 1,200 unique technology combinations to which level 1 turbocharging and downsizing (TURBO1) can be applied. It seems reasonable to assume that applying the same technology to vehicles with over a thousand different technology combinations will yield different levels of improvement for at least some of these combinations. As Figure 13.17 illustrates, that is indeed the case. Applying TURBO1 to a given vehicle changes the fuel economy of that vehicle depending upon the set of technologies already present when turbocharging is applied. Estimating the incremental improvement of adding level one turbocharging to an otherwise identical vehicle (i.e., identical except for the presence of other fuel economy improving technologies) produces a distribution of fuel economy improvements, rather than a single value, like the graph in Figure 13.18.

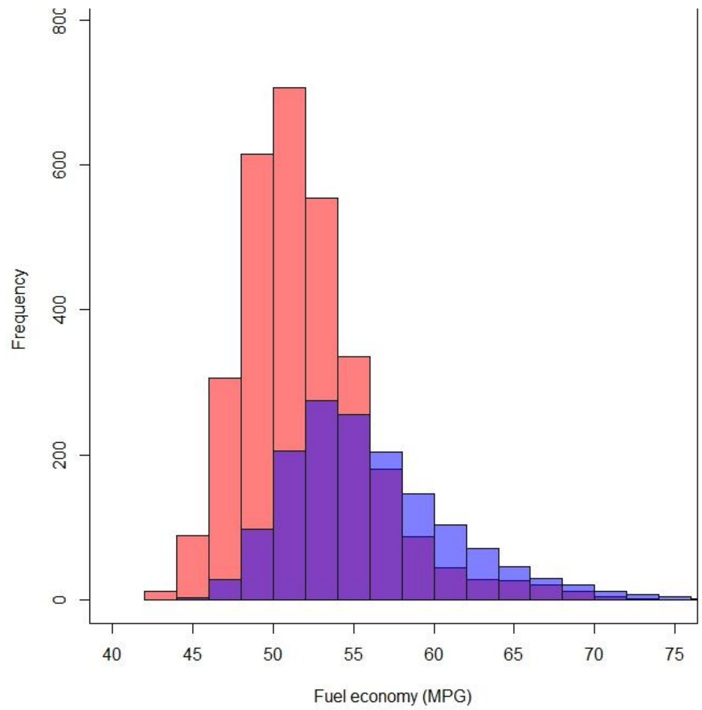

Figure 13.17 Fuel Economy of Simulated Vehicles before (Red) and after (Blue) Application of Level 1 Turbocharging

Not only does Figure 13.18 illustrate that applying TURBO1 produces some incremental fuel consumption improvements close to zero percent (where the red represents vehicles without TURBO1, blue is vehicles with TURBO1, and purple is the overlap in the distribution of fuel economy between the two), but that it also results in some incremental improvements greater than 15 percent depending upon the configuration to which it is applied. While only the distribution of incremental effectiveness for level 1 turbocharging is shown here, the distributions of incremental effectiveness for other technologies have similar levels of variation, if not similar shapes.

Despite the existence of absolute fuel consumption estimates from the Autonomie simulations, there are advantages to continuing to apply technology based on incremental effectiveness values – complicated, though it is, to incorporate the distribution of improvement illustrated by Figure 13.18.

The CAFE model was designed to consider, and apply, technologies based on the resulting incremental improvement in fuel economy. Additionally, the analysis fleet (described in Chapter 4.2), represents a wide array of technology combinations and vehicle attributes – even within a single class. For example, within the midsize car technology class (one of five technology classes to which vehicle models in the analysis fleet are assigned), the analysis fleet starts with over 200 unique technology combinations to which the CAFE model adds technology. Attempting to capture all of those technology combinations with a single effectiveness value for each technology (and even a limited set of synergy factors) is bound to result in distortions as more and more technology is applied within the CAFE model's compliance simulations.

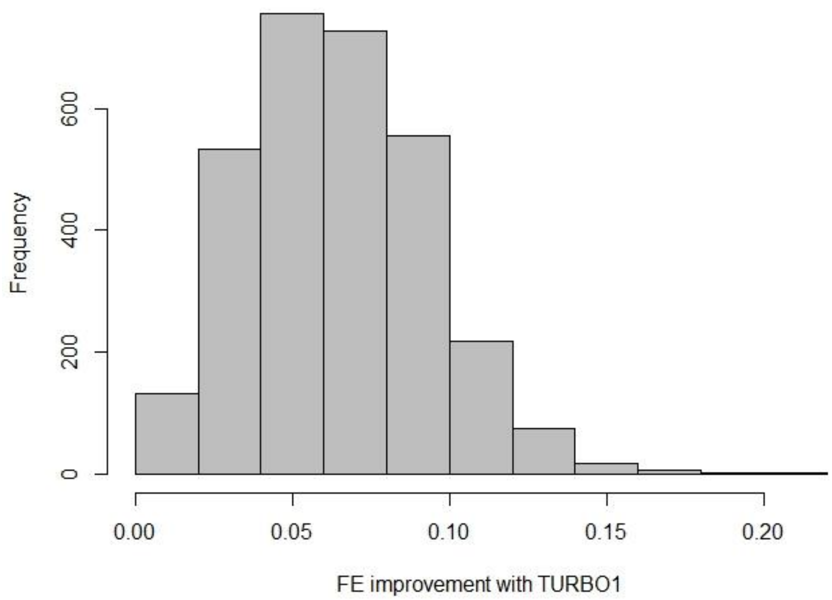

Figure 13.18 Fuel Economy Improvement to Vehicles That Acquire Level 1 Turbocharging In Simulation

But can the absolute fuel consumption values of the database be used in the CAFE model? In the current implementation, they are – though not directly. There is a wide variety of engine power and fuel consumption, even for a single technology combination, in the analysis fleet. Using the absolute fuel consumption values in the Argonne database would require mapping each vehicle to a point in the database, and measuring the difference between its starting fuel economy and that of the point in the database with identical technology content. Afterward, the improvement in fuel consumption resulting from any additional technology added to that vehicle can be based upon the difference of the points in the database and the initial fuel economy difference resulting from the mapping. While our approach appears different computationally, it produces identical results. However, in addition to circumventing some of the initial mapping, it allows the CAFE model to consider technologies that were not simulated as part of the Argonne project, and thus do not appear in the database. For example, reductions in a vehicle's accessory load produce small improvements in fuel economy, and are assumed to scale linearly with other technologies.

Additionally, the current approach required that we impose the structure of the decision tree, which describes a sequence in which technologies should be considered for application, in order to define incremental effectiveness. While the combinations simulated by Argonne did capture the exclusions represented by the decision tree (prohibiting variable valve lift on an engine that does not also have variable valve timing, for example), there is no innate structure to inform a sequential technology application process. For example, consider a vehicle in the analysis fleet that starts with a 5-speed automatic transmission. Present in the database are two points, each with an engine identical to the one in the analysis fleet under consideration, paired with a 6-speed automatic transmission and an 8-speed automatic transmission. Without imposing the decision tree structure on the incremental effectiveness values, the model would simply choose the more effective of those two combinations to implement (assuming the cost-effectiveness of the 8-speed is more attractive). While it might do this anyway, it is important that it consider the 6-speed first – doing so preserves the perspective of minimizing both the cost of compliance and the extent to which more advanced technologies penetrate the new vehicle market.

However, in order to translate the database of absolute fuel consumption values into some set of incremental improvements for each technology, it is necessary to define a reference point – the technology state (and fuel consumption) against which subsequent levels are measured to determine the level of improvement (specified as a percentage improvement in fuel consumption). *Incremental* effectiveness implies that the next technology provides some improvement in fuel economy over a previous technology state, *holding everything else constant*. This requires that we define a “reference vehicle” against which to compare increasing levels of technology.

For any given technology, there are many logical reference points. There a number of vehicles in the simulation database that are eligible to receive turbocharging and downsizing at the next technology application. However, as Figure 13.19 shows, there is a wide variety of power, fuel economy, and other technology content among them.

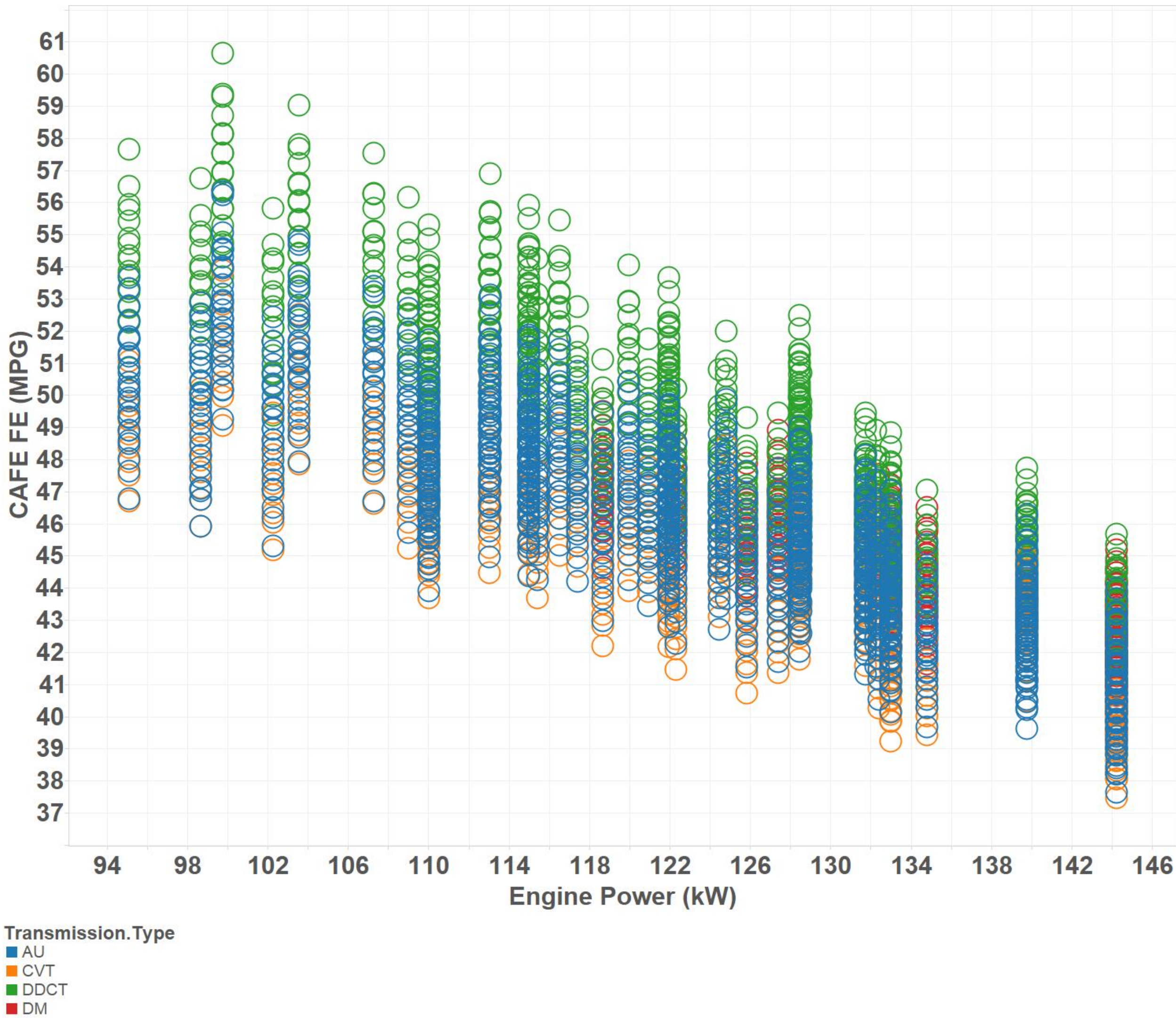

Figure 13.19 Midsize Vehicles in the Database Eligible to Receive TURBO1

Any of those points, with their variety of existing technology content, could be a logical reference point for the incremental improvement in fuel consumption that results from applying level 1 turbocharging. While the engines of the vehicles in Figure 13.19 all have similar levels of technology, there is a wide variety in other vehicle attributes: different transmissions (color coded by type), different levels of electrification, mass reduction, aerodynamic and rolling resistance improvements. While any of these points (of which there are over 2000) could serve as the reference point for TURBO1 improvement based on the interaction of the existing technologies with TURBO1, a better approach is to consider the technology tree holistically and define a series of reference points that are intuitive, and internally consistent.

Defining the reference point for incremental improvement

The technologies have always been considered as part of a tree, where a vehicle moves from one technology state to another in order of (generally) increasing complexity. While the engine technologies are (almost) all related to one another, there is no inherent connection between the engine technologies and technologies on other paths of the tree. For example, any of the transmissions can be combined with any of the engine technologies – so those can safely be considered separate paths. As Figure 13.20 shows, there are about 12 distinct paths that can be traversed by a vehicle to which the model applies technology. However, by combining logically sequential technologies into common paths, we are left with 6 distinct paths (which may have more than one branch where technologies are considered to be mutually exclusive).

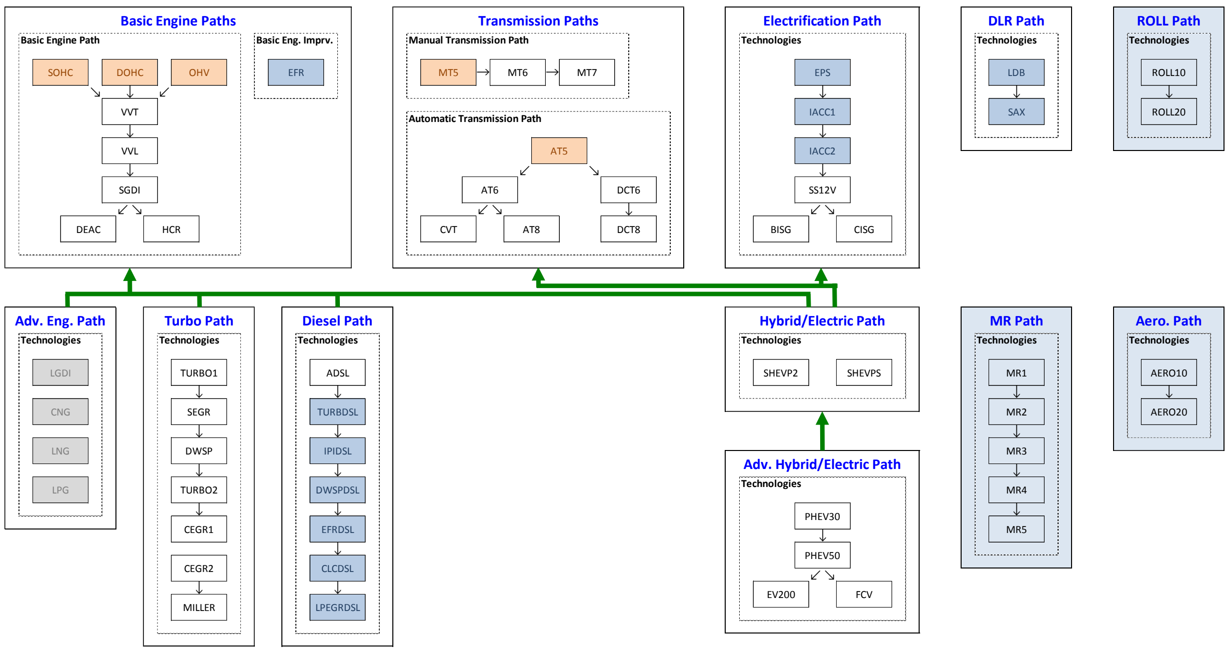

Figure 13.20 Technology Tree Used to Map Autonomie Simulations to Draft TAR Technology Set

Electrification technologies represent an exception to this general construction. While the stop/start technology is defined incrementally to the initial state across all paths, both of the integrated starter generator variants (belt, BISG, and crank, CISG) are defined relative to the 12V stop/start. The full hybrids are also different – with the power split hybrid (SHEVPS) defined relative to the crank-integrated starter generator (CISG), and the parallel hybrid (SHEVP2) defined relative to the belt-integrated starter generator (BISG). The 30-mile-range plug-in hybrid electric system is defined relative to the power split hybrid, and the subsequent electrification technologies follow the path described in the decision tree.

The "incremental effectiveness" values that appear in the model input files, and that are used in the fuel consumption calculations when new technology is added to a vehicle, are all based on incremental differences over a single reference point for each technology. However, progress along some technology paths is treated as linear (forcing consideration of 6-speed automatic transmission prior to considering application of CVT, for example), and along others as strictly sequential (mass reduction levels, for example, must logically be considered in order, since one cannot reduce the mass of a vehicle by 10 percent without first reducing it 5 percent). Thus, the reference point for each technology's incremental effectiveness estimate is the logical preceding technology along its path, and the null state along all other paths[7] – where the null state is defined as a vehicle with (only) variable valve timing (VVT), a 5-speed automatic transmission (AT5), no electrification, mass reduction, aerodynamic improvements, or low rolling resistance tires. For example, the reference engine for each class has only VVT. When considering the *incremental* impact of applying a 8-speed automatic transmission to a vehicle, the point of reference is the logical preceding technology on the transmission path (in this case, the 6-speed automatic transmission), and the base engine without any electrification, no mass reduction, and no improvements in aerodynamics or rolling resistance.

Translating the technology tree

In order to incorporate the results of the Argonne database, while still preserving the basic structure of the CAFE model's technology module, it was necessary to translate the points in the database into locations on the technology tree[8], shown in Figure 13.20. By recognizing that most of the paths on the technology tree are unrelated, or separable, it is possible to decompose the technology tree into a small number of paths and branches by technology type. To achieve this level of linearity, we define technology groups – only one of which is new. They are: engine cam configuration (CONFIG), engine technologies (ENG), transmission technologies (TRANS), electrification (ELEC), mass reduction levels (MR), aerodynamic improvements (AERO), and rolling resistance (ROLL). The combination of technology levels along each of these paths define a unique technology combination that corresponds to a single point in the database for each technology class. These technology state definitions are more important for defining synergies than for determining incremental effectiveness, but the paths are incorporated into both.

As an example, a technology combination with a SOHC engine, variable valve timing (only), a 6-speed automatic transmission, a belt-integrated starter generator, mass reduction (level 1), aerodynamic improvements (level 2), and rolling resistance (level 1) would be specified as SOHC;VVT;AT6;BISG;MR1;AERO2;ROLL1. By assigning each technology state a vector such as the one in the example, the CAFE model assigns each vehicle in the analysis fleet an initial state that corresponds to a point in the database. Next, the model determines a percentage improvement from the database for the new combination of technologies that is applied to each vehicle model and that percentage improvement is applied to the fuel consumption of that vehicle model in the analysis fleet.

Once a vehicle is assigned a technology state (one of the tens of thousands of unique 7-tuples, defined as CONFIG;ENG;TRANS;ELEC;MR;AERO;ROLL), adding a new technology to the vehicle simply represents progress from one technology state to another. The vehicle's fuel consumption is

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[7] There are a few exceptions to this general rule, where the decision tree merges after a fork. For example, power split strong hybrid is incremental to both the belt-integrated and crank-integrated starter generator (BISG and CISG), but is defined incrementally to the CISG. Similarly, TURBO1 is defined relative to cylinder deactivation (DEAC), even though it is incremental to both the high compression ratio engine (HCR) and DEAC. These instances are coded into the CAFE model, and accounted for in the technology effectiveness estimates and synergy factors.

[8] The technology tree was also modified to make some branches more sequential (or at least linear) and reduce the number of places where distinct branches converge.

$$FC_i = FC_0 \cdot (1 - FCI_i) \cdot S_k / S_0$$

Where: FC_i is the fuel consumption resulting from the application of technology i, FC_0 is the vehicle's fuel consumption before technology i is applied, FCI_i is the incremental fuel consumption (percentage) improvement associated with technology i, S_k is the synergy factor associated with the combination, k, of technologies the vehicle technology i is applied, and S_0 the synergy factor associated with the technology state that produced fuel consumption FC_0. The synergy factor is defined in a way that captures the incremental improvement of moving between points in the database, where each point is defined uniquely as a 7-tuple describing its cam configuration, highest engine technology, transmission, electrification type, mass reduction level, and level of aerodynamic or rolling resistance improvement.

Throughout successive application of technologies, the simple product of the incremental effectiveness associated with those technologies drifts away from the magnitude of the improvements determined by Autonomie, and represented in the database, since the simple product inadequately captures the interactions of those technologies. The synergy values correct for this. In the past, synergy values in the Volpe model were represented as pairs. However, the new values are 7-tuples and there is one for every point in the database. The synergy factors are based (entirely) on values in the Argonne database, producing one for each unique technology combination for each technology class, and are calculated as

$$S_k = \frac{FC_k}{FC_0 \cdot \prod(1 - x_i)}$$

Where: S_k is the synergy factor for technology combination k, FC_0 is the fuel consumption of the reference vehicle (in the database), x_i is the fuel consumption improvement of each technology i represented in technology combination k (where some technologies are present in combination k, and some are precedent technologies that were applied, incrementally, before reaching the current state on one of the paths).

Future direction

Integration of the database into the CAFE model resolves one of two important challenges - the combined impact of applying many new technologies simultaneously. Compared to past reliance on pairwise synergy factors, simulating all combinations explicitly provides a basis to more fully account for the overall impacts of combinations of multiple technologies. NHTSA will continue to consider means to address a second challenge, which is not new to the current approach, and that involves the application of simulation results for one vehicle to a much wider set of vehicles. Like past analyses, today's analysis assumes that improvements scale uniformly within a technology class. However, there are important differences between the range of vehicle power and mass in the MY2015 fleet compared to the range explicitly simulated by ANL, and these differences could impact the magnitude of fuel economy improvements that can be expected for the application of any particular technology combination. Volpe Center staff are exploring the potential to estimate a series of functions (given the current simulation database, likely over 3500 functions) that would control for the unique combination of technologies (e.g. a vehicle with VVT,VVL,SGDI, AT8, SS12V, and AERO10+ROLL10) when estimating the impact of vehicle mass and power on fuel economy. If successful, this effort could yield a set of estimated functions and fitted coefficients that can be used to estimate absolute fuel consumption associated with a given vehicle that has initial mass and engine power levels determined by the observed values in the analysis fleet.

NHTSA seeks comment on all of the above revisions to the model's approach to estimating the extent to which the addition of various combinations of technologies to specific vehicles could improve fuel economy, in particular on the approach to integrating the results of full vehicle simulation. The agency seeks information that could be used to further refine this aspect of the CAFE model and the supporting model inputs, as well as information that could be used to develop and implement any alternative approaches.

13.2.2 Overview and Technology Application

The CAFE model is the tool that NHTSA uses to simulate each manufacturer's decisions about how to comply with a given set of standards. The model is designed to accommodate standards with a variety of user-defined specifications regarding the slope of the curve that relates footprint to fuel economy by class, locations of the flat slope regions, and rates of increase over time that can vary by year and regulatory class. While the properties of technologies included in the analysis are specified by the user (e.g. fuel consumption improvement resulting from application, cost of the technology), the set of included technologies is part of the model itself, which contains the information about the relationships between technologies. In particular, the CAFE model contains the information about the sequence of technologies, the paths on which they reside, any prerequisites associated with a technology's application, and any exclusions that naturally follow once it is applied.

This section summarizes the representation of fuel saving technology in the CAFE model. Table 13.3 and Table 13.4 contain all of the technology assumed to be available for manufacturers in the Draft TAR analysis. The "application level" describes the system of the vehicle to which the technology is applied, which in turn determines the extent to which that decision affects other vehicles in a manufacturer's fleet. For example, if a technology is applied at the "engine" level, it naturally affects all other vehicles that share that same engine (though not until they themselves are redesigned, if it happens to be in a future model year). The application schedule identifies when manufacturers are assumed to be able to apply a given technology – with most available only during vehicle redesigns. The application schedule also accounts for which technologies the CAFE model tracks, but does not apply. These enter as part of the analysis fleet, and while they are necessary for accounting related to cost and incremental fuel economy improvement, they do not represent a choice that manufacturers make in the model.

Table 13.3 CAFE Model Technologies (1)

Technology	Application Level	Application Schedule	Description
SOHC	Engine	Baseline Only	Single Overhead Camshaft Engine
DOHC	Engine	Baseline Only	Double Overhead Camshaft Engine
OHV	Engine	Baseline Only	Overhead Valve Engine
TEFRI	Engine	Redesign Only	Engine Friction Reduction Improvements (time-based)
LUBEFR1	Engine	Refresh/Redesign	Improved Low Friction Lubricants and Engine Friction Reduction
LUBEFR2	Engine	Redesign Only	LUBEFR2, Level 2
LUBEFR3	Engine	Redesign Only	LUBEFR2, Level 3
VVT	Engine	Refresh/Redesign	Variable Valve Timing
VVL	Engine	Redesign Only	Variable Valve Lift
SGDI	Engine	Redesign Only	Stoichiometric Gasoline Direct Injection
DEAC	Engine	Redesign Only	Cylinder Deactivation
HCR	Engine	Redesign Only	High Compression Ratio Engine
HCRP	Engine	Redesign Only	High Compression Ratio "Plus" Engine
TURBO1	Engine	Redesign Only	Turbocharging and Downsizing, Level 1 (18 bar)
SEGR	Engine	Redesign Only	Stoichiometric Exhaust Gas Recirculation
DWSP	Engine	Redesign Only	Engine Downspeeding
TURBO2	Engine	Redesign Only	Turbocharging and Downsizing, Level 2 (24 bar)
CEGR1	Engine	Redesign Only	Cooled Exhaust Gas Recirculation, Level 1 (24 bar)
CEGR1P	Engine	Redesign Only	Cooled Exhaust Gas Recirculation, Level 1 "Plus" (24 bar)
CEGR2	Engine	Redesign Only	Cooled Exhaust Gas Recirculation, Level 2 (27 bar)
HCR2	Engine	Redesign Only	Advanced High Compression Ratio Engine
CNG	Engine	Baseline Only	Compressed Natural Gas Engine
ADSL	Engine	Redesign Only	Advanced Diesel
TURBODSL	Engine	Redesign Only	Improved Diesel Turbocharger
DWSPDSL	Engine	Redesign Only	Diesel Engine Downspeeding with Increased Boost
EFRDSL	Engine	Redesign Only	Diesel Engine Friction Reduction
CLCDSL	Engine	Redesign Only	Closed Loop Combustion Control
LPEGRDSL	Engine	Redesign Only	Low Pressure Exhaust Gas Recirculation
DSIZEDSL	Engine	Redesign Only	Diesel Engine Downsizing

As discussed in Chapter 4.2, the analysis fleet contains the information about each vehicle model, engine, and transmission selected for simulation and defines the initial technology state of the fleet relative to the sets of technologies in Table 13.3 and Table 13.4.

Table 13.4 CAFE Model Technologies (2)

Technology	Application Level	Application Schedule	Description
MT5	Transmission	Baseline Only	5-Speed Manual Transmission
MT6	Transmission	Redesign Only	6-Speed Manual Transmission
MT7	Transmission	Redesign Only	7-Speed Manual Transmission
TATI	Transmission	Refresh/Redesign	Automatic Transmission Improvements (time-based)
AT5	Transmission	Baseline Only	5-Speed Automatic Transmission
AT6	Transmission	Redesign Only	6-Speed Automatic Transmission
AT6P	Transmission	Redesign Only	6-Speed "Plus" Automatic Transmission
AT8	Transmission	Redesign Only	8-Speed Automatic Transmission
AT8P	Transmission	Redesign Only	8-Speed "Plus" Automatic Transmission
DCT6	Transmission	Redesign Only	6-Speed Dual Clutch Transmission
DCT8	Transmission	Redesign Only	8-Speed Dual Clutch Transmission
CVT	Transmission	Redesign Only	Continuously Variable Transmission
EPS	Vehicle	Refresh/Redesign	Electric Power Steering
IACC1	Vehicle	Refresh/Redesign	Improved Accessories - Level 1
IACC2	Vehicle	Refresh/Redesign	Improved Accessories - Level 2 (w/ Alternator Regen and 70% Efficient Alternator)
SS12V	Vehicle	Refresh/Redesign	12V Micro-Hybrid (Stop-Start)
BISG	Vehicle	Redesign Only	Belt Mounted Integrated Starter/Generator
CISG	Vehicle	Redesign Only	Crank Mounted Integrated Starter/Generator
SHEVP2	Vehicle	Redesign Only	P2 Strong Hybrid/Electric Vehicle
SHEVPS	Vehicle	Redesign Only	Power Split Strong Hybrid/Electric Vehicle
PHEV30	Vehicle	Redesign Only	30-mile Plug-In Hybrid/Electric Vehicle
PHEV50	Vehicle	Redesign Only	50-mile Plug-In Hybrid/Electric Vehicle
BEV200	Vehicle	Redesign Only	200-mile Electric Vehicle
FCV	Vehicle	Redesign Only	Fuel Cell Vehicle
LDB	Vehicle	Refresh/Redesign	Low Drag Brakes
SAX	Vehicle	Refresh/Redesign	Secondary Axle Disconnect
ROLL10	Vehicle	Refresh/Redesign	Low Rolling Resistance Tires, Level 1 (10% Reduction)
ROLL20	Vehicle	Refresh/Redesign	Low Rolling Resistance Tires, Level 2 (20% Reduction)
MR1	Platform	Refresh/Redesign	Mass Reduction, Level 1 (5% Reduction in Glider Weight)
MR2	Platform	Redesign Only	Mass Reduction, Level 2 (7.5% Reduction in Glider Weight)
MR3	Platform	Redesign Only	Mass Reduction, Level 3 (10% Reduction in Glider Weight)
MR4	Platform	Redesign Only	Mass Reduction, Level 4 (15% Reduction in Glider Weight)
MR5	Platform	Redesign Only	Mass Reduction, Level 5 (20% Reduction in Glider Weight)
AERO10	Platform	Refresh/Redesign	Aero Drag Reduction, Level 1 (10% Reduction)
AERO20	Platform	Redesign Only	Aero Drag Reduction, Level 2 (20% Reduction)

Vehicle technologies provide a set of possible improvements available for the vehicle fleet within the modeling system. The input assumptions for vehicle technologies, referred to below simply as “technologies,” are defined by the user in the technology input file for the model. As part of the technology definition, the input file includes: additional cost associated with application of the technology, an improvement factor (in terms of percent reduction of fuel consumption), initial year that the technology may be considered for application, whether it is applicable to a given class of vehicle, as well as other miscellaneous assumptions outlining additional technology characteristics.

The CAFE model defines several technology classes and pathways for logically grouping all available technologies for application on a vehicle. Technology classes provide costs and improvement factors shared by all vehicles with similar body styles, curb weights, footprints, and engine types, while technology pathways establish a logical progression of technologies on a vehicle.

The modeling system defines two types of technology classes: the vehicle technology classes and the engine technology classes. The system utilizes vehicle technology classes as a means for specifying common technology input assumptions for vehicles that share similar characteristics. Predominantly, these classes signify the degree of applicability of each of the available technologies to a specific class of vehicles, as well as determine the base improvement factors attributed to those technologies. Furthermore, for each technology, the vehicle technology classes also define the amount by which the vehicle's weight may decrease (resulting from application of mass reducing technology), and the additional cost associated with application of non-engine-level technologies. It is up to the user to assign each vehicle in the analysis fleet to one of these technology classes.

The model supports seven vehicle technology classes as shown in Table 13.5.

Table 13.5 Vehicle Technology Classes

Class	***Description***
SmallCar	*Small passenger cars*
MedCar	*Medium to large passenger cars*
SmallSUV	*Small sport utility vehicles and station wagons*
MedSUV	*Medium to large sport utility vehicles, minivans, and passenger vans*
Pickup	*Light duty pickups and other vehicles with ladder frame construction*
Truck 2b/3	*Class 2b and class 3 pickups*
Van 2b/3	*Class 2b and class 3 cargo vans*

Since the costs attributed to application of engine-level technologies vary based upon the engine configuration (such as number of engine cylinders or banks), the model defines separate engine classes for specifying input costs for these technologies. The modeling system provides sixteen engine technology classes as shown in Table 13.6. Once each vehicle is assigned a technology and engine class, the model uses these assignments to obtain the appropriate applicability, fuel economy improvement, and cost for each technology as appropriate for an individual vehicle.

Table 13.6 Engine Technology Classes

Class	Description
2C1B	SOHC/DOHC engine with 2 cylinders and 1 bank
3C1B	SOHC/DOHC engine with 3 cylinders and 1 bank
4C1B	SOHC/DOHC engine with 4 cylinders and 1 bank
4C2B	SOHC/DOHC engine with 4 cylinders and 2 banks
5C1B	SOHC/DOHC engine with 5 cylinders and 1 bank
6C1B	SOHC/DOHC engine with 6 cylinders and 1 bank
6C1B_ohv	OHV engine with 6 cylinders and 1 bank
6C2B	SOHC/DOHC engine with 6 cylinders and 2 banks
6C2B_ohv	OHV engine with 6 cylinders and 2 banks
8C2B	SOHC/DOHC engine with 8 cylinders and 2 banks
8C2B_ohv	OHV engine with 8 cylinders and 2 banks
10C2B	SOHC/DOHC engine with 10 cylinders and 2 banks
10C2B_ohv	OHV engine with 10 cylinders and 2 banks
12C2B	SOHC/DOHC engine with 12 cylinders and 2 banks
12C4B	SOHC/DOHC engine with 12 cylinders and 4 banks
16C4B	SOHC/DOHC engine with 16 cylinders and 4 banks

The modeling system defines technology pathways for grouping and establishing a logical progression of technologies on a vehicle. Each pathway (or, path) is evaluated independently and in parallel, with technologies on these paths being considered in sequential order. As the model traverses each path, the costs and improvement factors are accumulated on an incremental basis with relation to the preceding technology. The system stops examining a given path once a combination of one or more technologies results in a “best” technology solution for that path. After evaluating all paths, the model selects a most cost-effective solution among all pathways. This “parallel path” approach allows the modeling system to progress thorough technologies in any given pathway without being unnecessarily prevented from considering technologies in other paths.

Rather than rely on a specific set of technology combinations or packages, the model considers the universe of applicable technologies, dynamically identifying the most cost-effective combination of technologies for each manufacturer’s vehicle fleet based on the assumptions about each technology’s effectiveness, cost, and interaction with all other technologies both present and available.

The modeling system incorporates thirteen technology pathways for evaluation as shown in Table 13.7. Similar to individual technologies, each path carries an intrinsic application level that denotes the scope of applicability of all technologies present within that path, and whether the pathway is evaluated on one vehicle at a time, or on a collection of vehicles that share the same platform, engine, or transmission.

Table 13.7 Technology Pathways

Technology Pathway	Application Level
Basic Engine Path	Engine
Turbo Engine Path	Engine
Advanced Engine Path	Engine
Diesel Engine Path	Engine
Manual Transmission Path	Transmission
Automatic Transmission Path	Transmission
Electrification Path	Vehicle
Hybrid/Electric Path	Vehicle
Advanced Hybrid/Electric Path	Vehicle
Dynamic Load Reduction Path	Vehicle
Low Rolling Resistance Tires Path	Vehicle
Mass Reduction Path	Platform
Aerodynamic Improvements Path	Platform

The technologies that comprise the four Engine-Level paths available within the model are presented in Figure 13.21 below. Note that the baseline-level technologies (SOHC, DOHC, OHV, and CNG) are grayed out. As mentioned earlier, these technologies are used to inform the modeling system of the input engine’s configuration, and are not otherwise applicable during the analysis.

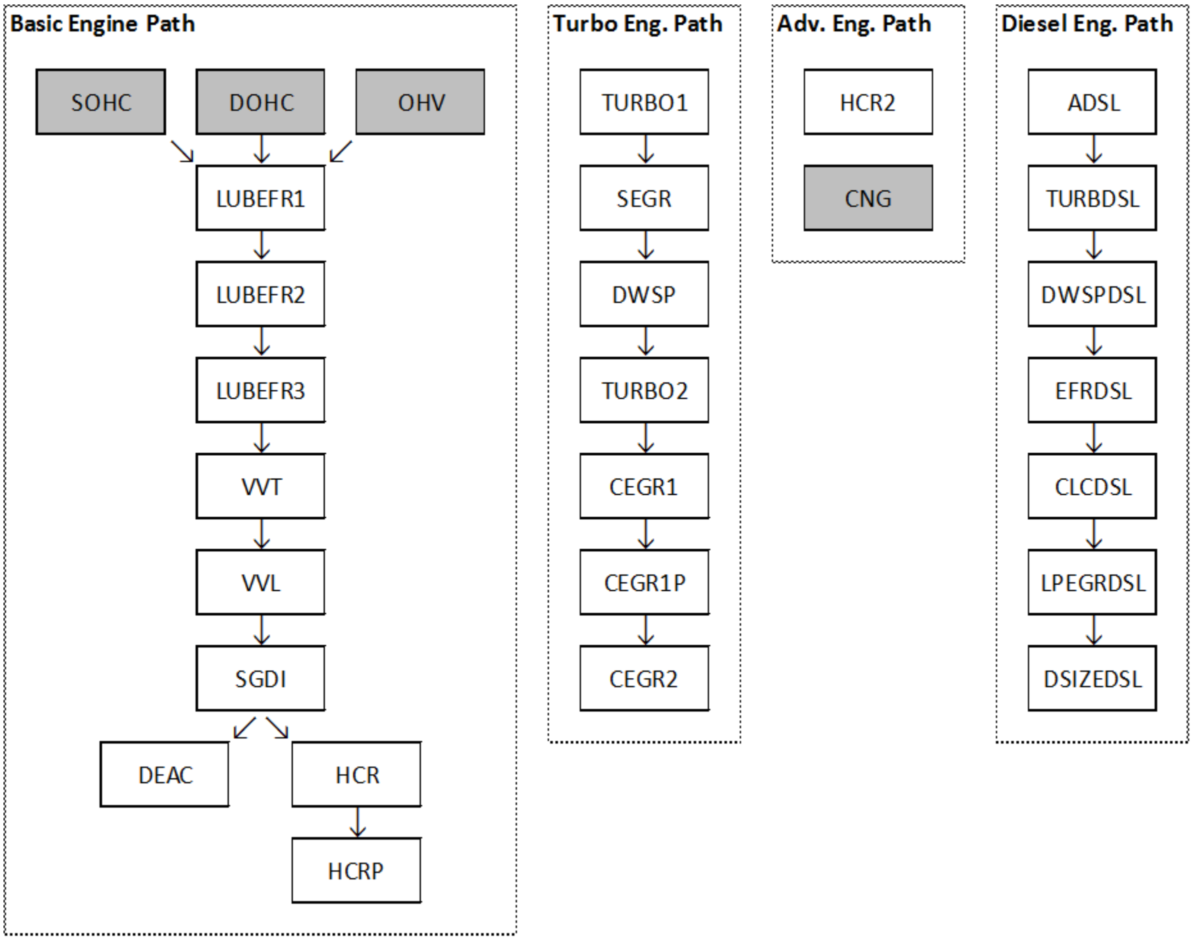

Figure 13.21 Engine-Level Paths

For all pathways, the technologies are evaluated and applied to a vehicle in sequential order, as shown, from top to bottom. In some cases, however, if a technology is deemed ineffective, the system will bypass it and skip ahead to the next technology. If the modeling system applies a technology that resides later in the pathway, it will “backfill” anything that was previously skipped in order to fully account for costs and improvement factors, each of which are specified on an incremental basis. For any technology that is already present on a vehicle (either from the input fleet or previously applied by the model), the system skips over those technologies as well and proceeds to the next. These skipped technologies, however, will not be applied again during backfill.

The Basic Engine path begins with SOHC, DOHC, and OHV technologies defining the initial configuration of the vehicle’s engine. Since these technologies are not available during modeling, the system evaluates this pathway starting with LUBEFR1 technology. Toward the end of the path, the model encounters a choice between DEAC and HCR technologies. Whenever a technology pathway forks into two or more branch points, all of the branches are treated as mutually exclusive. The system evaluates all technologies forming the branch simultaneously, and selects the most cost-effective for the application, while disabling the remaining paths not chosen. In the case of the Basic Engine path, that means if a vehicle continues with application of the DEAC technology, the HCR and HCRP technologies will be disabled. Likewise, if the vehicle applies the HCR technology, the HCRP technology will still be available for evaluation, while the DEAC technology will be disabled.

The technologies exposed by the Advanced Engine path (HCR2 and CNG) are not incremental over each other and do not follow a traditional progression logic present on other paths. Consequently, these technologies are treated as mutually exclusive within the model. Since CNG is a baseline-level technology, the only remaining choice for application within the Advanced Engine path is HCR2.

The technologies that make up the two Transmission-Level paths defined by the modeling system are shown in Figure 13.22 below. The baseline-level technologies (MT5 and AT5) are grayed and are only used to represent the initial configuration of the vehicle's transmission. For simplicity, all manual transmissions with five forward gears or fewer have been assigned the MT5 technology in the analysis fleet. Similarly, all automatic transmissions with five forward gears or fewer have been assigned the AT5 technology.

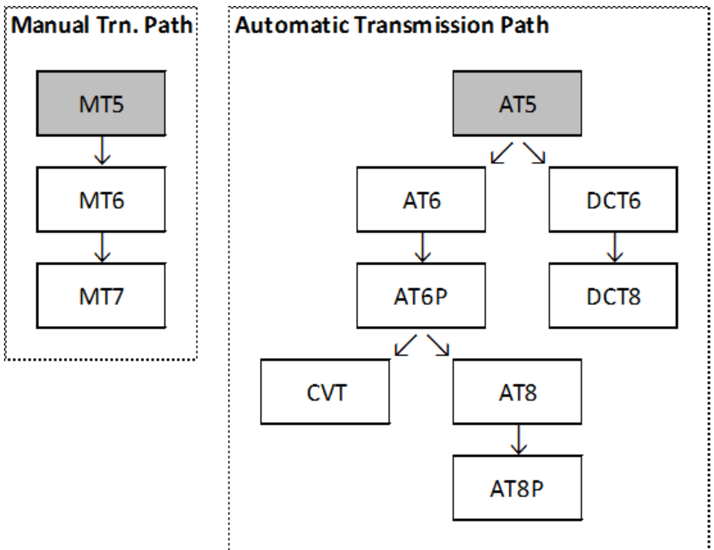

Figure 13.22 Transmission-Level Paths

Given the definition of incremental costs and fuel consumption improvement factors utilized during the analysis, the system assumes that all manual transmissions with seven or more gears are mapped to the MT7 technology. Moreover, the AT8 technology should map to all automatic transmissions with seven or more forward gears, DCT6 technology should map to all dual-clutch (DCT) or auto-manual (AMT) transmissions with five or six forward gears, and DCT8 technology should map to all DCT's or AMT's with seven or more forward gears. These transmission technology utilization assignments, however, are defined within the analysis fleet, and are not strictly enforced by the modeling system.

As mentioned earlier, the branch points shown in the Automatic Transmission path are mutually exclusive. For example, if a vehicle transitions to the DCT branch, the CVT and all automatic transmission technologies will become unavailable.

The technologies that compose the two Platform-Level paths provided by the model are displayed in Figure 13.23 below, and consist of mass reduction and aerodynamic improvements.

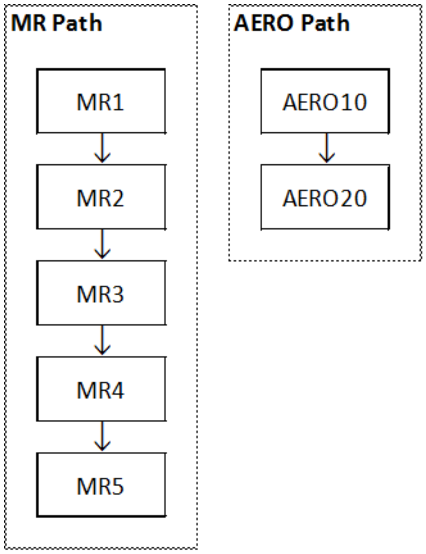

Figure 13.23 Platform-Level Paths

The technologies that constitute the two Vehicle-Level paths defined by the system are outlined in Figure 13.24 below.

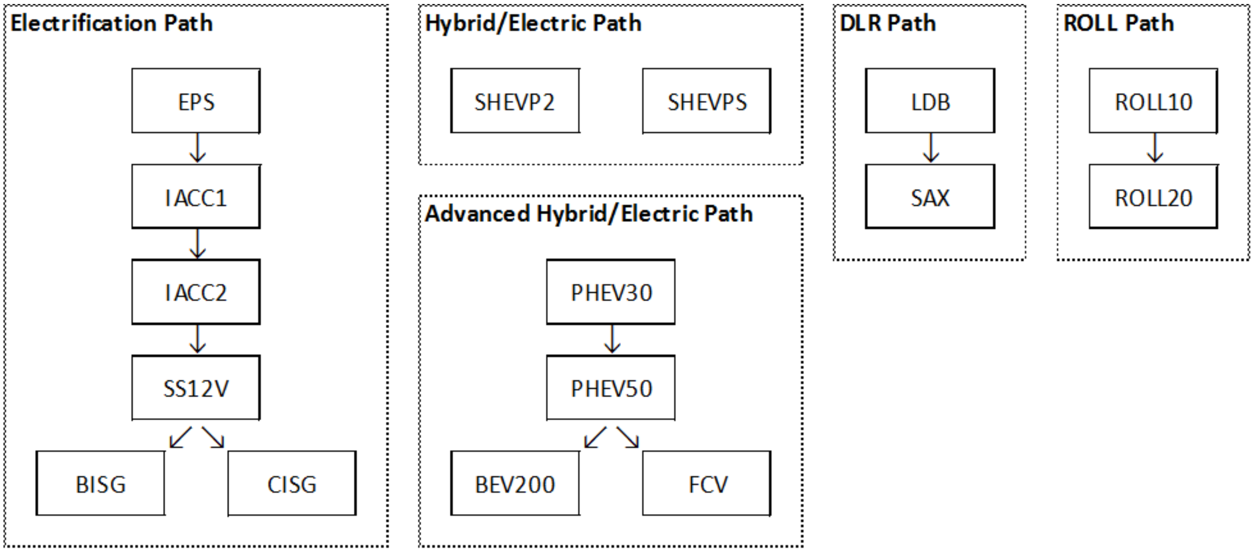

Figure 13.24 Vehicle-Level Paths

The technologies on the Hybrid/Electric path (SHEVP2 and SHEVPS) are defined as stand-alone and mutually exclusive. These technologies are not incremental over each other and do not follow a traditional progression logic present on other paths.

Even though the model evaluates each technology path independently, some of the pathways are interconnected to allow for additional logical progression and incremental accounting of technologies. For example, the SHEVPS (power-split strong hybrid/electric) technology on the Hybrid/Electric path is defined as incremental over the DEAC (cylinder deactivation) technology on the Basic Engine path, the AT5 (5-speed automatic) technology on the Automatic Transmission path, and the CISG (crank mounted integrated starter/generator) technology on the Electrification path. For that reason, whenever the system evaluates the SHEVPS technology for application on a vehicle, it ensures that, at a minimum, all the aforementioned technologies (as well as their predecessors) have already been applied on that vehicle. However, if it becomes necessary for a vehicle to progress to the power-split hybrid, the model will virtually apply the technologies associated with the reference point in order to evaluate the attractiveness of transitioning to the strong hybrid.

Of the thirteen technology pathways present in the model, all Engine paths, the Automatic Transmission path, the Electrification path, and both Hybrid/Electric paths are logically linked for incremental technology progression. This relationship between pathways is illustrated in Figure 13.25 below.

Some of the technology pathways, as defined in the CAFE model and shown in the diagram below, may not be compatible with a vehicle given its state at the time of evaluation. For example, a vehicle with a 6-speed automatic transmission will not be able to get improvements from a Manual Transmission path. For this reason, the system implements logic to explicitly disable certain paths whenever a constraining technology from another path is applied on a vehicle. On occasion, not all of the technologies present within a pathway may produce compatibility constraints with another path. In such a case, the system will selectively disable a conflicting pathway (or part of the pathway) as required by the incompatible technology.

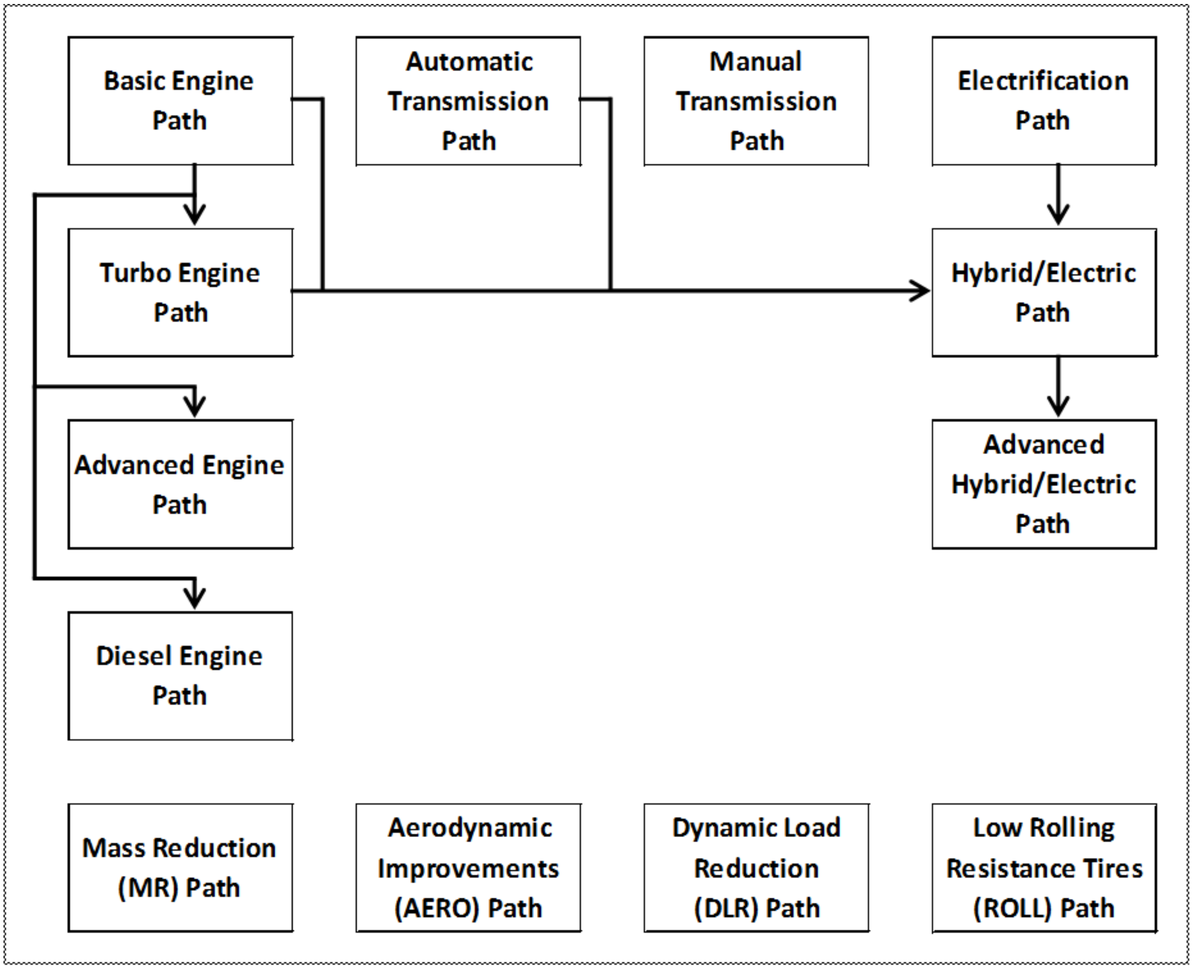

Figure 13.25 Technology Pathways Diagram

For any interlinked technology pathways shown in Figure 13.25 above, the system also disables all preceding technology paths whenever a vehicle transitions to a succeeding pathway. For example, if the model applies SHEVPS technology on a vehicle, the system disables the Turbo, Advanced, and Diesel Engine paths (as defined above), as well as the Basic Engine, the Automatic Transmission, and the Electrification paths (all of which precede the Hybrid/Electric path)[9]. This implicitly forces vehicles to always move in the direction of increasing technological sophistication each time they are reevaluated by the model.

[9] The only notable exception to this rule occurs whenever SHEVP2 technology is applied on a vehicle. This technology may be present in conjunction with any engine-level technology, and as such, the Basic Engine path is not disabled upon application of SHEVP2 technology, even though this pathway precedes the Hybrid/Electric path.

13.2.3 Simulating Manufacturer Compliance with Standards

In the U.S. market, the stringency of CAFE standards can influence the design of new vehicles offered for sale by requiring manufacturers to produce increasingly fuel efficient vehicles in order to meet program requirements. This is also true in the CAFE model simulation, where the standards can be defined with a great deal of flexibility to examine the impact of different program specifications on the auto industry. Standards are defined for each model year, and can represent different slopes that relate fuel economy to footprint (or work factor, in the case of medium-duty pickup trucks and vans), different regions of flat slopes, and different rates of increase for each of three regulatory classes covered by the CAFE program (passenger cars, light trucks, and medium-duty pickup trucks and vans).

As a starting point, the model needs enough information to represent each manufacturer covered by the program. The MY2015 analysis fleet contains information about each manufacturer's:

- Vehicle models offered for sale – their current (i.e., MY2015) and future production volumes, prices, fuel saving technology content (relative to the set of technologies described in Table 13.3 and Table 13.4 and other attributes (curb weight, drive type, assignment to technology class and regulatory class),
- Production constraints – product cadence of vehicle models (i.e., schedule of model redesigns and "freshening"), vehicle platform membership, degree of engine and/or transmission sharing (for each model variant) with other vehicles in the fleet,
- Compliance constraints and flexibilities – historical preference for full compliance or fine payment, willingness to apply additional cost-effective fuel saving technology in excess of CAFE requirements, projected applicable flexible fuel credits, and current CAFE credit balance in first model year of simulation.

Each manufacturer's CAFE requirement represents the harmonic average of their vehicle's sales-weighted targets. This means that no individual vehicle has a "standard," merely a target, and each manufacturer is free to identify a compliance strategy that makes the most sense given its unique combination of vehicle models, consumers, and competitive position in the various market segments. As the CAFE model provides flexibility when defining a set of CAFE standards, each manufacturer's requirement is dynamically defined based on the specification of the standards for any simulation.

In order to simulate a manufacturer's actions to bring its fleet into compliance with the standards, the CAFE model needs information about the context in which those decisions occur. In particular, the model requires:

- The universe of technologies that can be used to achieve compliance, as well as information about the logical progression among them, and any restrictions that occur when applying one, or more, or them (see Section 13.2.2),
- The cost of each technology and its fuel economy improvement, relative to a wide array of starting points that span not only the set of observed technology combinations in the MY2015 fleet, but also the set that will exist as the fleet evolves to achieve compliance with CAFE standards,

- The fuel prices that consumers will face when purchasing new vehicles, and the number of miles they expect to travel in those vehicles.

Given this information, the model estimates each manufacturer's potential year-by-year application of fuel-saving technologies to each engine, transmission, and vehicle. Subject to a range of engineering and planning-related constraints (e.g., secondary axle disconnects can't be applied to 2-wheel drive vehicles, many major technologies can only be applied practicably as part of a vehicle redesign, and applied technologies carry forward between model years), the model attempts to apply technology to each manufacturers' fleet in a manner that minimizes "effective costs."

The effective cost captures more than the incremental cost of a given technology – it represents the difference between their incremental cost and the value of fuel savings to a potential buyer over the first three years of ownership. This construction allows the model to choose technologies that both improve a manufacturer's CAFE compliance position and are most likely to be attractive to its consumers. This also means that different assumptions about future fuel prices will produce different rankings of technologies when the model evaluates available technologies for application. For example, in a high fuel price regime, an expensive but very efficient technology may look attractive to manufacturers because the value of the fuel savings is sufficiently high to both counteract the higher cost of the technology and, implicitly, satisfy consumer demand to balance price increases with reductions in operating cost. The model continues to add technology until a manufacturer either: (a) reaches compliance with CAFE standards (possibly through the accumulation and application of CAFE credits), (b) reaches a point at which it is more cost effective to pay fines than to add more technology, or (c) reaches a point beyond compliance where the manufacturer assumes its consumers will be unwilling to pay for additional fuel saving technologies (specified as a desired "payback period," assumed to be one year for all manufacturers in this analysis.

A graphical depiction of the compliance simulation loop appears in Figure 13.26, below. Having determined the applicability of each technology to each vehicle model, platform, engine, and transmission, the compliance simulation algorithm begins the process of applying technologies based on the CAFE standards applicable during the current model year. This involves repeatedly evaluating the degree of noncompliance, identifying the next "best" technology (ranked by the effective cost discussed above) available on each of the parallel technology paths described in Chapter 5, and applying the best of these. The algorithm combines some of the pathways, evaluating them sequentially instead of in parallel, in order to ensure appropriate incremental progression of technologies.

The algorithm first finds the best next applicable technology in each of the technology pathways, then selects the best among these. If a manufacturer is assumed to be unwilling to pay CAFE civil penalties, then the algorithm applies the technology to the affected vehicles. Afterwards, the algorithm reevaluates the manufacturer's degree of noncompliance and continues application of technology. Once a manufacturer reaches compliance (i.e., the manufacturer would no longer need to pay CAFE civil penalties), the algorithm proceeds to apply any additional technology determined to be cost-effective (as discussed above). Conversely, if a manufacturer is assumed to prefer to pay CAFE civil penalties, the algorithm only applies technology up to the point where doing so is less costly than paying fines. The algorithm stops applying additional technology to this manufacturer's products once no more cost-effective solutions are encountered. This process is repeated for each manufacturer present in the input fleet. It is then repeated again for each modeling year. Once all modeling years have been processed, the compliance simulation algorithm concludes.

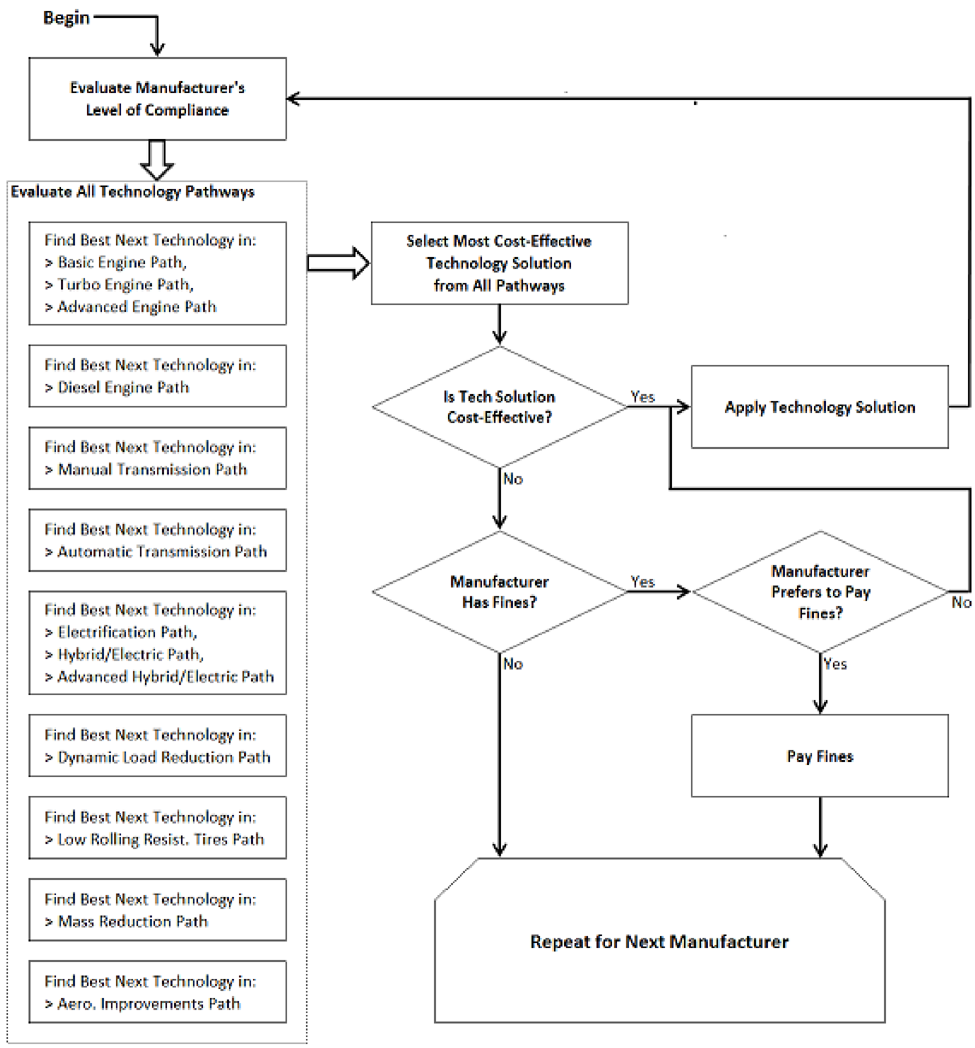

Figure 13.26 Compliance Simulation Diagram

Engine, transmission, and platform sharing represent constraints to a manufacturer as it attempts to modify its product lines in ways that achieve CAFE requirements. The combination of shared components and product cadence can create challenges for manufacturers in any given year, and strongly influence both the pace and extent of new fuel saving technology application. For example, Ford produces approximately 1,000 different model variants across the passenger car, light truck, and medium-duty pickup/van regulatory classes (though more than 800 of these are differently configured medium-duty pickup trucks and vans). However, all of these models are powered by only about 25 different engines. Even ignoring all of the class 2b3 trucks, the ratio of model variants to unique engines is about 10:1. So when Ford changes an engine on one of its vehicles to improve its fleet fuel economy for CAFE, the changes to that engine appear on an average of 10 other vehicles as well. Multi-year planning horizons in the CAFE model account for this nuance, and represent the fact that building a fleet of vehicles for compliance is different than modifying a single vehicle to exceed its fuel consumption target. Underlying the compliance simulation loop in Figure 13.26 is the selection of the “next best” technology within each path. In the new version of the CAFE model, “next best” incorporates both the product cadence and component sharing discussed in this chapter.

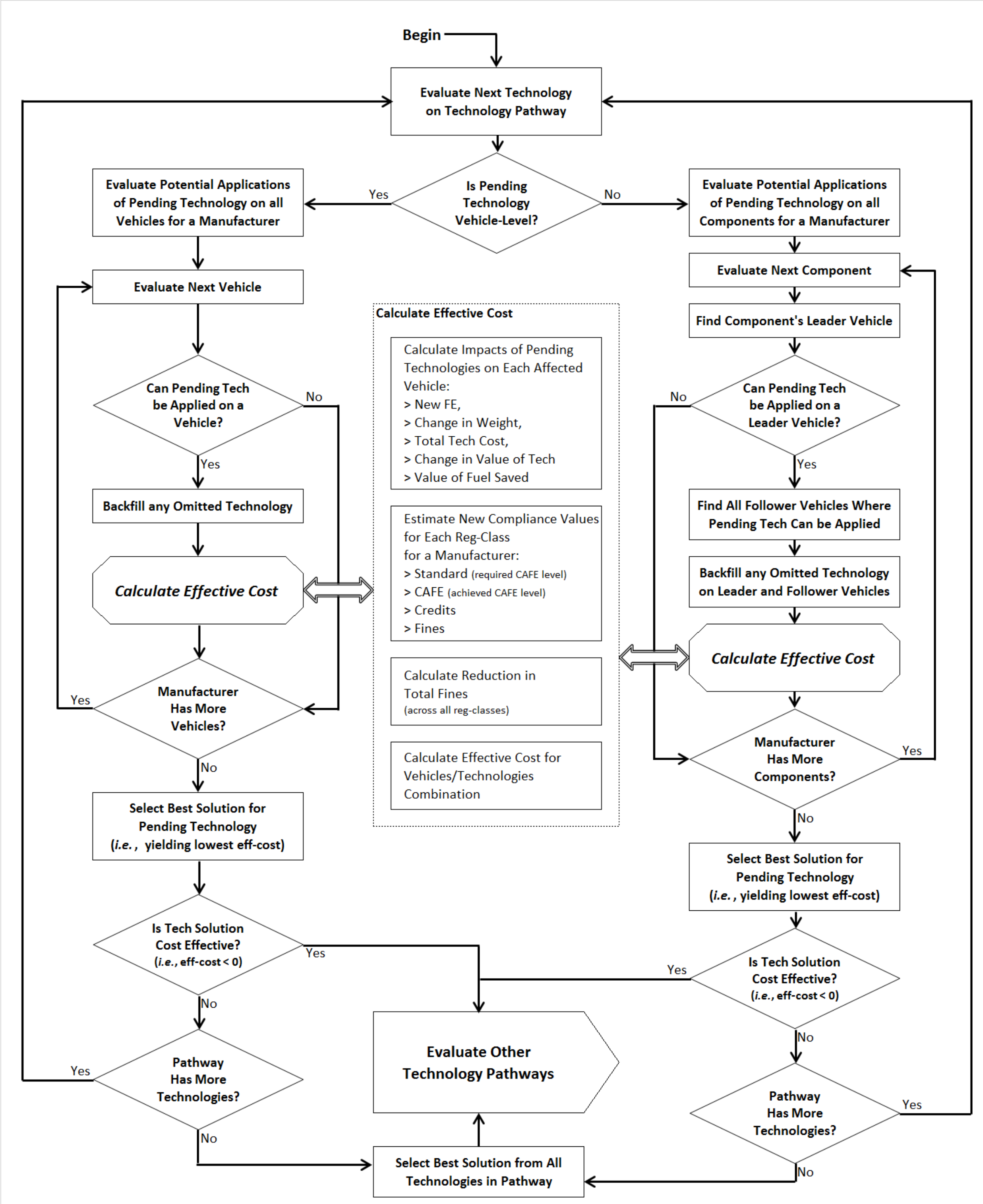

Figure 13.27 Selection of "Next Best" Technology within CAFE Compliance Simulation

Figure 13.27 illustrates the logic employed by the model when choosing the “next best” technology when simulating compliance for a manufacturer. Note, in the diagram above, a “component” is any platform, engine, or transmission produced by a manufacturer, where application of a technology is evaluated on a vehicle designated as a leader of that component. The model chooses a “leader” for each shared component – engine, transmission, platform – based on existing technology level, sales volume, and MSRP. New technologies (e.g., upgrades to engines) are first made on the component leader when it is redesigned. Because other vehicle models that share the same engine as the leader are likely to be redesigned at different model years, they will inherit the new component (e.g., a new engine) only when they are redesigned. However, the leader drives technology application. When a “follower” (who shares that component, but is not designated as the leader) is redesigned, it may not change the shared component in ways that differ from the implementation that exists on the leader in that year. The model accounts for this sharing among component explicitly. When selecting technologies to add to a component leader, any follower vehicles of the same component that are redesigned at the same time as the leader, will also be evaluated during technology application. Conversely, since vehicle-level technologies affect only one vehicle at a time, all technology improvements are applied immediately to just the one vehicle model during its refresh or redesign year.

When the model steps forward to a new model year, all vehicles that are scheduled to be redesigned in that year inherit the most current level of any shared components. For example, if vehicle A and vehicle B share an engine, where vehicle A is the leader, vehicle B will inherit the same engine that vehicle A has when it is redesigned before considering additional technology application. It is possible that a vehicle model can be the leader on one component and a follower on another. This means that when that vehicle is redesigned, it first inherits the current state of all technology components on which it is a follower, before making any improvements to components on which it is the leader. These restrictions help to preserve the size of the initial set of engines, transmissions, and platforms that are observable in the MY2015 fleet. The approach does not generate unique engines for each variant, based on NHTSA’s analysis of observed trends for managing platform and powertrain complexity given resource and cost considerations.

As shown in the figures above, the CAFE model considers each technology path separately within each analysis step – virtually applying each of the best technologies in each discrete path and choosing among them. Because this is an iterative process, for any vehicle in any single model year, the CAFE model dynamically constructs a package of technologies to improve its fuel economy, rather than choosing a package from a pre-defined set. The integration of the Argonne simulation study means that for each technology class, the full vehicle simulation results for over 20 thousand unique technology combinations are available to the CAFE model in this evaluation. Many of these combinations will not be cost-effective for a given vehicle’s starting technology state each time it is evaluated, but considering them allows the model to avoid applying new technology in manner that ignores the existing technology preferences specific manufacturers have exhibited in the MY2015 fleet.

The CAFE model also simulates compliance on a yearly basis, over the entire period – making choices in any given year with an eye toward compliance in future years. While the compliance simulation loop is accurately described in Figure 13.26, the first step in the process, “Evaluate Manufacturer’s Level of Compliance,” is more nuanced that the figure suggests. The first step in the evaluation is the application of expiring credits – any CAFE credits carried forward from earlier model years that will expire in the model year under consideration are applied to the manufacturer’s CAFE level. Then all of the models redesigned in that year inherit the most current versions of shared engines, transmissions, and platforms if they are eligible to do so. The CAFE model also considers the application of older, but not yet expiring, credits if the opportunities for technology application in a given model year are limited. In this way, a manufacturer need not apply enough technology in any given model year to exactly comply with the CAFE standard for that year. Instead, the CAFE model allows manufacturers to apply technology more aggressively when opportunities exist in order to generate enough credits to comply with standards when opportunities for technology application are more limited. The CAFE model represents all of the credits that manufacturers currently hold (and their expiration dates) when the simulation begins. The fact that the existing credit balances are significant (and expected to be necessary for some manufacturers to comply with standards in the short-term) suggests that capturing this behavior in the CAFE model is important.

The following example demonstrates how manufacturer choices with respect to product cadence may lead to blocky improvements in fleet fuel economy, generating credits in some years that can then be applied in future years. Figure 13.28 shows the compliance pathway simulated for FCA under both the final CAFE standards through MY2021 and the Augural Standards through MY2025 (and assumed to remain constant after MY2025). Figure 13.3 showed the product cadence assumed for each manufacturer in this analysis. As that figure shows, FCA has a number of model years where relatively little of their total sales volume is expected to be redesigned and several years where 20 percent or more of their total volume is expected to be redesigned. As Figure 13.28 shows, the years with the highest increases in CAFE, MY2018 and MY2020, correspond to years with high degrees of redesigns. However, the figure also shows that FCA is simulated to exceed the standard in MY2018 for light trucks and MY2020 for passenger cars by a large amount. Due to limited credit trading between passenger car and light trucks fleets, it would be necessary for FCA to increase both fleets in order to avoid paying fines (rather than simply relying on the over compliance in one or the other overcome shortfalls). While FCA exceeds the standard for a number of years, generating credits which it then carries forward, it also falls short of compliance around MYs 2022 – 2024, when it applies the earned credits from previous years to account for the shortfall.

As discussed above, these results provide an estimate, based on analysis inputs, of one way FCA could add fuel-saving technologies to its products, and are not a prediction of what FCA will do under these standards.

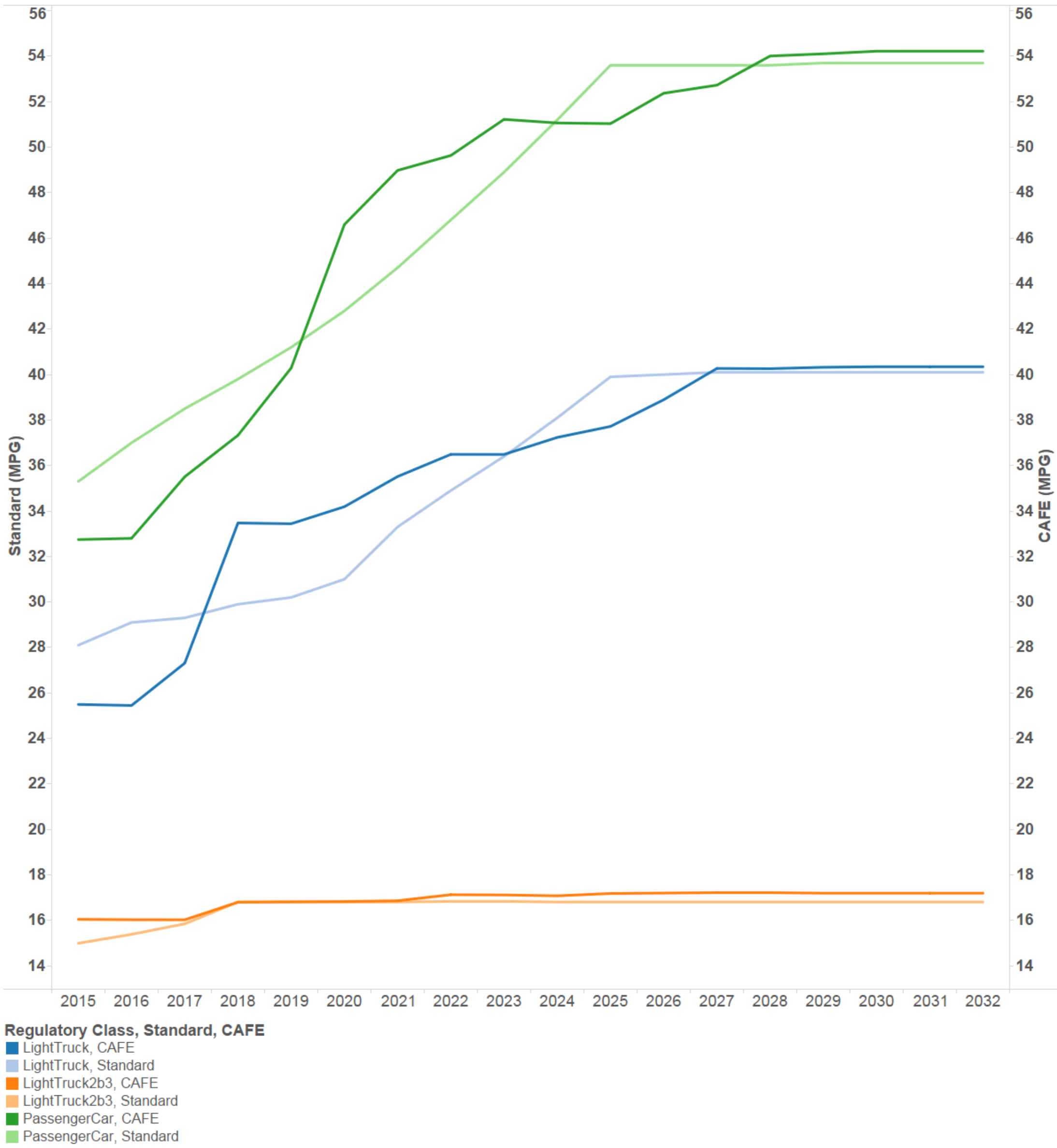

Figure 13.28 FCA Compliance Example

13.2.4 Simulating the Economic and Environmental Effects of CAFE Standards

In addition to simulating compliance with CAFE standards, the CAFE model also estimates the economic and environmental impacts associated with the changes to the vehicle fleet that are estimated to occur as a result of the standards. To this, the model requires information about the economic and environmental impacts of fuel consumption and travel. In particular, it requires information about:

- All of the information related to travel demand and energy prices that influence compliance simulation also influence effects calculations,
- The fuel economy rebound effect (the extent to which reductions in operating cost increase demand for miles traveled),
- The value of refueling time saved by consumers who have to refuel more efficient vehicles less often,
- Functions that determine the safety impacts of increased travel and vehicle mass reduction,
- The social costs of increases in the amount of congestion and noise (from additional travel demand) and the number of crashes and fatalities,
- The social cost of dependence on oil and the social cost of carbon emissions,
- Tailpipe and upstream emission factors, fuel density and carbon content associated with a variety of fuels.

Having estimated the extent to which each manufacturer might add fuel-saving technologies under each specified regulatory alternative, the model calculates a range of physical impacts, such as changes in highway travel (i.e., VMT), changes in fleetwide fuel consumption, changes in highway fatalities, and changes in vehicular and upstream greenhouse gas and criteria pollutant emissions. The model then uses the information supplied about economic and environmental values to calculate economic costs and benefits to vehicle owners and society, based on these physical impacts. The CAFE model calculates these changes and economic impacts for each scenario, producing differences relative to a no-action case. The values assigned to all of the required environmental and economic inputs can be downloaded from NHTSA's website.

13.3 Simulation Results for Augural MY2022 – 2025 Standards

In the results that follow, NHTSA considered the impact of implementing the Augural Standards described in the 2012 Final Rule for MYs 2022 – 2025 relative to the current final standards through MY2021 as the reference point. NHTSA uses the CAFE model to evolve the analysis fleet in order reach the point where the Augural Standards begin in MY2022. It does this by simulating manufacturers' compliance decisions in response to the standards, discussed in greater detail below.

EPCA/EISA constrains how NHTSA conducts its analysis in order to inform the actual determination of the maximum feasible stringency of CAFE standards. For example, the statute requires NHTSA to set aside EPCA/EISA's CAFE credit carry-forward provisions from such analysis. In recent CAFE rulemakings, NHTSA has included both a "standard setting" analysis and a "real world" analysis, with the latter accounting for some of these factors, as practicable. This draft TAR is not a rulemaking document to inform actual decisions regarding the maximum feasible stringency of future CAFE standards; therefore, today's analysis is all conducted on a "real world" basis. The analysis accounts for the potential that manufacturers, as allowed by EPCA/EISA, could transfer CAFE credits between the passenger car and light truck fleet, or carry CAFE credits forward for later use. Except for CAFE credits earned prior to MY2015, today's analysis does not account for the potential that manufacturers could trade CAFE credits.

Today's analysis also does not attempt to simulate the potential that manufacturers could carry CAFE credits back from future model years.

Like both recent "standard setting" and "real world" analyses, today's analysis also accounts for the potential that some manufacturers might, as allowed by EPCA/EISA, elect to pay civil penalties if doing so would likely be less expensive than applying additional fuel-saving technology (accounting for technology costs and avoided fuel expenditures). Recent legislation requires the civil penalty rate be increased from the current level of $5.50 per 0.1 mpg per vehicle to a considerably higher level of $14 per 0.1 mpg per vehicle, and today's analysis uses the updated rate.[10]

As discussed in Chapter 4, today's analysis includes PHEVs and EVs estimated to be produced after MY2015. Today's analysis also allows that manufacturers may elect to produce additional PHEVs or EVs in response to new CAFE standards; however, as shown below, compared to other technologies, PHEVs and EVs are not estimated to be cost-effective responses to the augural CAFE standards (i.e., the CAFE model identifies more cost-effective solutions than building additional PHEVs or EVs). Had it included more PHEVs or EVs either in the analysis fleet or as a forced additional application of technology, today's analysis would have shown lower application rates for some other technologies (e.g., full HEVs) in the results shown below.

Some of the aspects of today's analysis, such as the change in the civil penalty rate, are considerably different from those in NHTSA's 2012 analysis supporting the final rule for MYs 2017-2021. Together with other improvements and updates to data and methods, these combine to produce updated results from those presented in 2012. Especially with a view toward understanding incremental impacts, today's analysis evaluates the potential response to the existing standards in place through MY2021, referred to here as the "No Action Alternative." Defining the No Action Alternative aids understanding of changes in inputs and methods, and provides a proper point of reference for understanding the estimated impacts of the Augural Standards. NHTSA is not considering changes to the already-final CAFE standards through MY2021.

13.3.1 Industry Impacts

The footprint-based CAFE standards finalized in 2012 will require manufacturers to improve the average fuel economy of their fleets between now and MY2021. In the baseline case, the standards are assumed to remain constant at the MY 2021 level indefinitely. The analysis in this report compares this baseline case with the augural CAFE standards for MY2022 – MY2025.

[10] As a result of the Federal Civil Penalties Inflation Adjustment and Improvement Act of 2015 (Pub. L. 114-74), Section 701, and OMB guidance from February 2016 on how agencies should implement that Act, NHTSA is required to increase the $5-per-tenth-of-an-mpg civil penalty. NHTSA will publish our proposal to implement that increase in a forthcoming Federal Register notice; for purposes of the current analysis, we have used $14-per-tenth-of-an-mpg, which is consistent with the OMB guidance.

Table 13.8, below, summarizes the actual CAFE requirement for each manufacturer in MY2015 (based on the MY2015 analysis fleet, described in Chapter 4.2); the estimated CAFE requirement in MY2021 through which CAFE standards are final; and the estimated CAFE requirement in MY2030, when NHTSA modeling indicates that the Augural Standards would produce a fully stable fleet. The Augural Standards are assumed to remain constant at the MY 2025 level through MY 2030. Due to credit carry-forward, trading between fleets, and product cadence considerations, NHTSA estimates that some manufacturers will be taking actions to reach compliance with MY2025 standards for several model years thereafter. Table 13.8 indicates that, between MY2015 and MY2030, manufacturers as a group will be required to increase required vehicle fuel economy levels by more than 50 percent for passenger cars and 40 percent for light trucks. As in previous analyses, NHTSA's analysis assumes that manufacturers who have consistently chosen to pay CAFE fines in the past may continue to do so. However, this analysis also assumes an increase in NHTSA's CAFE non-compliance fine rate from $55 per MPG under the required level per vehicle sold to $140 per MPG. As a result, the modeling indicates that many fine-paying manufacturers will respond more aggressively to CAFE requirements than in previous analyses.

Table 13.8 Expected Manufacturer Standards and Expected CAFE levels with Augural Standards through MY2030

Manufacturer	Regulatory Class	2015		2021		2030	
		Standard	CAFE	Standard	CAFE	Standard	CAFE
BMW	Passenger Car	35.5	33.9	44.8	39.0	54.0	48.5
	Light Truck	29.0	29.3	35.0	32.7	42.1	42.1
Daimler	Passenger Car	34.8	33.6	43.8	41.1	52.6	50.8
	Light Truck	29.1	26.9	35.1	33.0	42.3	42.2
FCA	Passenger Car	35.3	32.7	44.7	49.0	53.7	54.2
	Light Truck	28.1	25.5	33.3	35.5	40.1	40.3
Ford	Passenger Car	35.6	35.0	45.0	49.1	54.0	56.7
	Light Truck	26.5	25.5	30.1	33.9	36.3	37.4
General Motors	Passenger Car	35.6	33.5	45.2	49.0	54.4	54.6
	Light Truck	26.0	24.5	29.9	31.8	36.0	36.0
Honda	Passenger Car	36.8	41.3	46.4	44.0	56.0	58.1
	Light Truck	29.4	31.8	36.1	36.0	43.2	43.8
Hyundai Kia	Passenger Car	35.9	35.5	45.5	46.6	54.7	55.9
	Light Truck	29.3	27.7	36.3	36.9	43.7	43.7
JLR	Passenger Car	33.9	26.8	42.3	32.1	50.7	35.0
	Light Truck	29.1	25.2	35.0	31.0	42.2	41.2
Mazda	Passenger Car	36.1	42.4	45.8	46.1	55.1	55.4
	Light Truck	30.4	31.8	36.9	36.1	44.5	44.8
Mitsubishi	Passenger Car	38.7	41.7	48.9	51.3	59.0	63.3
	Light Truck	31.9	35.2	39.5	44.6	47.6	55.0
Nissan	Passenger Car	36.3	41.4	45.8	49.1	55.0	57.3
	Light Truck	28.9	29.0	34.6	37.5	41.7	42.1
Subaru	Passenger Car	37.3	38.8	46.9	52.1	56.4	57.5
	Light Truck	31.4	37.2	39.0	46.6	47.1	47.4
Toyota	Passenger Car	36.4	40.3	46.0	48.1	55.3	56.4
	Light Truck	28.5	26.1	33.6	36.8	40.5	40.6
Volvo	Passenger Car	35.3	35.6	44.5	41.9	53.5	48.4
	Light Truck	30.1	26.6	36.6	33.2	44.0	33.4
VWA	Passenger Car	36.8	36.5	46.7	40.6	56.1	51.8
	Light Truck	29.3	27.7	35.7	32.0	43.2	38.2
TOTAL	Passenger Car	36.0	37.1	45.5	47.1	54.8	55.8
	Light Truck	27.8	26.5	32.9	35.1	39.6	39.9

As Table 13.8 shows, among those manufacturers assumed willing to pay civil penalties as allowed under EPCA/EISA, a few (e.g., JLR, Volvo) could find that option attractive enough to fall well short of one or both standards by MY2030. However, also by MY2030, all manufacturers assumed to be averse to paying CAFE fines (e.g., Ford, GM, and FCA) are estimated to be able to reach compliance without the use of credits. Among those manufacturers, several exceed the standard as fuel savings technologies applied in earlier years propagate through shared components across platforms (discussed in greater detail in Section 13.3).

In NHTSA's modeling, manufacturer's fleets evolve from a starting point, which is generally defined as a description, including number of vehicles sold, fuel economy, weight, footprint, engine and transmission type, and aerodynamic drag, of each "model" built by each manufacturer in some recent historical model year. In the 2012 FRM, the starting point was the MY 2010 fleet. In this analysis, the starting point has been updated to the MY2015 fleet. Figure 13.29 shows the required and achieved CAFE levels for the MY2025 fleet simulated from the MY2010 analysis fleet in the 2012 FRM and the MY2025 fleet simulated from the MY2015 fleet in the current analysis. Total industry average CAFE level and standard are lower using the MY2015 fleet in the current analysis than they were using the MY2010 fleet in the FRM, largely attributable to the shifts in sales between light trucks and passenger cars, described earlier in this chapter. Both simulations show manufacturers achieving CAFE levels close to the requirements, albeit generally closer for the passenger cars than the light trucks.

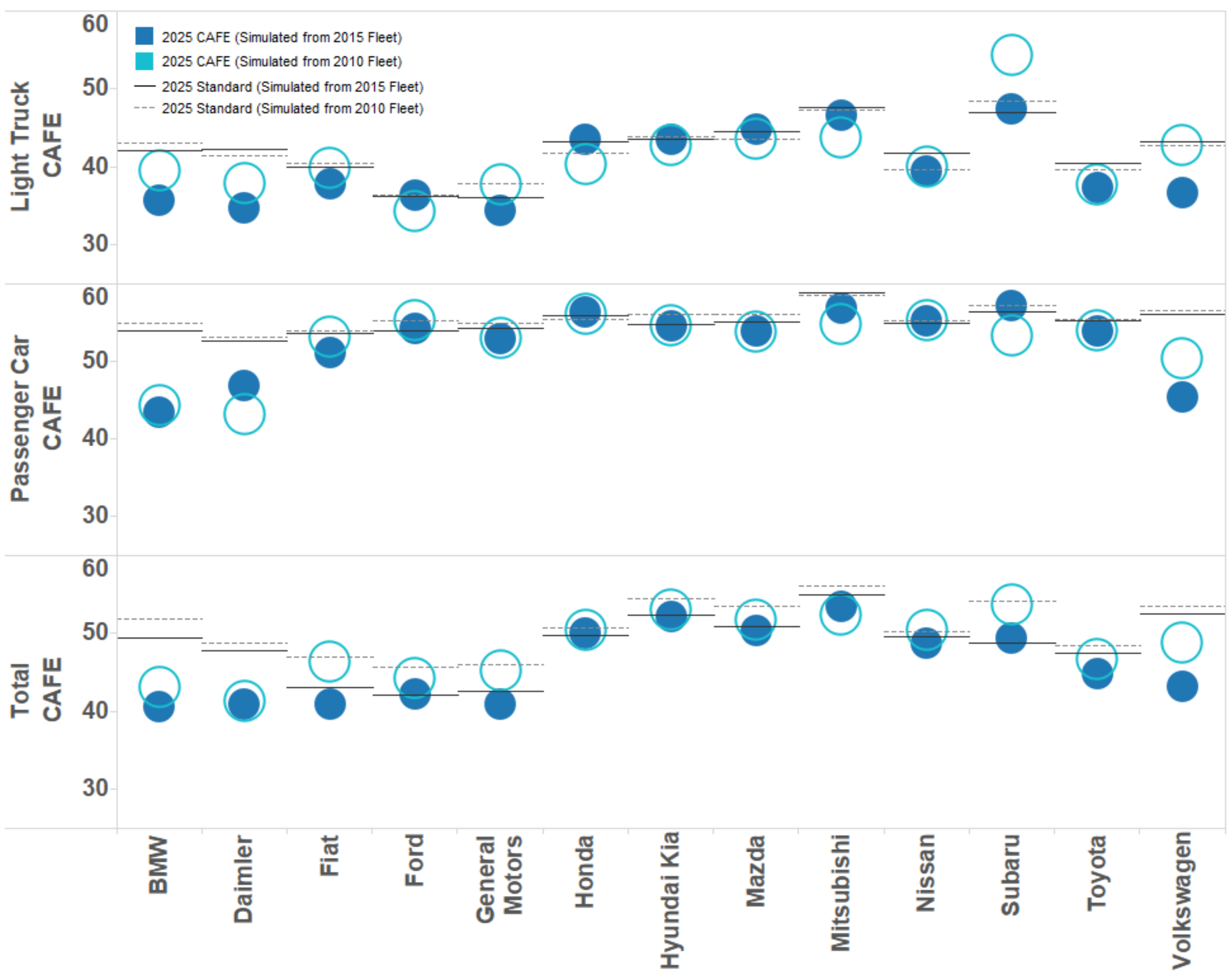

Figure 13.29 CAFE and Standard from 2010 Fleet Simulations vs. 2015 Observed Fleet (miles per gallon)

Technology penetration rates for passenger cars and light trucks

The analysis that follows explains how the CAFE model projects manufacturers could reach Augural Standards for both passenger cars and light trucks. This analysis simulates the application of fuel efficiency improving technologies, however does not change vehicle footprint or mix as a compliance strategy. The analysis is not intended to be a prediction of how any given manufacturer will actually respond to CAFE requirements, but represents a low cost technology solution in the context of the assumptions made in this analysis. Figure 13.30 through Figure 13.33 show passenger car technology penetration rates for engine, transmission, electrification, and load reduction technologies, respectively.

Figure 13.34 through present comparable analysis for light trucks. The green values in the tables show that reliance upon a given technology is modeled at less than 50 percent of the sales volume for a manufacturer, and the red values highlight progressively higher dependence upon a technology within the market. As the tables illustrate, different manufacturers apply different sets of technologies to raise CAFE levels and achieve compliance with the standards.

In each table, technology complexity generally increases moving left to right, though each group of technologies has interdependencies and mutually exclusive choices so this progression of complexity is not always strictly increasing. For example, the DCT8 appears at the far right of the transmission table (after the DCT6), but may be less complex than the CVT. However, the CAFE model's logic progresses to CVTs along the automatic transmission path and models that start as DCTs remain DCTs. The ranking merely reflects this progression.

As Figure 13.30 shows, manufacturers across the industry are projected to deploy most of the lower complexity engine technologies (e.g.,variable valve timing and lift, direct injection) at levels approaching 100 percent for most manufacturers by MY2030. However, after deploying all of these engine technologies, manufacturers choose different levels of turbocharging technology. At the industry level, the penetration rate of level 1 turbocharging (TURBO1) drops over time as the rates of level 2 turbocharging (TURBO2) and cooled EGR both steadily increase. This trend is observable for individual manufacturers as well, though most pronounced among the primarily European manufacturers (and Ford) that already rely on TURBO1 to a significant degree in MY2015. Some of these manufacturers continue along the engine path to cooled EGR, though only VWA relies on advanced diesel engines to any meaningful degree, and at a level that is projected to decrease over time.

Figure 13.30 Passenger Car Engine Technology Penetration Rates By Manufacturer (sales weighted share of fleet)

OEM	Model Year	VVT	VVL	SGDI	Cylinder Deac	High Comp Ratio	TURBO1	TURBO2	Cooled EGR	Adv. Diesel
Industry	2015	89%	23%	45%	2%	3%	16%	1%	0%	1%
	2021	90%	58%	67%	23%	3%	14%	5%	21%	1%
	2030	94%	62%	69%	22%	0%	5%	14%	29%	1%
BMW	2015	98%	98%	96%	0%	0%	92%	4%	0%	1%
	2021	98%	95%	96%	2%	0%	82%	11%	0%	2%
	2030	98%	54%	54%	0%	0%	30%	24%	0%	2%
Daimler	2015	83%	0%	94%	0%	0%	77%	1%	0%	1%
	2021	85%	12%	75%	12%	0%	61%	0%	0%	1%
	2030	85%	12%	19%	4%	0%	15%	0%	0%	1%
FCA	2015	96%	49%	0%	3%	0%	10%	0%	0%	0%
	2021	93%	67%	67%	4%	0%	28%	0%	39%	0%
	2030	95%	57%	55%	4%	0%	24%	0%	30%	0%
Ford	2015	100%	0%	66%	0%	0%	33%	0%	0%	0%
	2021	100%	24%	69%	0%	0%	23%	0%	29%	0%
	2030	100%	39%	63%	0%	0%	4%	0%	59%	0%
General Motors	2015	81%	18%	72%	0%	0%	18%	3%	0%	0%
	2021	82%	71%	77%	22%	0%	3%	0%	57%	0%
	2030	82%	64%	67%	3%	0%	0%	5%	60%	0%
Honda	2015	55%	98%	45%	13%	0%	0%	0%	0%	0%
	2021	69%	98%	45%	46%	0%	0%	0%	0%	0%
	2030	100%	98%	87%	75%	0%	0%	24%	0%	0%
Hyundai Kia	2015	100%	0%	82%	1%	3%	1%	0%	0%	0%
	2021	100%	79%	87%	23%	2%	2%	0%	56%	0%
	2030	100%	91%	93%	1%	0%	0%	0%	93%	0%
JLR	2015	100%	0%	0%	0%	0%	95%	0%	0%	0%
	2021	100%	3%	3%	3%	0%	88%	0%	0%	0%
	2030	100%	3%	3%	3%	0%	43%	33%	0%	0%
Mazda	2015	100%	2%	98%	0%	98%	0%	0%	0%	0%
	2021	100%	5%	95%	0%	91%	5%	4%	0%	0%
	2030	100%	6%	94%	0%	0%	0%	53%	0%	0%
Mitsubishi	2015	100%	0%	0%	0%	0%	0%	5%	0%	0%
	2021	100%	35%	35%	0%	0%	0%	41%	0%	0%
	2030	100%	91%	91%	0%	0%	0%	91%	5%	0%
Nissan	2015	97%	10%	3%	0%	0%	3%	0%	0%	0%
	2021	95%	64%	58%	46%	0%	8%	5%	0%	0%
	2030	94%	89%	93%	72%	0%	0%	22%	0%	0%
Subaru	2015	100%	0%	7%	0%	0%	10%	0%	0%	0%
	2021	100%	83%	90%	79%	0%	0%	14%	0%	0%
	2030	100%	89%	94%	37%	0%	0%	47%	14%	0%
Toyota	2015	98%	2%	8%	0%	0%	1%	0%	0%	0%
	2021	97%	43%	46%	35%	2%	9%	0%	0%	0%
	2030	98%	52%	55%	37%	2%	8%	10%	0%	0%
Volvo	2015	100%	0%	0%	0%	0%	100%	0%	0%	0%
	2021	100%	0%	0%	0%	0%	77%	23%	0%	0%
	2030	100%	0%	0%	0%	0%	0%	69%	0%	0%
VWA	2015	77%	30%	76%	0%	0%	72%	1%	0%	15%
	2021	88%	35%	87%	6%	0%	28%	52%	0%	12%
	2030	88%	20%	47%	0%	0%	4%	42%	0%	12%

Figure 13.31 Passenger Car Transmission Penetration Rates By Manufacturer (sales weighted share of fleet)

OEM	Model Year	5-Speed auto	6-Speed auto	8-Speed auto	CVT	DCT6	DCT8
Industry	2015	1%	44%	14%	24%	6%	1%
	2021	0%	25%	30%	21%	5%	2%
	2030	0%	1%	44%	21%	4%	1%
BMW	2015	0%	15%	75%	0%	0%	5%
	2021	0%	15%	73%	0%	0%	4%
	2030	0%	0%	34%	0%	13%	3%
Daimler	2015	3%	0%	95%	0%	0%	0%
	2021	0%	4%	72%	0%	0%	0%
	2030	0%	0%	12%	0%	7%	0%
FCA	2015	2%	18%	65%	4%	5%	0%
	2021	0%	6%	60%	2%	0%	0%
	2030	0%	0%	54%	0%	0%	0%
Ford	2015	0%	64%	0%	0%	14%	0%
	2021	0%	42%	14%	0%	0%	0%
	2030	0%	0%	48%	0%	0%	0%
General Motors	2015	0%	92%	2%	2%	0%	0%
	2021	0%	42%	38%	3%	0%	0%
	2030	0%	0%	60%	3%	0%	0%
Honda	2015	2%	10%	4%	74%	0%	3%
	2021	0%	14%	5%	73%	0%	2%
	2030	0%	2%	15%	74%	0%	2%
Hyundai Kia	2015	0%	92%	4%	0%	2%	0%
	2021	0%	26%	68%	0%	2%	1%
	2030	0%	2%	87%	0%	0%	3%
JLR	2015	0%	5%	95%	0%	0%	0%
	2021	0%	3%	88%	0%	0%	0%
	2030	0%	0%	78%	0%	0%	0%
Mazda	2015	0%	87%	0%	0%	0%	0%
	2021	0%	49%	37%	0%	0%	0%
	2030	0%	0%	86%	0%	0%	0%
Mitsubishi	2015	0%	1%	0%	87%	0%	0%
	2021	0%	1%	0%	87%	0%	0%
	2030	0%	0%	0%	83%	0%	0%
Nissan	2015	1%	0%	9%	85%	0%	0%
	2021	0%	0%	12%	81%	0%	0%
	2030	0%	0%	12%	80%	0%	0%
Subaru	2015	0%	1%	0%	83%	0%	0%
	2021	0%	2%	0%	82%	0%	0%
	2030	0%	0%	1%	80%	0%	0%
Toyota	2015	5%	49%	10%	17%	0%	0%
	2021	0%	49%	15%	16%	0%	0%
	2030	0%	4%	59%	16%	0%	0%
Volvo	2015	0%	25%	75%	0%	0%	0%
	2021	0%	26%	74%	0%	0%	0%
	2030	0%	23%	46%	0%	0%	0%
VWA	2015	0%	0%	0%	1%	72%	17%
	2021	0%	0%	0%	2%	73%	16%
	2030	0%	0%	0%	2%	42%	7%

Figure 13.32 Passenger Car Electrification Technology Penetration Rates By Manufacturer (sales weighted share of fleet)

OEM	Model Year	Stop/ Start	ISG	Strong Hybrid	PHEV	BEV200	FCV
Industry	2015	7%	0%	4%	0%	1%	0%
	2021	15%	14%	10%	1%	2%	0%
	2030	29%	24%	22%	1%	2%	0%
BMW	2015	86%	0%	0%	0%	0%	0%
	2021	79%	3%	2%	0%	0%	0%
	2030	4%	33%	57%	0%	0%	0%
Daimler	2015	88%	0%	0%	0%	1%	0%
	2021	66%	0%	22%	0%	2%	0%
	2030	1%	8%	85%	0%	2%	0%
FCA	2015	0%	0%	0%	0%	1%	0%
	2021	0%	51%	24%	0%	2%	0%
	2030	3%	51%	39%	0%	3%	0%
Ford	2015	0%	0%	5%	2%	0%	0%
	2021	7%	50%	27%	2%	0%	0%
	2030	0%	48%	35%	2%	0%	0%
General Motors	2015	18%	0%	0%	1%	0%	0%
	2021	39%	28%	11%	2%	0%	0%
	2030	24%	39%	30%	2%	0%	0%
Honda	2015	0%	0%	2%	0%	0%	0%
	2021	0%	0%	2%	0%	0%	0%
	2030	80%	0%	2%	0%	0%	0%
Hyundai Kia	2015	0%	0%	3%	0%	0%	0%
	2021	18%	2%	3%	0%	0%	0%
	2030	55%	34%	7%	0%	0%	0%
JLR	2015	80%	0%	0%	0%	0%	0%
	2021	71%	0%	8%	0%	0%	0%
	2030	0%	58%	22%	0%	0%	0%
Mazda	2015	0%	1%	0%	0%	0%	0%
	2021	0%	1%	0%	0%	0%	0%
	2030	33%	1%	0%	0%	0%	0%
Mitsubishi	2015	0%	0%	0%	0%	0%	0%
	2021	32%	34%	0%	0%	0%	0%
	2030	55%	28%	4%	0%	0%	0%
Nissan	2015	0%	0%	0%	0%	3%	0%
	2021	0%	0%	0%	0%	5%	0%
	2030	56%	0%	0%	0%	6%	0%
Subaru	2015	0%	0%	0%	0%	0%	0%
	2021	43%	0%	0%	0%	0%	0%
	2030	82%	0%	2%	0%	0%	0%
Toyota	2015	0%	0%	16%	0%	0%	0%
	2021	0%	0%	19%	1%	0%	0%
	2030	12%	0%	18%	0%	0%	0%
Volvo	2015	0%	0%	0%	0%	0%	0%
	2021	0%	0%	0%	0%	0%	0%
	2030	0%	27%	31%	0%	0%	0%
VWA	2015	0%	0%	0%	0%	1%	0%
	2021	8%	1%	0%	0%	1%	0%
	2030	2%	45%	44%	0%	1%	0%

Figure 13.33 Passenger Car Load Reduction Technology Penetration Rates By Manufacturer (sales weighted share of fleet)

OEM	Model Year	Mass Reduc 7.5%	Mass Reduc 10%	Mass Reduc 15%	Mass Reduc 20%	AERO10	AERO20	ROLL10	ROLL20
Industry	2015	16%	9%	0%	0%	10%	3%	0%	0%
	2021	42%	12%	3%	3%	86%	47%	97%	75%
	2030	80%	20%	8%	8%	100%	100%	98%	98%
BMW	2015	0%	0%	0%	0%	18%	0%	0%	0%
	2021	0%	0%	0%	0%	89%	49%	89%	88%
	2030	68%	0%	0%	0%	100%	100%	100%	100%
Daimler	2015	53%	0%	0%	0%	72%	54%	0%	0%
	2021	75%	3%	0%	0%	100%	93%	98%	94%
	2030	95%	3%	0%	0%	100%	100%	98%	98%
FCA	2015	0%	0%	0%	0%	0%	0%	0%	0%
	2021	57%	27%	27%	27%	93%	62%	95%	95%
	2030	62%	27%	27%	27%	100%	100%	97%	97%
Ford	2015	0%	0%	0%	0%	0%	0%	0%	0%
	2021	18%	0%	0%	0%	58%	58%	100%	100%
	2030	92%	28%	28%	28%	100%	100%	100%	100%
General Motors	2015	2%	2%	2%	0%	1%	0%	0%	0%
	2021	65%	7%	7%	5%	96%	96%	100%	100%
	2030	68%	6%	6%	4%	100%	100%	100%	100%
Honda	2015	0%	0%	0%	0%	2%	0%	0%	0%
	2021	0%	0%	0%	0%	42%	0%	100%	20%
	2030	15%	15%	15%	15%	100%	100%	100%	100%
Hyundai Kia	2015	42%	42%	0%	0%	2%	0%	0%	0%
	2021	69%	46%	0%	0%	97%	23%	100%	100%
	2030	100%	52%	5%	5%	100%	100%	100%	100%
JLR	2015	27%	0%	0%	0%	0%	0%	0%	0%
	2021	30%	0%	0%	0%	100%	97%	100%	100%
	2030	80%	0%	0%	0%	100%	100%	100%	100%
Mazda	2015	78%	52%	0%	0%	0%	0%	0%	0%
	2021	74%	50%	0%	0%	77%	45%	100%	26%
	2030	100%	80%	0%	0%	100%	100%	100%	100%
Mitsubishi	2015	0%	0%	0%	0%	39%	0%	0%	0%
	2021	0%	0%	0%	0%	100%	71%	100%	100%
	2030	0%	0%	0%	0%	100%	100%	100%	100%
Nissan	2015	56%	13%	0%	0%	9%	0%	0%	0%
	2021	89%	11%	0%	0%	100%	5%	95%	90%
	2030	100%	18%	0%	0%	100%	100%	94%	94%
Subaru	2015	0%	0%	0%	0%	0%	0%	0%	0%
	2021	94%	0%	0%	0%	100%	94%	100%	62%
	2030	100%	0%	0%	0%	100%	100%	100%	100%
Toyota	2015	4%	4%	0%	0%	30%	10%	0%	0%
	2021	17%	5%	0%	0%	100%	50%	100%	21%
	2030	100%	5%	0%	0%	100%	100%	100%	100%
Volvo	2015	0%	0%	0%	0%	17%	0%	0%	0%
	2021	93%	0%	0%	0%	100%	93%	100%	100%
	2030	100%	0%	0%	0%	100%	100%	100%	100%
VWA	2015	0%	0%	0%	0%	1%	0%	0%	0%
	2021	8%	0%	0%	0%	83%	36%	100%	98%
	2030	100%	19%	0%	0%	100%	100%	100%	100%

As shown in the tables above, for the passenger car fleet, the Augural Standards are projected to result in large increases in a wide range of technologies over the 15 year period from MY 2015 through MY2030. All manufacturers are projected to exhibit consistent and heavy reliance on dynamic load reduction technologies like aerodynamic improvements and low rolling resistance tires, fully utilizing opportunities for improvement in those areas, as well as modest levels of mass reduction. However, the projections show manufacturers following a range of different technology pathways, with differences in areas like engine, transmission, and electrification technology, and improvements in different areas.

As Figure 13.31shows, passenger cars are projected to displace 6-speed automatic transmissions with 8-speed automatic transmissions over time, with the share of CVT and DCT remaining relatively steady over the study period. However, a number of manufacturers are projected to heavily deploy CVTs at levels considerably higher than their application in MY2015 – Honda, Mitsubishi, Nissan, and Subaru, in particular.

As shown in Figure 13.32, the analysis projects a consistent and increasing reliance on start/stop, integrated starter generators (ISG), and strong hybrids. While the penetration rate of pure electric vehicles also increases over the period, only Nissan is projected to convert more than 3 percent of its passenger car fleet to battery electric vehicles, and most manufacturers show no significant deployment of pure EVs[11]. Similarly, the CAFE simulations project that manufacturers would be able to achieve compliance without any reliance on fuel cell vehicles (FCV).

In the regulatory analysis of the MY2017 – MY2021 standards, which included Augural Standards for MYs 2022 – 2025, NHTSA concluded that compliance could be achieved primarily through transmission improvements and technological advances to the internal combustion engine – without significant reliance on hybridization. Compared to the 2012 final rule, DOT's current analysis reflects a range of updates to the CAFE model and inputs. These include: changes to the market forecast (involving some changes in fleet mix and technology and fuel economy levels, as well as changes in other vehicle and fleet characteristics); changes in the estimated cost and effectiveness for different technology combinations; model revisions that improve the accuracy of the Volpe model's accounting for product cadence and shared technologies (e.g., shared engines);[12] an increase in the civil penalty rate (from $5.50 per 0.1 mpg to $14 per 0.1 mpg); and other changes have combined to result in new estimates of potential technology application in response to the augural standards, including wider application of strong hybrid penetrations for this Draft TAR as shown in Figure 13.32. As in the FRM, there

[11] As Tesla Motors only produces electric vehicles, the CAFE program does not represent a binding standard. The industry totals include the contribution of Tesla sales to the new vehicle market, but individual results for that manufacturer are not expected to vary as a result of CAFE standards and are omitted from the tables.

[12] Note, for engine and hybrid technologies and mass reduction levels of 10 percent or more, the NHTSA analysis assumes manufacturers would reduce engine displacement to maintain vehicle performance, because the change in performance and displacement would be moderate. For other technologies and lower levels of mass reduction, the NHTSA analysis assumes manufacturers would not redesign engines to preserve vehicle performance because performance impacts and changes in engine displacement would be smaller and would not justify the engineering resources and costs that would be incurred to do so. Therefore, for those other technologies, some portion of the fuel saving potential results in an increase in vehicle performance.

remains a significant reliance on turbocharging and CEGR improvements to the internal combustion engine.[13]

Notably, each manufacturer is projected to move far along one or more technology pathways where it has little engagement in MY 2015. For example:

- Most European manufacturers today are producing relatively few integrated start-generator (ISG) or strong hybrid vehicles for the U.S. market in MY2015. But, they are projected to deploy those technologies on more than 75 percent (combined) of their passenger car fleets produced for U.S. sale by MY2030, in response to the Augural Standards.
- Some firms are not projected to have large increases in ISG or strong hybrids, but are expected to focus instead on advanced gasoline engines. For example, Honda and Hyundai Kia have negligible levels of turbocharging in their passenger car fleets in MY2015, and are projected to include turbocharging in over 20 percent of their passenger car engines by MY2030.
- Ford, GM and Fiat-Chrysler are projected to increase market share for their full hybrid systems from 0-5 percent in MY2015 to 30-39 percent in MY2030, and increase ISG systems from 0 percent in MY2015 to 39-51 percent in MY2030.

A similar, but not identical, story emerges for light trucks, with the biggest differences between technology application levels for passenger cars and light trucks being greater use of mass reduction technology in the latter, and greater use of ISG and strong hybrids in the former.

[13] This section is focused on describing internal changes within the Volpe model. As noted in the executive summary and elsewhere, there are differences between the DOT and EPA approaches that derive different penetration rates for hybrid as well as other technologies. These derive from a range of factors, including but not limited to different penetration rates of EVs and PHEVs in the two agencies' reference fleets, differences in technology effectiveness assumptions, and others.

Figure 13.34 Light Truck Engine Technology Penetration Rates By Manufacturer (sales weighted share of fleet)

OEM	Model Year	VVT	VVL	SGDI	Cylinder Deac	High Comp Ratio	TURBO1	TURBO2	Cooled EGR	Adv. Diesel
Industry	2015	93%	11%	41%	24%	1%	12%	0%	0%	1%
	2021	94%	61%	83%	37%	1%	26%	3%	20%	1%
	2030	98%	82%	88%	32%	0%	21%	14%	27%	1%
BMW	2015	91%	91%	91%	0%	0%	91%	0%	0%	9%
	2021	91%	91%	91%	0%	0%	91%	0%	0%	9%
	2030	91%	78%	78%	0%	0%	56%	23%	0%	9%
Daimler	2015	72%	0%	89%	0%	0%	40%	0%	0%	9%
	2021	73%	50%	91%	49%	0%	42%	0%	0%	9%
	2030	73%	37%	56%	0%	0%	56%	0%	0%	9%
FCA	2015	96%	7%	0%	16%	0%	0%	0%	0%	4%
	2021	96%	85%	84%	17%	0%	18%	0%	48%	4%
	2030	96%	96%	96%	17%	0%	20%	0%	59%	4%
Ford	2015	100%	0%	55%	0%	0%	51%	0%	0%	0%
	2021	100%	38%	89%	0%	0%	42%	0%	47%	0%
	2030	100%	49%	93%	0%	0%	35%	0%	59%	0%
General Motors	2015	97%	0%	97%	68%	0%	2%	0%	0%	0%
	2021	98%	23%	96%	75%	0%	1%	10%	7%	0%
	2030	98%	98%	98%	60%	0%	10%	12%	18%	0%
Honda	2015	38%	100%	50%	62%	0%	0%	0%	0%	0%
	2021	57%	100%	54%	100%	0%	0%	0%	0%	0%
	2030	100%	100%	52%	100%	0%	0%	0%	0%	0%
Hyundai Kia	2015	100%	0%	100%	0%	0%	0%	0%	0%	0%
	2021	100%	67%	85%	29%	0%	0%	0%	38%	0%
	2030	100%	85%	85%	0%	0%	0%	0%	85%	0%
JLR	2015	100%	0%	0%	0%	0%	100%	0%	0%	0%
	2021	100%	0%	0%	0%	0%	80%	0%	0%	0%
	2030	100%	0%	0%	0%	0%	45%	0%	0%	0%
Mazda	2015	100%	12%	63%	0%	63%	0%	0%	0%	0%
	2021	100%	29%	100%	0%	71%	28%	0%	0%	0%
	2030	100%	29%	100%	0%	0%	28%	66%	0%	0%
Mitsubishi	2015	95%	33%	0%	0%	0%	0%	0%	0%	0%
	2021	100%	33%	33%	0%	0%	5%	27%	0%	0%
	2030	100%	100%	100%	0%	0%	5%	95%	0%	0%
Nissan	2015	100%	4%	4%	0%	0%	0%	0%	0%	0%
	2021	100%	71%	70%	35%	0%	35%	0%	0%	0%
	2030	100%	93%	93%	42%	0%	19%	31%	0%	0%
Subaru	2015	100%	0%	2%	0%	0%	2%	0%	0%	0%
	2021	100%	95%	97%	91%	0%	2%	4%	0%	0%
	2030	100%	94%	96%	70%	0%	2%	24%	0%	0%
Toyota	2015	100%	0%	1%	0%	0%	1%	0%	0%	0%
	2021	100%	81%	82%	18%	0%	64%	0%	0%	0%
	2030	100%	88%	89%	19%	0%	30%	41%	0%	0%
Volvo	2015	100%	0%	0%	0%	0%	90%	0%	0%	0%
	2021	100%	7%	7%	7%	0%	2%	92%	0%	0%
	2030	100%	7%	7%	7%	0%	0%	93%	0%	0%
VWA	2015	84%	29%	84%	0%	0%	67%	0%	0%	16%
	2021	85%	30%	84%	5%	0%	49%	19%	0%	15%
	2030	85%	38%	84%	15%	0%	46%	23%	0%	15%

Figure 13.35 Light Truck Transmission Technology Penetration Rates By Manufacturer (sales weighted share of fleet)

OEM	Model Year	5-Speed auto	6-Speed auto	8-Speed auto	CVT	DCT6	DCT8
Industry	2015	10%	59%	16%	12%	0%	1%
	2021	1%	31%	50%	14%	1%	2%
	2030	0%	20%	58%	14%	3%	1%
BMW	2015	0%	0%	100%	0%	0%	0%
	2021	0%	0%	100%	0%	0%	0%
	2030	0%	0%	39%	0%	48%	0%
Daimler	2015	0%	0%	100%	0%	0%	0%
	2021	0%	0%	100%	0%	0%	0%
	2030	0%	0%	26%	0%	39%	0%
FCA	2015	18%	24%	56%	0%	0%	0%
	2021	0%	17%	81%	0%	0%	0%
	2030	0%	8%	90%	0%	0%	0%
Ford	2015	0%	100%	0%	0%	0%	0%
	2021	0%	2%	98%	0%	0%	0%
	2030	0%	0%	93%	0%	0%	0%
General Motors	2015	0%	94%	5%	0%	0%	0%
	2021	0%	85%	15%	0%	0%	0%
	2030	0%	71%	29%	0%	0%	0%
Honda	2015	18%	44%	0%	38%	0%	0%
	2021	0%	52%	0%	48%	0%	0%
	2030	0%	52%	3%	45%	0%	0%
Hyundai Kia	2015	0%	100%	0%	0%	0%	0%
	2021	0%	46%	38%	0%	0%	0%
	2030	0%	0%	85%	0%	0%	0%
JLR	2015	0%	2%	98%	0%	0%	0%
	2021	0%	2%	78%	0%	0%	0%
	2030	0%	0%	0%	0%	45%	0%
Mazda	2015	12%	88%	0%	0%	0%	0%
	2021	0%	100%	0%	0%	0%	0%
	2030	0%	0%	100%	0%	0%	0%
Mitsubishi	2015	0%	5%	0%	95%	0%	0%
	2021	0%	0%	5%	95%	0%	0%
	2030	0%	0%	5%	95%	0%	0%
Nissan	2015	21%	0%	4%	73%	0%	0%
	2021	18%	0%	11%	69%	0%	0%
	2030	0%	0%	29%	69%	0%	0%
Subaru	2015	0%	0%	0%	96%	0%	0%
	2021	0%	0%	0%	95%	0%	0%
	2030	0%	0%	0%	95%	0%	0%
Toyota	2015	22%	75%	1%	0%	0%	0%
	2021	0%	29%	68%	0%	0%	0%
	2030	0%	0%	98%	0%	0%	0%
Volvo	2015	0%	100%	0%	0%	0%	0%
	2021	0%	100%	0%	0%	0%	0%
	2030	0%	100%	0%	0%	0%	0%
VWA	2015	0%	0%	0%	0%	11%	89%
	2021	0%	0%	0%	0%	23%	76%
	2030	0%	0%	0%	0%	43%	56%

Figure 13.36 Light Truck Electrification Technology Penetration Rates By Manufacturer (sales weighted share of fleet)

OEM	Model Year	Stop/ Start	ISG	Strong Hybrid	PHEV	BEV200	FCV
Industry	2015	3%	0%	0%	0%	0%	0%
	2021	28%	1%	1%	0%	0%	0%
	2030	47%	2%	6%	0%	0%	0%
BMW	2015	100%	0%	0%	0%	0%	0%
	2021	100%	0%	0%	0%	0%	0%
	2030	39%	0%	61%	0%	0%	0%
Daimler	2015	78%	0%	0%	0%	0%	0%
	2021	78%	0%	0%	0%	0%	0%
	2030	7%	0%	74%	0%	0%	0%
FCA	2015	0%	0%	0%	0%	0%	0%
	2021	34%	5%	0%	0%	0%	0%
	2030	74%	5%	0%	0%	0%	0%
Ford	2015	0%	0%	0%	0%	0%	0%
	2021	75%	0%	0%	0%	0%	0%
	2030	93%	0%	7%	0%	0%	0%
General Motors	2015	0%	0%	0%	0%	0%	0%
	2021	7%	0%	0%	0%	0%	0%
	2030	40%	0%	0%	0%	0%	0%
Honda	2015	0%	0%	0%	0%	0%	0%
	2021	0%	0%	0%	0%	0%	0%
	2030	45%	0%	0%	0%	0%	0%
Hyundai Kia	2015	0%	0%	0%	0%	0%	0%
	2021	67%	0%	15%	0%	0%	0%
	2030	68%	0%	15%	0%	0%	0%
JLR	2015	94%	0%	0%	0%	0%	0%
	2021	74%	0%	20%	0%	0%	0%
	2030	0%	0%	100%	0%	0%	0%
Mazda	2015	0%	0%	0%	0%	0%	0%
	2021	0%	0%	0%	0%	0%	0%
	2030	0%	0%	0%	0%	0%	0%
Mitsubishi	2015	0%	0%	0%	0%	0%	0%
	2021	0%	100%	0%	0%	0%	0%
	2030	0%	100%	0%	0%	0%	0%
Nissan	2015	0%	0%	0%	0%	0%	0%
	2021	9%	0%	0%	0%	0%	0%
	2030	21%	0%	0%	0%	0%	0%
Subaru	2015	0%	0%	3%	0%	0%	0%
	2021	0%	0%	3%	0%	0%	0%
	2030	0%	0%	4%	0%	0%	0%
Toyota	2015	0%	0%	1%	0%	0%	0%
	2021	0%	0%	1%	0%	0%	0%
	2030	16%	0%	1%	0%	0%	0%
Volvo	2015	0%	0%	0%	0%	0%	0%
	2021	0%	0%	0%	0%	0%	0%
	2030	0%	0%	0%	0%	0%	0%
VWA	2015	0%	0%	0%	1%	0%	0%
	2021	15%	0%	0%	0%	0%	0%
	2030	15%	23%	16%	0%	0%	0%

Figure 13.37 Light Truck Load Reduction Technology Penetration Rates By Manufacturer (sales weighted share of fleet)

OEM	Model Year	Mass Reduc 7.5%	Mass Reduc 10%	Mass Reduc 15%	Mass Reduc 20%	AERO10	AERO20	ROLL10	ROLL20
Industry	2015	15%	8%	0%	0%	6%	0%	0%	0%
	2021	49%	24%	15%	5%	87%	60%	99%	76%
	2030	84%	61%	42%	29%	100%	97%	100%	95%
BMW	2015	0%	0%	0%	0%	0%	0%	0%	0%
	2021	5%	0%	0%	0%	100%	5%	100%	100%
	2030	93%	0%	0%	0%	100%	100%	100%	100%
Daimler	2015	17%	0%	0%	0%	33%	0%	0%	0%
	2021	33%	16%	0%	0%	100%	100%	100%	100%
	2030	97%	16%	0%	0%	100%	100%	100%	100%
FCA	2015	0%	0%	0%	0%	1%	0%	0%	0%
	2021	22%	22%	22%	22%	100%	76%	100%	66%
	2030	61%	61%	61%	38%	100%	100%	100%	100%
Ford	2015	45%	45%	0%	0%	0%	0%	0%	0%
	2021	63%	63%	59%	5%	70%	70%	100%	100%
	2030	100%	100%	95%	42%	100%	100%	100%	100%
General Motors	2015	6%	6%	0%	0%	0%	0%	0%	0%
	2021	77%	8%	2%	2%	94%	94%	100%	100%
	2030	77%	77%	48%	48%	100%	100%	100%	100%
Honda	2015	56%	0%	0%	0%	27%	0%	0%	0%
	2021	49%	0%	0%	0%	49%	0%	100%	19%
	2030	100%	48%	48%	48%	100%	100%	100%	100%
Hyundai Kia	2015	30%	30%	0%	0%	0%	0%	0%	0%
	2021	17%	17%	0%	0%	55%	0%	83%	83%
	2030	100%	71%	54%	54%	100%	100%	100%	100%
JLR	2015	0%	0%	0%	0%	0%	0%	0%	0%
	2021	0%	0%	0%	0%	96%	65%	100%	100%
	2030	100%	100%	0%	0%	100%	100%	100%	100%
Mazda	2015	0%	0%	0%	0%	0%	0%	0%	0%
	2021	0%	0%	0%	0%	100%	0%	100%	0%
	2030	71%	71%	0%	0%	100%	100%	100%	100%
Mitsubishi	2015	0%	0%	0%	0%	0%	0%	0%	0%
	2021	0%	0%	0%	0%	100%	67%	100%	100%
	2030	0%	0%	0%	0%	100%	100%	100%	100%
Nissan	2015	34%	0%	0%	0%	0%	0%	0%	0%
	2021	87%	24%	0%	0%	95%	24%	100%	94%
	2030	100%	62%	0%	0%	100%	100%	100%	100%
Subaru	2015	0%	0%	0%	0%	0%	0%	0%	0%
	2021	51%	0%	0%	0%	97%	51%	100%	9%
	2030	48%	0%	0%	0%	100%	48%	100%	14%
Toyota	2015	0%	0%	0%	0%	19%	0%	0%	0%
	2021	41%	41%	0%	0%	100%	59%	100%	80%
	2030	100%	39%	0%	0%	100%	100%	100%	100%
Volvo	2015	0%	0%	0%	0%	0%	0%	0%	0%
	2021	98%	0%	0%	0%	100%	98%	100%	100%
	2030	100%	0%	0%	0%	100%	100%	100%	100%
VWA	2015	0%	0%	0%	0%	0%	0%	0%	0%
	2021	0%	0%	0%	0%	70%	12%	90%	90%
	2030	100%	36%	0%	0%	100%	100%	100%	100%

All manufacturers make increasing, and consistently high use of engine technologies such as variable valve timing and lift (VVT and VVL, respectively) and direct injection (SGDI). As Figure 13.34 illustrates, those technologies are already present in the MY2015 fleet at very high levels for some manufacturers, but, industry-wide, at lower levels than they are simulated for MY2030. Turbocharged engines, whose penetration varies by manufacturer, are expected to be present, in some form, on over half of the light trucks offered for sale in MY2030 compared to slightly more than 10 percent of the MY2015 fleet.

The penetration rates of transmission technologies for light trucks are broadly similar to those for passenger cars, with manufacturers generally projected to rely on the same mix of technologies for both classes. As reflected in Figure 13.35, the manufacturers projected to rely most heavily on CVTs for their passenger car fleets are projected to have similar reliance in their light truck fleets.

As with passenger cars, dynamic load reduction technologies (aerodynamic improvements and LRR tires) are simulated to reach high levels of penetration in the light truck market for all manufacturers by MY2030 (Figure 13.37). Mass reduction technologies are projected to be deployed at higher rates for light trucks than passenger cars. NHTSA's analysis restricts the applicability of mass reduction technologies for passenger cars, but not for the light trucks. In the modeling, most manufacturers make increasing use of all levels of mass reduction, with the highest-volume pickup truck producers (Ford, GM, and FCA) deploying the highest available level (20 percent reduction) on around 40 percent of their light trucks. Honda and Hyundai Kia both apply mass reduction at the highest available level on 50 percent of their fleets by MY2030.

NHTSA modeling projects a significant increase in the use of start/stop systems within the light truck class, but, in contrast to the passenger car fleet, comparatively little reliance on ISG or strong hybrid systems, as reflected in Figure 13.36, as compared with Figure 13.32.

Projected compliance costs

The technology changes described above carry associated costs. In the NHTSA model, manufacturers can only redesign a fraction of their fleet each year, and have flexibility to over- or under comply in a particular year by banking or borrowing credits, manufacturers compliance pathway over time can be complex. Thus, costs for compliance with current standards and the Augural Standards are interconnected, and evolve on a year-by-year basis to reflect annual redesign cycles and other factors. Table 13.9 divides aggregate annual average per vehicle manufacturers' compliance costs into three categories: the investments manufacturers would have to make to comply with current standards through 2016, costs to comply with current standards through MY2021, and the cost to comply with the MY 2022-2025 Augural Standards.

Table 13.9 Average Per Vehicle Cost for Primary Analysis Using RPE to Mark Up Direct Costs

	Average Per-Vehicle Costs (2013 $)			
	Costs added with stringency increases through 2016	Additional costs with stringency increases through 2021	Additional costs under Mys 2022-2025 Augural Standards	Total costs
2016	200	40	-	240
2017	250	150	10	400
2018	340	280	70	690
2019	350	390	100	830
2020	370	560	190	1,120
2021	380	670	450	1,500
2022	380	680	610	1,670
2023	380	670	750	1,800
2024	370	670	860	1,900
2025	370	670	1,020	2,070
2026	370	680	1,120	2,160
2027	370	670	1,230	2,260
2028	360	670	1,250	2,270
2029	350	660	1,250	2,260
2030	350	660	1,240	2,250
2031	350	660	1,250	2,260
2032	350	660	1,250	2,260

Note that, in NHTSA's modeling, manufacturers begin investing in compliance with the Augural Standards as early as 2017, redesigning vehicles that will continue to be built in 2022 and beyond, as well as accumulating credits for future compliance.

The chart below (Figure 13.38) shows the rate at which average regulatory costs increase relative to the required and achieved CAFE levels for the industry. The figure combines the passenger car and light truck fleets, and presents compliance with the Augural Standards. Manufacturer-specific results have more variance (especially for manufacturers with relatively limited ranges of product offerings). Those seeking more detail can download the simulation results in full from NHTSA's website[14].

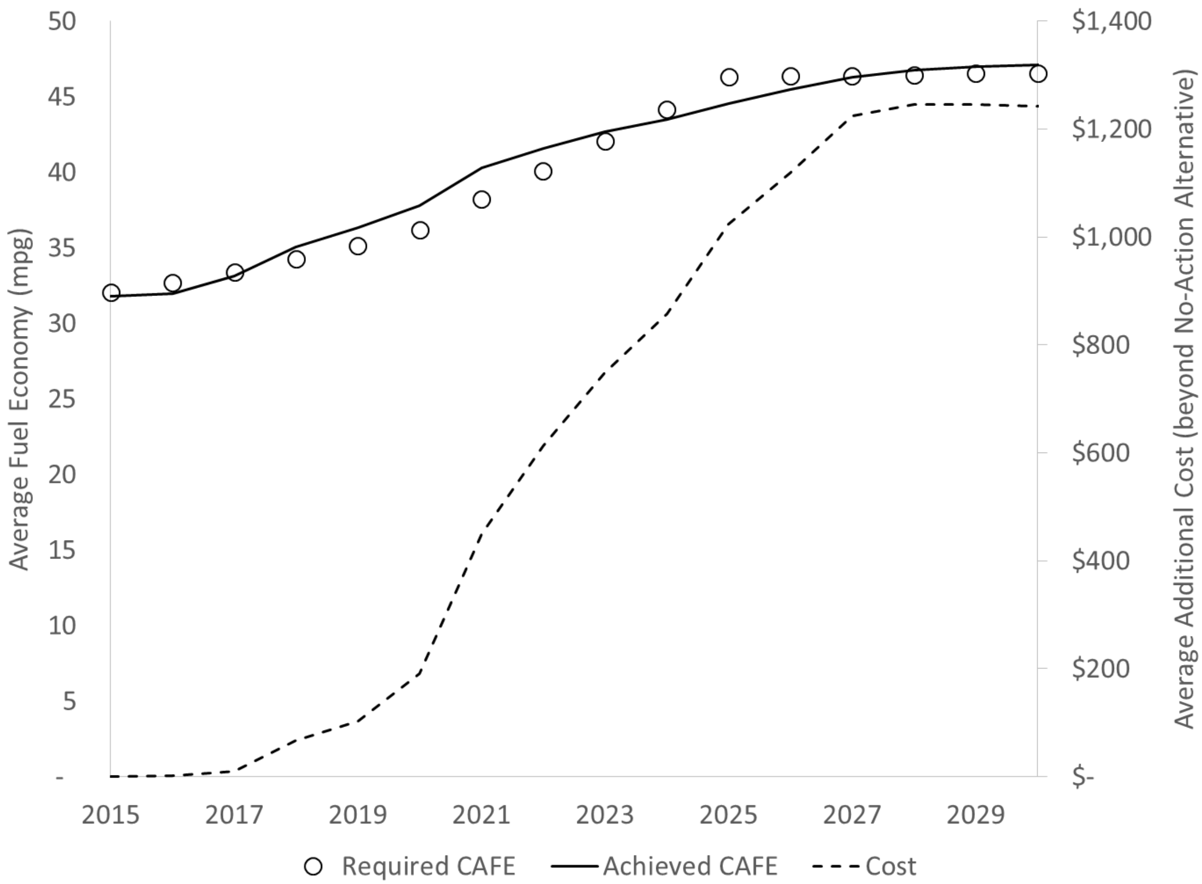

Figure 13.38 Industry-Wide Combined Average Fuel Economy Levels and Average Costs (2015 $)

[14] CAFE – Fuel Economy: http://www.nhtsa.gov/Laws+&+Regulations/CAFE+-+Fuel+Economy/ld-cafe-midterm-evaluation-2022-25

Table 13.10 below provides additional information on the distribution of projected sales and compliance (technology plus fines/credits) costs. The current projection of manufacturer sales volumes (described in greater detail in Section 4.2) combines a projection of total vehicle sales and the division between passenger cars and light trucks form the AEO, a proprietary forecast of manufacturer market shares from IHS/Polk, and sales volume projections for MY2015 submitted to NHTSA by the manufacturers.

Table 13.10 Draft TAR Average Per Vehicle Cost and Production Volume in MY 2025 for Primary Analysis Using RPE to Mark Up Direct Costs

Production Volumes and Average Costs for NHTSA Draft TAR Analysis							
	MY2025 Production for Sale in U.S. (m)			Average Per-Vehicle Costs[1] in MY2025			
	Passenger Cars	Light Trucks	Total	Costs added with stringency increases through 2016[2]	Additional costs with stringency increases through 2021	Additional costs under MYs 2022-2025 Augural Standards	Total costs
BMW	0.30	0.14	0.44	240	1,010	1,180	2,430
Daimler	0.23	0.16	0.39	400	960	1,180	2,530
Fiat-Chrysler	0.61	1.48	2.09	1,070	720	880	2,660
Ford	0.94	1.29	2.23	260	1,080	1,540	2,880
General Motors	1.20	1.44	2.64	260	550	1,300	2,110
Honda	0.88	0.65	1.53	90	120	1,140	1,350
Hyundai Kia	1.08	0.23	1.32	200	1,200	1,230	2,700
Jaguar Land Rover	0.02	0.07	0.10	1,010	1,030	1,050	3,090
Mazda	0.22	0.12	0.34	60	380	870	1,320
Mitsubishi	0.06	0.03	0.09	90	650	1,170	1,910
Nissan	0.89	0.46	1.35	120	440	780	1,340
Subaru	0.15	0.50	0.65	50	510	610	1,170
Toyota	1.22	1.02	2.24	510	460	260	1,230
Volvo	0.04	0.05	0.09	400	830	1,140	2,360
Volkswagen	0.63	0.18	0.82	500	950	1,300	2,750
Industry Average	8.59	7.84	16.43	370	670	1,020	2,070
2012 Final Rule[3]	10.98	5.47	16.45	790		1,700	2,480

[1] Draft TAR costs in 2013 $.
[2] Costs estimated to be accrued under standards through 2016 reflect different analysis fleets and credits. The 2012 Final Rule analysis uses a MY 2010 baseline fleet and includes costs for MYs 2011-2016, whereas the Draft TAR uses a MY 2015 baseline fleet and includes costs for MY 2016, alone.
[3]2012 Final Rule costs in 2010 $. For manufacturer-specific costs in 2012 Final Rule, see 77 FR 99, at 63047-63049, 63063-63067 and accompanying Final RIA, pp. 675-762.

A number of factors may affect the spread of costs across these different compliance periods covered by the program. Notably, drops in overall costs for compliance through 2016, relative to analysis in the 2012 final rule, reflect, among other things, choices that manufacturers across the sector have made since 2010 (the model year providing the foundation for NHTSA's 2012 analysis) with respect applying technology and to achieving compliance in the early years. Manufacturers' choices to integrate certain technological innovations first, as part of a multi-year program, affect the range of additional technologies available for later integration and future savings. The CAFE model recognizes that technologies, once implemented, are no longer available to generate additional savings. Multi-year regulatory certainty, combined with out-year GHG regulations as well as Augural Standards, has provided companies with a framework for planning that allows them to implement individual redesign cycles with the ability to understand how each may affect their range of compliance options in the future. While NHTSA's analysis fleet for today's analysis, being based on the 2015 fleet, reflects the application of fuel-saving technologies between 2010 and 2015, our analysis does not attempt to quantify the cost of those improvements. Additionally, unlike NHTSA's 2012 analysis, today's analysis includes CAFE credits that manufacturers are estimated to have available to carry forward (and, in some cases, trade) from model year 2010-2015 and apply toward compliance obligations during 2015-2019.

Among the metrics that can be used to weigh the relative cost of fuel economy improvements, one is the cost of added fuel-saving technology as compared to the resultant reduction of fuel consumption. The latter could be measured in terms of expected gallons or dollars of avoided fuel consumption, using estimates of future vehicle survival, vehicle use, the gap between laboratory and real-world fuel economy, and future fuel prices. Without applying such estimates, the reduction of fuel consumption can be measured on a percentage basis, considering the inverses of CAFE levels (e.g., such that increasing CAFE level from 20 to 30 mpg represents a 33.3 percent reduction in average fuel consumption, from 0.05 to 0.033 gallons per mile, or gpm).

Below, Table 13.11 shows estimated model year 2028 CAFE levels under the No-Action Alternative and the Augural Standards. On an industry-wide basis, the Augural Standards are estimated to improve average fuel consumption by about 14 percent, with similar average improvements for the passenger car and light truck fleets, with variance in both directions.

Table 13.11 Estimated MY2028 CAFE Levels and Average Fuel Consumption Improvement

	CAFE (mpg) under No-Action Alternative			CAFE (mpg) under Augural Standards			Fuel Consumption Improvement (% gpm)		
Manufacturer	PC	LT	Combined	PC	LT	Combined	PC	LT	Combined
BMW[1]	44.9	35.0	41.4	47.0	35.7	42.8	4%	2%	3%
Daimler[1]	44.2	35.1	40.0	50.8	42.2	47.0	13%	17%	15%
Fiat-Chrysler	45.2	34.7	37.4	54.0	40.3	43.7	16%	14%	14%
Ford	48.9	31.5	37.2	56.7	37.4	43.7	14%	16%	15%
General Motors	46.2	30.6	36.2	54.4	35.9	42.5	15%	15%	15%
Honda	46.8	37.5	42.5	58.1	44.0	51.3	20%	15%	17%
Hyundai Kia	46.9	39.7	45.6	55.9	43.6	53.4	16%	9%	15%
Jaguar Land Rover[1]	35.1	34.6	34.7	35.1	38.8	37.8	0%	11%	8%
Mazda	48.6	39.5	44.9	55.8	44.8	51.3	13%	12%	12%
Mitsubishi	49.9	39.5	46.4	58.1	46.6	54.3	14%	15%	14%
Nissan	45.6	35.8	41.7	55.7	42.0	50.2	18%	15%	17%
Subaru	49.7	41.8	43.5	57.6	47.4	49.5	14%	12%	12%
Tesla	282.9	282.9	282.9	282.9	282.9	282.9	0%	0%	0%
Toyota	48.5	37.2	42.7	55.5	40.5	47.7	13%	8%	10%
Volvo[1]	44.5	33.4	38.0	48.2	33.4	39.3	8%	0%	3%
Volkswagen	47.1	35.4	44.0	51.4	38.0	47.8	8%	7%	8%
Total	47.4	34.4	40.3	55.4	39.6	46.7	14%	13%	14%

NOTE:
[1]Manufacturer assumed to be willing to pay civil penalties as allowed under EPCA/EISA, if doing so would be more financially attractive than further increasing average fuel economy.

Table 13.12 shows the estimated average additional cost in MY 2028 (compared to the No-Action Alternative) of fuel-saving technologies producing these incremental fuel consumption improvements under the Augural Standards. On an industry-wide basis, and excluding any estimated civil penalties, these estimated incremental costs average about $1,110 for passenger cars, $1,250 for light trucks, and $1,175 for the combined fleet. Estimated average incremental costs vary considerably between manufacturers' respective fleets. However, after normalizing for relative improvements in average fuel consumption, these cost differences are more tightly distributed around the industry-wide average levels of $77 per % for passenger cars, $95 per % for light trucks, and $86 per % for the combined fleet.

Table 13.12 Estimated Technology Cost per Percent Fuel Consumption Improvement in MY2028

	Fuel Consumption Improvement (% gpm)			Add'l. Tech. Cost (2013 $) under Augural Standards			Add'l. Tech. Cost (2013 $) per % Improvement		
Manufacturer	PC	LT	Combined	PC	LT	Combined	PC	LT	Combined
BMW[1]	4%	2%	3%	431	119	336	97	68	96
Daimler[1]	13%	17%	15%	1,224	1,719	1,422	94	101	96
Fiat-Chrysler	16%	14%	14%	1,288	1,335	1,321	79	97	92
Ford	14%	16%	15%	1,374	1,931	1,693	100	123	113
General Motors	15%	15%	15%	1,637	1,604	1,620	109	109	109
Honda	20%	15%	17%	1,208	1,095	1,162	62	75	67
Hyundai Kia	16%	9%	15%	1,443	1,037	1,378	90	118	94
Jaguar Land Rover[1, 2]	0%	11%	8%	-	1,029	769		96	96
Mazda	13%	12%	12%	923	866	903	72	73	72
Mitsubishi	14%	15%	14%	976	1,468	1,115	69	96	77
Nissan	18%	15%	17%	902	878	894	50	59	53
Subaru	14%	12%	12%	949	497	609	69	42	50
Tesla[2]	0%	0%	0%	-	-	-			
Toyota	13%	8%	10%	617	652	632	49	80	61
Volvo[1, 2]	8%	0%	3%	764	-	376	98		115
Volkswagen[1]	8%	7%	8%	729	650	712	87	94	89
Total	14%	13%	14%	1,111	1,246	1,174	77	95	86

[1]Manufacturer assumed to be willing to pay civil penalties as allowed under EPCA/EISA, if doing so would be more financially attractive than further increasing average fuel economy.

[2]Blank entry indicates no incremental change compared to No-Action Alternative.

Table 13.12 reports average fuel consumption improvements and technology costs on an incremental basis. Measured relative to vehicles that continue with fuel economy and technology at model year 2015 levels, the added fuel-saving technologies appear considerably more cost-efficient.

Table 13.13, Table 13.14, and Table 13.15 show total costs and average additional per vehicle costs (above 2015 levels) for the baseline case, or the "No Action Alternative." The three tables show passenger cars, light trucks, and cars and trucks combined, respectively. The No Action Alternative encompasses compliance with existing standards through MY 2021. The variations in post-2021 costs have diverse causes. Specialty manufacturers, such as Volvo or Jaguar Land Rover, selling few models, may have very "lumpy" redesign costs, while manufacturers may liquidate credit balances in particular years. And all manufacturers are projected to incur additional technology costs as redesigns to shared engines, transmissions, and platforms that occurred in prior model years propagate through to all the models on which they are shared. In some cases, this sharing crosses the boundary between light trucks and passenger cars – where an engine (for example) must be updated to achieve compliance with the passenger car standard, but then eventually filters through to all of the light trucks that share that engine when they are redesigned. It is also the case, for some manufacturers, that credits earned in earlier model years have been carried forward (in the simulation), provide opportunities for technology application to bring the fleet into compliance with MY2021 standards in model years 2022 and beyond.

Table 13.13 Passenger Cars: Total Cost and Average per Vehicle Costs for the No-Action Alternative for the Primary Analysis Using RPE to Mark Up Direct Costs

	Total Costs (2013 $b) under No-Action Alternative						Average Costs (2013 $) under No-Action Alternative							
Manufacturer	2015-2021	2022	2023	2024	2025	2026-2028	2021	2022	2023	2024	2025	2026	2027	2028
BMW	1.0	0.4	0.4	0.4	0.4	1.5	1,391	1,420	1,475	1,447	1,455	1,508	1,537	1,510
Daimler	0.8	0.4	0.4	0.3	0.3	1.0	1,469	1,706	1,620	1,549	1,518	1,488	1,462	1,449
Fiat-Chrysler	5.2	1.3	1.2	1.2	1.2	3.6	2,118	2,079	2,019	1,973	1,930	1,909	1,884	1,872
Ford	4.5	1.5	1.5	1.4	1.6	5.1	1,653	1,636	1,613	1,603	1,666	1,695	1,735	1,706
General Motors	5.0	1.2	1.3	1.3	1.3	3.7	1,106	1,092	1,078	1,065	1,046	1,035	1,021	1,007
Honda	0.6	0.1	0.2	0.2	0.2	0.7	109	172	216	238	234	234	235	233
Hyundai Kia	5.4	1.4	1.4	1.4	1.4	4.3	1,284	1,349	1,320	1,304	1,278	1,268	1,255	1,242
Jaguar Land Rover	0.2	0.1	0.1	0.1	0.0	0.1	2,333	2,281	2,236	2,217	1,666	1,647	1,786	1,991
Mazda	0.1	0.0	0.1	0.1	0.1	0.2	126	238	334	359	351	371	368	365
Mitsubishi	0.1	0.1	0.1	0.1	0.1	0.2	827	940	926	916	893	885	875	875
Nissan	1.2	0.3	0.4	0.4	0.4	1.1	389	414	414	417	410	409	406	403
Subaru	0.6	0.2	0.1	0.1	0.1	0.4	1,083	1,076	1,068	1,048	1,013	998	1,002	1,001
Toyota	2.3	0.6	0.6	0.6	0.6	1.9	493	534	518	531	522	510	504	501
Volvo	0.2	0.0	0.0	0.0	0.0	0.2	1,027	1,076	1,070	1,055	1,059	1,050	1,198	1,182
Volkswagen	2.2	0.9	0.9	0.9	1.0	2.9	1,574	1,554	1,574	1,540	1,571	1,538	1,538	1,525
Total	29.5	8.5	8.6	8.6	8.7	26.9	1,019	1,047	1,035	1,020	1,016	1,014	1,015	1,008

Table 13.14 Light Trucks: Total Cost and Average per Vehicle Costs for the No-Action Alternative for the Primary Analysis Using RPE to Mark Up Direct Costs

	Total Costs (2013 $b) under No-Action Alternative						Average Costs (2013 $) under No-Action Alternative							
Manufacturer	2015-2021	2022	2023	2024	2025	2026-2028	2021	2022	2023	2024	2025	2026	2027	2028
BMW	0.3	0.1	0.1	0.1	0.1	0.3	764	786	742	852	831	776	721	714
Daimler	0.8	0.2	0.2	0.2	0.2	0.5	1,124	990	1,050	1,157	1,134	1,156	1,143	1,144
Fiat-Chrysler	11.8	2.6	2.6	2.5	2.6	7.4	1,738	1,775	1,751	1,718	1,727	1,708	1,688	1,669
Ford	5.0	1.5	1.5	1.4	1.4	4.8	1,129	1,126	1,110	1,099	1,102	1,209	1,178	1,159
General Motors	4.1	0.9	0.9	0.9	0.9	2.6	630	616	607	596	613	607	601	595
Honda	0.3	0.1	0.1	0.1	0.1	0.4	94	90	134	142	180	178	230	228
Hyundai Kia	1.8	0.4	0.5	0.5	0.5	1.3	2,003	1,946	1,980	2,023	1,986	1,965	1,949	1,921
Jaguar Land Rover	0.5	0.1	0.1	0.1	0.2	0.5	1,661	1,697	1,720	1,695	2,164	2,163	2,139	2,100
Mazda	0.3	0.0	0.1	0.1	0.1	0.2	416	408	649	637	625	620	615	609
Mitsubishi	0.0	0.0	0.0	0.0	0.0	0.0	417	409	401	393	385	381	377	373
Nissan	1.7	0.4	0.4	0.4	0.4	1.2	890	882	861	845	842	848	841	845
Subaru	0.7	0.2	0.2	0.2	0.2	0.6	464	453	432	422	423	422	420	405
Toyota	7.5	1.6	1.6	1.6	1.5	4.5	1,627	1,576	1,553	1,522	1,496	1,477	1,461	1,446
Volvo	0.2	0.1	0.1	0.1	0.1	0.2	1,382	1,438	1,425	1,404	1,376	1,365	1,280	1,258
Volkswagen	0.7	0.2	0.2	0.2	0.2	0.5	1,119	1,035	943	1,064	1,005	983	971	955
Total	35.6	8.5	8.4	8.3	8.4	25.0	1,087	1,075	1,067	1,061	1,067	1,076	1,067	1,051

Table 13.15 All Vehicles: Total Cost and Average per Vehicle Costs for the No-Action Alternative for the Primary Analysis Using RPE to Mark Up Direct Costs

Manufacturer	Total Costs (2013 $b) under No-Action Alternative						Average Costs (2013 $) under No-Action Alternative							
	2015-2021	2022	2023	2024	2025	2026-2028	2021	2022	2023	2024	2025	2026	2027	2028
BMW	1.2	0.5	0.5	0.6	0.6	1.8	1,180	1,208	1,237	1,258	1,252	1,267	1,277	1,269
Daimler	1.5	0.5	0.5	0.5	0.5	1.5	1,313	1,389	1,377	1,383	1,358	1,352	1,332	1,327
Fiat-Chrysler	17.0	3.8	3.8	3.7	3.7	11.1	1,847	1,865	1,829	1,792	1,786	1,769	1,748	1,732
Ford	9.5	3.1	2.9	2.9	3.0	9.9	1,342	1,333	1,314	1,303	1,339	1,415	1,415	1,393
General Motors	9.1	2.2	2.2	2.1	2.1	6.3	836	821	820	809	811	799	791	783
Honda	0.8	0.2	0.3	0.3	0.3	1.1	102	136	180	197	211	211	233	231
Hyundai Kia	7.2	1.9	1.8	1.9	1.8	5.6	1,414	1,456	1,439	1,432	1,403	1,387	1,372	1,351
Jaguar Land Rover	0.7	0.2	0.2	0.2	0.2	0.6	1,808	1,832	1,847	1,823	2,040	2,033	2,049	2,072
Mazda	0.4	0.1	0.1	0.1	0.1	0.5	225	299	450	457	446	457	453	452
Mitsubishi	0.2	0.1	0.1	0.1	0.1	0.2	701	782	771	770	745	738	729	733
Nissan	3.0	0.7	0.7	0.7	0.8	2.3	567	580	565	563	556	560	553	552
Subaru	1.3	0.4	0.4	0.4	0.4	1.0	603	604	576	564	557	552	566	552
Toyota	9.8	2.2	2.2	2.2	2.2	6.4	1,037	1,029	1,010	994	966	947	934	920
Volvo	0.4	0.1	0.1	0.1	0.1	0.3	1,218	1,275	1,264	1,244	1,223	1,213	1,240	1,221
Volkswagen	2.8	1.1	1.1	1.1	1.2	3.4	1,464	1,431	1,430	1,434	1,444	1,416	1,418	1,404
Total	65.1	17.0	16.9	16.9	17.1	51.9	1,053	1,061	1,051	1,040	1,040	1,043	1,039	1,028

Table 13.16, Table 13.17, and Table 13.18 show the additional cost and average per vehicle cost by manufacturer of complying with the Augural Standards for MY2022 – 2025. The three tables cover passenger cars, light trucks, and all light duty vehicles, respectively. These costs are in addition to the costs for the "No Action" alternative, shown in Table 13.13, Table 13.14, and Table 13.15.

As noted above, manufacturers, as simulated by the model, begin investing in compliance with the Augural Standards from 2016, both to get ahead of the redesign cycle and also to obtain bankable credits by applying relatively lower cost technologies. Costs rise with time, are mostly trivial before MY2019 and then flatten after MY2027 as manufacturers exhaust carried-forward credits and bring both fleets into compliance. Per vehicle compliance costs are generally similar for passenger cars and light trucks, though there are large variations across manufacturers, based on each manufacturer's product line and available technology choices.

Table 13.16 Passenger Cars Additional Total Cost and Average per Vehicle Costs for the MYs 2022-2025 Augural Standards for the Primary Analysis Using RPE to Mark Up Direct Costs

Manufacturer	Total Additional Costs (2013 $b) under Augural Standards						Additional Average Costs (2013 $) under Augural Standards							
	2015-2021	2022	2023	2024	2025	2026-2028	2021	2022	2023	2024	2025	2026	2027	2028
BMW	-	0.1	0.2	0.3	0.4	1.3	-	310	604	952	1,265	1,243	1,259	1,404
Daimler	-	0.1	0.2	0.2	0.3	0.9	-	402	712	1,079	1,370	1,263	1,257	1,398
Fiat-Chrysler	1.0	0.6	0.7	0.7	0.7	2.4	911	975	1,170	1,145	1,127	1,239	1,226	1,288
Ford	1.4	1.0	0.9	0.9	1.1	4.1	789	1,020	999	1,018	1,215	1,389	1,382	1,374
General Motors	2.4	1.3	1.6	1.6	1.9	5.9	1,078	1,125	1,313	1,376	1,591	1,577	1,660	1,637
Honda	0.2	0.4	0.6	0.8	1.0	3.3	89	493	707	952	1,127	1,114	1,222	1,208
Hyundai Kia	0.3	0.9	1.0	1.1	1.5	5.0	269	879	972	1,063	1,341	1,476	1,465	1,443
Jaguar Land Rover	-	0.0	0.0	0.0	0.0	0.1	-	363	642	930	1,624	1,629	1,508	1,456
Mazda	0.2	0.1	0.2	0.2	0.2	0.6	375	576	866	869	852	944	933	923
Mitsubishi	0.1	0.1	0.1	0.1	0.1	0.2	699	1,103	1,068	1,045	1,014	1,014	996	976
Nissan	0.9	0.5	0.6	0.7	0.7	2.4	398	562	674	819	827	845	857	902
Subaru	0.1	0.1	0.1	0.1	0.1	0.4	424	803	918	1,013	998	977	960	949
Toyota	0.1	0.1	0.2	0.2	0.6	2.1	68	70	139	207	458	469	577	617
Volvo	-	0.0	0.0	0.0	0.1	0.2	-	244	555	877	1,193	1,208	1,442	1,425
Volkswagen	-	0.2	0.4	0.6	0.8	2.7	-	309	609	956	1,295	1,369	1,410	1,409
Total	6.6	5.4	6.6	7.7	9.5	31.4	422	657	801	917	1,102	1,151	1,190	1,207

Table 13.17 Light Trucks: Additional Total Cost and Average per Vehicle Costs for the MYs 2022-2025 Augural Standards for the Primary Analysis Using RPE to Mark Up Direct Costs

Manufacturer	Total Additional Costs (2013 $b) under Augural Standards						Additional Average Costs (2013 $) under Augural Standards							
	2015-2021	2022	2023	2024	2025	2026-2028	2021	2022	2023	2024	2025	2026	2027	2028
BMW	-	0.0	0.1	0.1	0.1	0.5	-	192	471	728	1,010	1,052	1,093	1,030
Daimler	-	0.0	0.1	0.1	0.1	0.7	-	177	408	593	902	1,319	1,313	1,871
Fiat-Chrysler	2.1	0.9	0.9	1.1	1.2	5.4	550	627	618	763	776	1,037	1,349	1,335
Ford	2.0	1.9	2.1	2.1	2.3	7.9	1,351	1,428	1,605	1,568	1,773	1,960	1,949	1,931
General Motors	1.9	0.6	1.0	1.3	1.5	6.2	424	420	714	927	1,055	1,114	1,570	1,604
Honda	0.1	0.3	0.3	0.4	0.8	2.2	175	510	520	582	1,159	1,144	1,115	1,095
Hyundai Kia	-	0.1	0.1	0.2	0.3	0.7	-	278	544	851	1,081	1,064	1,046	1,037
Jaguar Land Rover	-	0.0	0.0	0.1	0.1	0.3	-	213	449	703	859	1,025	1,334	1,359
Mazda	-	0.0	0.1	0.1	0.1	0.3	-	4	940	920	902	888	875	866
Mitsubishi	0.1	0.0	0.0	0.0	0.0	0.1	1,281	1,247	1,214	1,333	1,546	1,520	1,493	1,468
Nissan	0.3	0.2	0.2	0.2	0.3	1.1	384	446	474	509	699	702	739	878
Subaru	0.2	0.2	0.3	0.2	0.3	0.7	397	527	526	517	500	492	493	497
Toyota	-	-	0.0	0.0	0.0	1.6	-	-	25	26	33	314	578	652
Volvo	-	0.0	0.0	0.0	0.1	0.2	-	279	529	796	1,085	1,084	1,107	1,114
Volkswagen	-	0.0	0.1	0.2	0.2	0.7	-	236	513	1,023	1,330	1,369	1,342	1,268
Total	6.7	4.5	5.4	6.2	7.4	28.5	477	568	695	792	939	1,081	1,264	1,289

Table 13.18 All Vehicles: Additional Total Costs and Average per Vehicle Costs for the MYs 2022-2025 Augural Standards for the Primary Analysis Using RPE to Mark Up Direct Costs

Manufacturer	Total Additional Costs (2013 $b) under Augural Standards						Additional Average Costs (2013 $) under Augural Standards							
	2015-2021	2022	2023	2024	2025	2026-2028	2021	2022	2023	2024	2025	2026	2027	2028
BMW	-	0.1	0.2	0.4	0.5	1.7	-	271	561	881	1,182	1,180	1,206	1,291
Daimler	-	0.1	0.2	0.3	0.5	1.6	-	302	583	874	1,175	1,286	1,280	1,587
Fiat-Chrysler	3.1	1.5	1.6	1.8	1.8	7.9	653	730	778	874	878	1,097	1,311	1,321
Ford	3.5	2.9	3.0	3.0	3.4	12.0	1,122	1,262	1,359	1,345	1,538	1,718	1,708	1,693
General Motors	4.2	1.9	2.6	3.0	3.4	12.1	706	723	985	1,131	1,299	1,322	1,611	1,620
Honda	0.3	0.8	0.9	1.2	1.7	5.5	127	500	624	793	1,141	1,127	1,178	1,162
Hyundai Kia	0.3	1.0	1.2	1.3	1.7	5.7	221	771	895	1,025	1,295	1,406	1,395	1,378
Jaguar Land Rover	-	0.0	0.1	0.1	0.1	0.4	-	248	497	759	1,050	1,177	1,379	1,384
Mazda	0.2	0.1	0.3	0.3	0.3	0.9	247	373	893	887	869	925	913	903
Mitsubishi	0.2	0.1	0.1	0.1	0.1	0.3	879	1,146	1,111	1,126	1,169	1,161	1,141	1,115
Nissan	1.2	0.7	0.8	0.9	1.1	3.4	393	521	606	714	783	796	817	894
Subaru	0.2	0.4	0.4	0.4	0.4	1.1	403	594	614	629	613	602	610	609
Toyota	0.1	0.1	0.2	0.3	0.6	3.7	36	37	84	122	264	399	578	632
Volvo	-	0.0	0.0	0.1	0.1	0.3	-	263	541	833	1,138	1,144	1,269	1,267
Volkswagen	-	0.2	0.4	0.8	1.1	3.4	-	291	587	971	1,303	1,369	1,395	1,379
Total	13.3	9.8	12.1	13.9	16.8	59.9	450	613	749	857	1,024	1,118	1,225	1,245

Table 13.19, Table 13.20, and Table 13.21 show total costs and average per-vehicle costs for each manufacturer, based on compliance both with existing standards and the Augural Standards, with the three tables showing passenger cars, light trucks, and all light duty vehicles, respectively. These tables are the sum/average of the corresponding tables for the no-action

alternative and Augural Standards (above), and may be interpreted as an estimate of future costs to be incurred by manufacturers for all current and Augural post-2015 fuel economy standards.

Table 13.19 Passenger Costs: Total Cost and Total Average per Vehicle Costs for the MYs 2022-2025 Augural Standards for the Primary Analysis Using RPE to Mark Up Direct Costs

Manufacturer	Total Costs (2013 $b) under Augural Standards						Total Average Costs (2013 $) under Augural Standards							
	2015-2021	2022	2023	2024	2025	2026-2028	2021	2022	2023	2024	2025	2026	2027	2028
BMW	1.0	0.5	0.6	0.7	0.8	2.7	1,391	1,730	2,079	2,399	2,720	2,751	2,796	2,914
Daimler	0.8	0.4	0.5	0.6	0.7	1.9	1,469	2,108	2,333	2,627	2,889	2,751	2,718	2,847
Fiat-Chrysler	6.1	1.9	1.9	1.8	1.9	6.1	3,029	3,054	3,189	3,118	3,058	3,148	3,110	3,160
Ford	6.0	2.5	2.4	2.3	2.7	9.3	2,442	2,656	2,612	2,621	2,881	3,083	3,117	3,080
General Motors	7.4	2.5	2.8	2.9	3.2	9.5	2,185	2,217	2,391	2,441	2,637	2,612	2,682	2,645
Honda	0.7	0.6	0.8	1.0	1.2	4.0	198	664	923	1,190	1,361	1,349	1,457	1,441
Hyundai Kia	5.8	2.3	2.4	2.5	2.8	9.2	1,553	2,228	2,292	2,367	2,619	2,745	2,720	2,685
Jaguar Land Rover	0.2	0.1	0.1	0.1	0.1	0.3	2,333	2,644	2,878	3,147	3,290	3,276	3,294	3,447
Mazda	0.3	0.2	0.2	0.3	0.3	0.9	501	814	1,200	1,228	1,204	1,315	1,300	1,288
Mitsubishi	0.2	0.1	0.1	0.1	0.1	0.3	1,527	2,043	1,994	1,961	1,907	1,899	1,871	1,851
Nissan	2.1	0.8	0.9	1.1	1.1	3.5	787	976	1,088	1,237	1,237	1,255	1,264	1,305
Subaru	0.6	0.3	0.3	0.3	0.3	0.9	1,507	1,879	1,986	2,061	2,011	1,975	1,962	1,949
Toyota	2.4	0.7	0.7	0.9	1.2	4.0	562	604	656	738	980	979	1,082	1,119
Volvo	0.2	0.1	0.1	0.1	0.1	0.3	1,027	1,319	1,625	1,933	2,252	2,258	2,640	2,607
Volkswagen	2.2	1.1	1.3	1.5	1.8	5.6	1,574	1,862	2,183	2,497	2,866	2,907	2,948	2,934
Total	36.1	13.9	15.2	16.3	18.2	58.3	1,441	1,704	1,836	1,937	2,118	2,164	2,205	2,215

Table 13.20 Light Trucks: Total Cost and Total Average per Vehicle Costs for the MYs 2022-2025 Augural Standards for the Primary Analysis Using RPE to Mark Up Direct Costs

Manufacturer	Total Costs (2013 $b) under Augural Standards						Total Average Costs (2013 $) under Augural Standards							
	2015-2021	2022	2023	2024	2025	2026-2028	2021	2022	2023	2024	2025	2026	2027	2028
BMW	0.3	0.1	0.2	0.2	0.3	0.8	764	977	1,213	1,580	1,841	1,828	1,814	1,744
Daimler	0.8	0.2	0.2	0.3	0.3	1.2	1,124	1,167	1,457	1,750	2,036	2,475	2,457	3,015
Fiat-Chrysler	13.9	3.5	3.5	3.6	3.7	12.9	2,288	2,403	2,369	2,481	2,503	2,745	3,037	3,004
Ford	7.0	3.5	3.6	3.5	3.7	12.7	2,480	2,553	2,715	2,667	2,875	3,170	3,126	3,090
General Motors	5.9	1.5	1.9	2.2	2.4	8.8	1,055	1,036	1,322	1,522	1,668	1,721	2,170	2,199
Honda	0.4	0.4	0.4	0.5	0.9	2.6	269	600	654	723	1,339	1,323	1,345	1,323
Hyundai Kia	1.8	0.5	0.6	0.7	0.7	2.0	2,003	2,224	2,525	2,874	3,067	3,028	2,995	2,958
Jaguar Land Rover	0.5	0.2	0.2	0.2	0.2	0.8	1,661	1,910	2,169	2,398	3,023	3,187	3,473	3,459
Mazda	0.3	0.0	0.2	0.2	0.2	0.5	416	412	1,589	1,557	1,527	1,508	1,490	1,475
Mitsubishi	0.1	0.0	0.0	0.0	0.1	0.1	1,698	1,656	1,615	1,726	1,931	1,900	1,870	1,841
Nissan	2.0	0.6	0.6	0.6	0.7	2.2	1,275	1,329	1,335	1,354	1,541	1,551	1,580	1,724
Subaru	0.9	0.4	0.5	0.5	0.5	1.3	860	980	958	939	923	914	913	902
Toyota	7.5	1.6	1.6	1.6	1.6	6.0	1,627	1,576	1,578	1,547	1,529	1,792	2,039	2,098
Volvo	0.2	0.1	0.1	0.1	0.1	0.3	1,382	1,718	1,954	2,200	2,462	2,449	2,386	2,373
Volkswagen	0.7	0.2	0.3	0.4	0.4	1.2	1,119	1,271	1,457	2,088	2,336	2,352	2,313	2,224
Total	42.3	13.0	13.8	14.5	15.7	53.5	1,565	1,642	1,762	1,852	2,006	2,157	2,331	2,340

Table 13.21 All Vehicles: Total Cost and Total Average per Vehicle Costs for the MYs 2022-2025 Augural Standards for the Primary Analysis Using RPE to Mark Up Direct Costs

Manufacturer	Total Costs (2013 $b) under Augural Standards						Total Average Costs (2013 $) under Augural Standards							
	2015-2021	2022	2023	2024	2025	2026-2028	2021	2022	2023	2024	2025	2026	2027	2028
BMW	1.2	0.6	0.8	1.0	1.1	3.5	1,180	1,479	1,798	2,139	2,434	2,447	2,483	2,560
Daimler	1.5	0.6	0.7	0.9	1.0	3.1	1,313	1,691	1,959	2,257	2,534	2,638	2,611	2,914
Fiat-Chrysler	20.0	5.3	5.4	5.5	5.6	18.9	2,500	2,594	2,607	2,666	2,664	2,866	3,059	3,052
Ford	13.0	5.9	6.0	5.8	6.4	21.9	2,464	2,595	2,673	2,648	2,878	3,133	3,122	3,086
General Motors	13.3	4.1	4.7	5.1	5.6	18.4	1,542	1,544	1,805	1,940	2,109	2,121	2,402	2,403
Honda	1.2	1.0	1.2	1.5	2.1	6.6	229	636	804	989	1,352	1,338	1,411	1,393
Hyundai Kia	7.6	2.8	3.0	3.2	3.6	11.2	1,635	2,228	2,334	2,457	2,698	2,793	2,767	2,729
Jaguar Land Rover	0.7	0.2	0.2	0.3	0.3	1.0	1,808	2,080	2,343	2,582	3,090	3,210	3,428	3,456
Mazda	0.6	0.2	0.4	0.4	0.4	1.4	472	672	1,343	1,344	1,315	1,382	1,366	1,355
Mitsubishi	0.3	0.1	0.2	0.2	0.2	0.5	1,580	1,928	1,882	1,895	1,914	1,899	1,871	1,848
Nissan	4.2	1.4	1.5	1.7	1.8	5.7	960	1,101	1,171	1,277	1,340	1,356	1,370	1,446
Subaru	1.5	0.7	0.7	0.7	0.8	2.1	1,006	1,197	1,190	1,194	1,169	1,155	1,176	1,161
Toyota	9.9	2.3	2.4	2.5	2.8	10.0	1,073	1,066	1,095	1,116	1,230	1,346	1,511	1,552
Volvo	0.4	0.1	0.2	0.2	0.2	0.7	1,218	1,538	1,805	2,077	2,360	2,357	2,509	2,488
Volkswagen	2.8	1.3	1.5	1.9	2.2	6.8	1,464	1,722	2,017	2,405	2,747	2,785	2,813	2,784
Total	78.4	26.8	29.0	30.8	33.9	111.8	1,502	1,674	1,800	1,896	2,065	2,161	2,264	2,273

Sensitivity of Cost to Key Inputs

Just as the estimated costs and technology application rates developed in the 2012 analysis have been demonstrated to be sensitive to changing conditions in the real world over time, so the results of the Draft TAR analysis are as well. NHTSA examined how alternative assumptions about critical inputs to the simulation would change outcomes of interest. Table 13.22 describes the range of assumptions considered for each sensitivity case as well as the aspects of the CAFE compliance and effects simulation that are impacted by the assumption. As the remainder of this section shows, not all assumptions will impact all metrics of interest.

Table 13.22 Definition of Sensitivity Cases Considered For Draft TAR

Sensitivity	Description	High case	Low case	Affects
Fuel prices	AEO 2015 fuel price cases	AEO 2015 high	AEO 2015 low	Value of fuel savings, PC/LT split, over compliance, technology choices, combined required CAFE, achieved CAFE, fine payment
MR restrictions	Vary the PC restriction with existing costs	No restrictions	All PCs stop at MR1 (unless they already have > MR1)	Tech choices, societal safety, net benefits, achieved CAFE
Lifetime VMT	Higher/Lower Lifetime VMT than current schedule	35% - 55% higher lifetime	14% - 27% lower lifetime	Tech choices, crash exposure and societal safety, fuel savings
Battery costs	Higher/Lower battery costs than current	None	$100/kwh	Tech choices/penetration, tech costs, fuel savings, achieved CAFE
MR costs	Higher/lower MR cost curves	NAS cost	Fraction of NAS	Tech choices, tech cost, fine payers, safety
Product Cadence	Vary length of existing redesigns	2 years longer	2 years shorter, adds as many as two redesigns to study period	Tech choices, tech cost, achieved CAFE, over compliance
Rebound Effect	Span range in rebound literature	30%	0%	Fuel savings, crash exposure and societal safety, externalities, mobility benefit
Demand for FE	Varies amount that OEMs assume consumers are willing to pay for additional fuel economy beyond CAFE levels (months)	36 months	0 months	Fuel savings, Achieved CAFE, net benefits, over compliance, tech choices
Safety coefficients	5th and 95th percentile of safety coefficients	95^{th}	5^{th}	Societal safety, net benefits

The two bar plots in Figure 13.39 and Figure 13.40, show the percentage change in regulatory costs (technology costs plus fines) under these alternative assumptions. The first of these shows the change in total regulatory costs under the Augural Standards over the study period (for the industry) incremental to the continuation of the final standards through MY2021. Figure 13.39 shows that considerably lower battery costs can lower estimated compliance costs for the industry – which also produces a different technology solution than described earlier in this section, as higher levels of electrification become more cost competitive. Battery costs are an important element in the cost of employing battery electric vehicles and hybrids. However, they also affect how these two technologies compete with each other and with other technologies.

One result that may seem counterintuitive is the fact that longer product cadence (more years between redesigns) actually reduces the incremental cost. However, this is a result of increasing costs in the baseline relative to the central analysis described above – as manufacturers have fewer opportunities to apply technology during the augural standard period, more technology is added in earlier model years, reducing the incremental cost of the Augural Standards. Changes in the price of oil (relative to the AEO2015 reference case that informs the central Draft TAR analysis) influences the share of light trucks in the new vehicle fleet, as well as consumer preferences for fuel saving technology. Both factors influence incremental (and total) regulatory cost attributable to the Augural Standards. Similarly, by assuming that consumers are willing to pay for more fuel saving technology above and beyond the levels required by CAFE standards, more technology is applied in the baseline to satisfy consumer demand for fuel economy, leaving less technology that needs to be applied under the Augural Standards and reducing the incremental cost attributable to them. Other alternative assumptions had smaller impact on incremental cost.

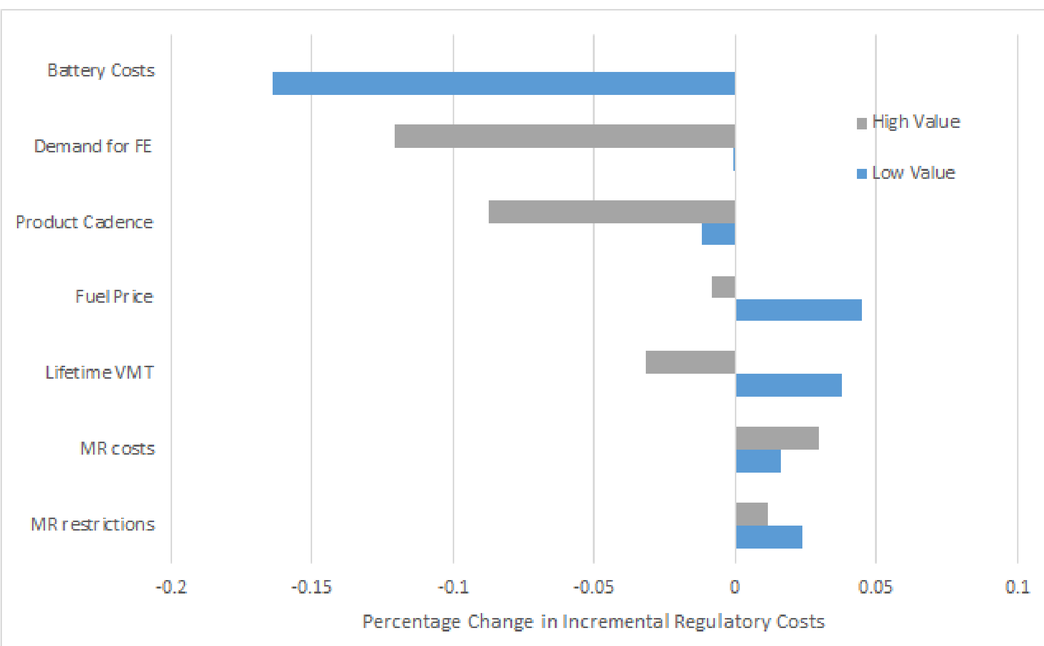

Figure 13.39 Sensitivity of Incremental Regulatory Costs (MY2016 – MY2030) to Alternative Assumptions

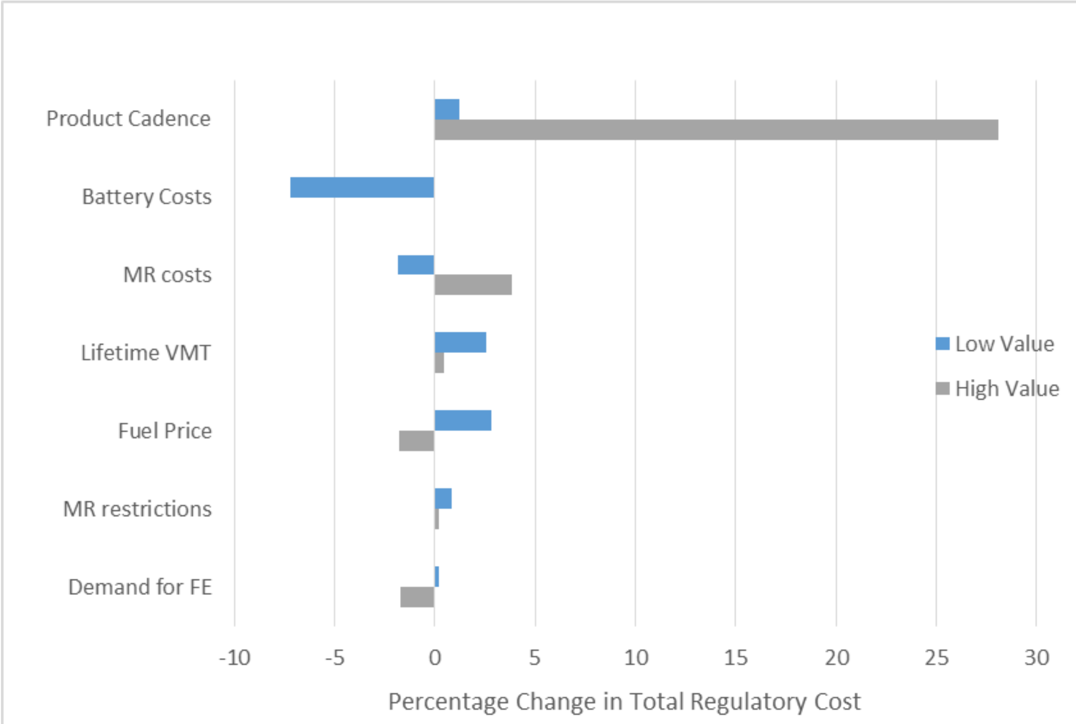

Figure 13.40 Sensitivity of Total Regulatory Costs (MY2016 - MY2030) to Alternative Assumptions

As Figure 13.40 shows, the rank ordering of importance changes in the context of total, rather than incremental, regulatory cost over the period. Where assumed demand for fuel economy was of critical importance to the attribution of cost to the Augural Standards, when accounting for the change in total cost between MY2016 and MY2030, it makes a much smaller difference – influencing total cost only through the series of technology solutions that appear attractive to manufacturers. However, the assumption with the highest influence on total cost is now product cadence – where longer design cycles limit manufacturers' choices and lead to cost increases approaching 30 percent over the central analysis. Battery costs, while less important than product cadence, influences total cost in the direction one would expect (as do mass reduction cost cases), though by less than 10 percent.

NHTSA also conducted a sensitivity case analysis using indirect cost multiplier (ICM) in place of retail price equivalent (RPE) which was used for the primary analysis. In developing cost estimates for technologies applied to new vehicles, the manufacturing cost of a particular element, for example, a continuously variable transmission, is only a portion of the total cost of placing a new technology on a vehicle. The full cost of the part includes not just manufacturing, but also research and development costs, overhead, future warranty costs, and other elements. RPE and ICM methodologies for estimating indirect costs are discussed in Chapter 5. Table 13.23 shows production volumes and average per vehicle costs for both in the 2012 final rule analysis and the Draft TAR analysis.

Table 13.23 Comparison of Cost Estimates Using Retail Price Equivalent and Indirect Cost Multiplier Mark Up

	MY2025 Production for Sale in U.S.			Average Per-Vehicle Costs[1] in MY2025 (using RPE to Mark Up Direct Costs)			
	Passenger Cars	Light Trucks	Total	Costs added with stringency increases through 2016 [2]	Additional costs with stringency increases through 2021	Additional costs under MYs 2022-2025 Augural Standards	Total costs added under augural standards
2012 Final Rule	10.98	5.47	16.45	785	1,698		2,483
Draft TAR	8.59	7.84	16.43	370	671	1,024	2,065

	MY2025 Production for Sale in U.S.			Average Per-Vehicle Costs[1] in MY2025 (Side Case using ICM to Mark Up Direct Costs)			
	Passenger Cars	Light Trucks	Total	Costs added with stringency increases through 2016 [2]	Additional costs with stringency increases through 2021	Additional costs under MYs 2022-2025 Augural Standards	Total costs added under augural standards
2012 Final Rule	10.98	5.47	16.45	588	1,325		1,913
Draft TAR	8.59	7.84	16.43	322	599	938	1,859

[1] Note: 2012 Final Rule costs in 2010 $. Draft TAR costs in 2013 $.

[2] Costs estimated to be accrued under standards through 2016 reflect different analysis fleets and credits.

13.3.2 <u>Consumer Impacts</u>

As the stringency of CAFE standards increase over time, the average technology cost required for manufacturers to reach compliance will generally increase as well. Cost inputs to today's analysis reflect DOT's judgment that manufacturers are likely to pass future increases in production costs on to consumers, recouping direct and indirect costs, and realizing profits that reflect historical norms. To the extent that demand is elastic, manufacturers may absorb some of the increased technology costs or elect to cross-subsidize some vehicles. Manufacturers might wish to cross-subsidize as a compliance strategy, and/or to *r*espond to competitive pressures, to build volume, to encourage particular customer classes to buy their vehicles, or as a profit-maximization strategy. Since we do not have sufficient information to model the way in which manufacturers actually price their current and future fleets, we cannot make credible assumptions about what share of increased technology costs will be passed directly onto the buyer of a specific vehicle, absorbed by the manufacturer, and/or subsidized by the purchase of other vehicles. Without the information to establish representative assumptions about how each manufacturer will allocate increased costs, we track the increase in technology costs associated with a vehicle, but do not project the change in vehicle price to the consumer.

However, given the uncertainty about how manufacturers will actually allocate costs across their individual models, NHTSA uses the average per-vehicle regulatory cost[15] increase as a means of characterizing the magnitude of the impact of increased technology costs at the manufacturer level.

Although the CAFE model does not currently estimate a potential market response to changes in vehicle prices, it does contain data on initial purchase cost (defined as current year (2015) MSRP reported by the manufacturer) and pro-forma final vehicle purchase cost (defined as 2015 MSRP plus added technology cost to meet the applicable standard) for each specific vehicle model and configuration. NHTSA staff have tested a variety of approaches to allocating regulatory costs, and the CAFE model currently applies a "pay as you go" approach—for example, if a given vehicle model configuration incurs $1,000 in additional technology costs (after markup), the CAFE model currently reports that vehicle model configuration's purchase cost increasing by $1,000 for the Augural Standards, compared with the cost of compliance with the baseline standards. As noted, these are not an accurate estimate of either initial production cost or initial consumer price, nor the compliance production cost or compliance consumer price. They do, however, provide a general indication of the price range of particular models, and also gives some indication of the starting point for manufacturer's consumer price optimization decisions.

NHTSA simulates each model year explicitly and includes several years beyond MY2025, during which the Augural Standards are assumed to remain static at their MY2025 level. As manufacturers use earned and traded credits to manage the degree of modification to either fleet in a single year, it may still be necessary to apply technology after MY2025 in order to reach a stable compliance solution where the fleet can comply with CAFE without using the credit carry-forward provision (though trades between passenger car and truck fleets are likely, even once the standards stabilize). Table 13.24 summarizes information that is available in a cross-section of tables in the section discussing industry impacts, and illustrates the industry average cost increase projected between MY2016 and MY2028 as a result of the final and augural CAFE standards. At the industry level, the average cost increase is similar for passenger cars and light trucks, though individual manufacturers can observe larger differences in average cost between the two classes over the course of the simulation. By the time the fleet reaches a stable compliance level in MY2028, both classes of vehicles are projected to incur over $2,000/vehicle in compliance costs relative to the MY2015 vehicle (assuming RPE methodology).

[15] The combination of technology cost and fines for non-compliance.

Table 13.24 Average Regulatory Cost per Vehicle by Model Year, 2015 - 2028

	Light Trucks			Passenger Cars		
Model Year	Baseline Standards Through MY 2021	Augural CAFE Standards MYs 2022-2025	Total	Baseline Standards Through MY2021	Augural CAFE Standards MYs 2022-2025	Total
2016	300	-	300	200	-	200
2017	450	-	450	350	-	350
2018	750	100	800	500	50	550
2019	850	100	950	600	100	700
2020	950	150	1,100	900	200	1,150
2021	1,100	500	1,550	1,000	400	1,450
2022	1,050	550	1,650	1,050	650	1,700
2023	1,050	700	1,750	1,050	800	1,850
2024	1,050	800	1,850	1,000	900	1,950
2025	1,050	950	2,000	1,000	1,100	2,100
2026	1,100	1,100	2,150	1,000	1,150	2,150
2027	1,050	1,250	2,350	1,000	1,200	2,200
2028	1,050	1,300	2,350	1,000	1,200	2,200

While, as noted above, initial purchase cost as measured by MSRP combined with technology cost are not accurate indicators of either actual consumer prices, nor the increment to consumer prices that would be induced by the Augural Standards, they do provide a general indication of the expected costs that manufacturers would face, based on NHTSA modeling, and hence may represent a reasonable starting point in determining incremental changes in consumer prices.

NHTSA staff have examined how model-by-model estimates of technology costs are distributed by a range of possible proxies for production cost or consumer prices, including footprint (bigger vehicles might cost more), initial MSRP, MSRP plus technology cost, (higher MSRP would generally indicate higher consumer prices), and curb weight (heavier vehicles might cost more). Regression results indicate that there is little relationship between modeled per-vehicle incremental technology costs and any of these indicators, as scatter plots show a classic "cloud" with an essentially arbitrary regression line and show estimated elasticities of around -0.01, and R^2 of 0.02 to 0.04. In other words, individual vehicle technology costs are rather evenly distributed across the range of vehicle cost, measured by multiple proxies for vehicle price or cost, and almost none of the variation in technology costs is explained by these proxies.

The analysis does not attempt to account for any potential cross-subsidy by manufacturers. Although additional analysis could explore various hypotheses about manufacturers' pricing strategies, in the absence of proprietary information about manufacturers' actual costs, prices, and production plans, it would not be possible to demonstrate whether any particular hypothesis was true or false. NHTSA modeling suggests that Augural Standards will increase average vehicle technology costs by about $1,000 per vehicle relative to the average price of a new vehicle under continuation of the MY2021 standard, and we can reasonably expect that manufacturers will wish to raise vehicle prices on average. We cannot, however, predict the extent to which each manufacturer will choose to mix price increases, other cost reductions, and reduced margins in the aggregate, nor how these decisions will be distributed across the vehicles in each manufacturer's fleet.

All of these factors come into play in considering how manufacturers might choose to set prices for new vehicles in the lower price range of the new car market. The initial vehicle fleet contains 8 models that have an initial MSRP under $15,000 (see Chapter 6.5 for a discussion of affordability). Manufacturers have historically used pricing strategies that allow them to service both high and low margin market segments while maintaining overall profitability, often with a view toward building enduring brand loyalty.

Consumer response to manufacturers' pricing decisions is also likely to be heterogeneous across consumer classes. Consumers' are likely to place varying valuations on improvements in fuel economy and other attributes of particular vehicles, and buyers of some vehicles are likely to be more price sensitive than others. Manufacturers' strategies, in turn, will be based, in part, on their a priori assessments of consumer response.

In addition to the probability that vehicles will have higher costs, the deployment of some new fuel economy technologies is likely to be noticeable to new car buyers. While incremental technology changes have often been transparent to new car buyers, for whom an automatic transmission with more gears or a somewhat lighter or more aerodynamic vehicle would not necessarily be obvious, the pace and degree of new technology deployment estimated in the Draft TAR analysis suggests that even casual observers will be aware that new vehicles may be different in important ways.[16] For example by MY 2030, 76 percent of passenger cars and 55 percent of light trucks are projected to have technology that shuts the engine off at idle, including stop-start, integrated starter-generator (mild hybrid), full hybrid system, or plug in hybrid (PHEV) technology. Turbocharged engines account for almost half of new vehicles by MY2030. These technologies may be perceived as positive or negative changes by consumers or as items that provide greater or lesser value. Accordingly, this may influence consumer choices about new vehicle purchases. (See Chapter 6.4 for more detail on consumer acceptance.)

To the extent that new vehicle cost increases are passed on to consumers, other consumer cost elements that scale with purchase price, including interest on car loans, insurance, and some taxes and fees would also increase. NHTSA's analysis includes estimates of some of these types of impacts.

[16] Compared to the 2012 final rule, DOT's current analysis reflects a range of updates to the CAFE model and inputs. These are described further earlier in this chapter in section 13.3.1.

While NHTSA modeling supports that new car buyers are likely to pay more to purchase, register, and insure their new vehicles under the CAFE standards, they as well as subsequent owners will definitely pay less to operate them. A commonly used approach to describing the heuristic that consumers might use to consider the impact of a higher purchase cost offset by reduced operating cost is the "payback period" for incremental technology. Payback period is defined as the number of years of the accumulated dollar value of fuel savings needed to recover the additional cost of technology included in the purchase price of a new vehicle. Payback period is related to, but different from, an economic benefit calculated as a net present value of social benefits and costs over the life of the vehicle. Since payback periods are used to simulate consumer decisions, they use private costs and benefits, including any avoided excise taxes, rather than social costs and benefits. While regulations with short payback periods will usually have net economic benefits, regulations with long payback periods do not necessarily have negative economic benefits.

Figure 13.41 shows the payback period associated with the technology cost increases for new cars and trucks in each as a result of three regimes, using the same projected fuel prices, based on the EIA's Annual Energy Outlook, as the rest of the analysis. The payback periods for the baseline standards are calculated relative to the costs and fuel economy in the MY2015 fleet. The payback periods for the Augural Standards are based on the incremental costs and fuel savings relative to the baseline (i.e., current standards through MY2021 carried forward). The "total" case, represents the world consumers would actually see if the Augural Standards are implemented, and it is defined relative to the MY2015 fleet fuel economy. In the case of the total scenario, it represents the payback period associated with cost increases in all future model years (assuming the final standards through MY2021 and the Augural Standards from MY2022 – MY2025, then carried forward unchanged through MY 2032) and fuel savings relative to the MY2015 fuel economy levels.

Figure 13.41 Payback Periods for the Baseline Standards, Augural Standards, and Total over the Period

The payback periods in the early model years (prior to MY 2019 or MY 2020) are not really meaningful for the Augural Standards, as the incremental cost associated with the Augural Standards in those years are small (under $100/vehicle) and the resulting fuel savings nearly trivial. As the figure shows, payback periods under all three scenarios are longer for cars than for trucks. Passenger cars have comparable average per-vehicle costs under the total program, but start from higher fuel economy levels in general. Improving the fuel economy of a less efficient vehicle leads to greater savings because the same percentage improvement (say, 20 percent, for example) represents a larger absolute savings, since the number of gallons consumed by the less efficient vehicle was larger to start with (so, 20 percent of 600 gallons compared to 20 percent of 250 gallons). In addition, light trucks, on average, are also driven more miles annually than passenger cars, so they accrue greater fuel savings per year. These factors cause the trucks to pay back faster than the cars, in general. Additionally, the trend for the augural standard payback periods is generally downward (trending shorter in successive model years), despite representing fewer gallons of savings relative to the baseline standards. Rising fuel prices over the study period are sufficient to counteract the rising costs associated with increasingly stringent standards, so that payback periods decline even when the average cost increase for a new vehicle is rising over successive model years.

The payback period associated with the incremental impact of the Augural Standards is longer than both the baseline and the combined program, for much the same reason. Fuel economy has diminishing returns – once a vehicle becomes very efficient, improving its fuel economy further saves progressively less fuel because the vehicle consumes so little in the first place. For example, a vehicle that gets 60 MPG and drives 15,000 miles per year consumes 250 gallons of fuel per year. If we improve the fuel economy of that vehicle by 20 percent, improving its fuel economy to 72 MPG at a cost of $500, we save 40 gallons per year. However, at a fuel price of $3/gallon that fuel economy improvement takes more than 4 years to pay back. If instead, we increase the fuel economy of a vehicle that also drives 15,000 miles per year, but gets only 25 MPG, by the same 20 percent, we save 100 gallons per year. At a fuel price of $3/gallon, that same $500 investment pays back in less than 2 years.

The consumer effects of the standards are likely to be heterogeneous across different consumers. The amount of the additional technology costs that manufacturers are able to pass onto consumers, and the amount of the technology costs that are borne by the consumer of the vehicles with these technologies, will depend on the elasticity of demand of particular models, the price of gasoline, and acceptance of new technologies, and the value that consumers place on fuel economy Without this information, we are only able to talk in terms of average costs across the industry without making the assumption that demand is inelastic and manufacturers will not cross-subsidize.

Another aspect of consumer cost is depreciation, defined as the difference between the purchase price of the vehicle and its subsequent market value as a used vehicle. NHTSA does not attempt to model depreciation, and how depreciation would be affected by Augural Standards depends, in part, on how new and used car buyers value improved fuel economy, and if there is a difference. If new car buyers value fuel economy, and manufacturers notice, then they will face higher prices for fuel efficient vehicles, not necessarily at a level related to the cost of providing fuel economy. If new car buyers place low or zero value on fuel economy, then manufacturers will be less able to raise prices.

If new car buyers and used car buyers have similar attitudes towards fuel economy, then depreciation will scale with the price of the vehicle, but if used car buyers value fuel economy but new car buyers do not, then new car buyers would get a benefit in the form of reduced depreciation, while used car buyers have to pay extra for their fuel savings. In the reverse case, where used car buyers do not value fuel economy, but new car buyers do, then new car buyers face increased depreciation, while used car buyers get a double bonus: used cars are less expensive and have reduced operating costs.

Car buyers might value fuel economy, but they may be willing to pay less for a more fuel-efficient vehicle than the out-of-pocket fuel savings anticipated over the vehicle's expected life. This could occur if fuel economy improvements are associated with decreases in other desirable vehicle attributes. Car buyers' willingness to pay may also be less than the value of fuel savings calculated here because buyers have a higher apparent discount rate than what is assumed in this TAR. As discussed above, NHTSA applies a one-year payback period in its compliance and technology application analysis (and assumes manufacturers will recoup all direct and indirect costs and realize normal levels of profit). This one-year payback assumption attempts to address the possible concerns with assuming either that new car and truck buyers place no value on fuel economy or place a sufficiently high value on additional fuel economy to contradict historical observations of preferences in the new car market (where trends toward smaller, more fuel efficient vehicles under high fuel price scenarios have typically retreated as the fuel price fell).

13.3.3 Social and Environmental Impacts

While the concept of incremental social benefits more appropriately used to rank a series of alternatives, it is still possible to characterize some of the trends that NHTSA expects to see as a result of the current final standards and Augural Standards. In addition to conserving the nation's energy, two significant benefits of CAFE standards are the reduction in criteria pollutants that affect individual health and the reduction in greenhouse gas emissions that affect climate change. And Figure 13.42, below, compares the impact on criteria emissions and greenhouse gas emissions of the Draft TAR analysis and the 2012 final rule analysis.

The figure shows that the savings in emissions, fuel gallons, and fuel quads of total energy consumption are generally larger under the Draft TAR analysis than the 2012 analysis. While the savings attributable to passenger cars decreased for both gallons and metric tons of CO_2 saved, the increases attributable to light trucks more than offset those reductions. Although the schedule that (largely) determines lifetime mileage accumulation for each vehicle is lower in the Draft TAR than in the 2012 analysis, the number of vehicles on the road is higher, and total VMT for the overall fleet is higher in the Draft TAR than in the 2012 final rule.

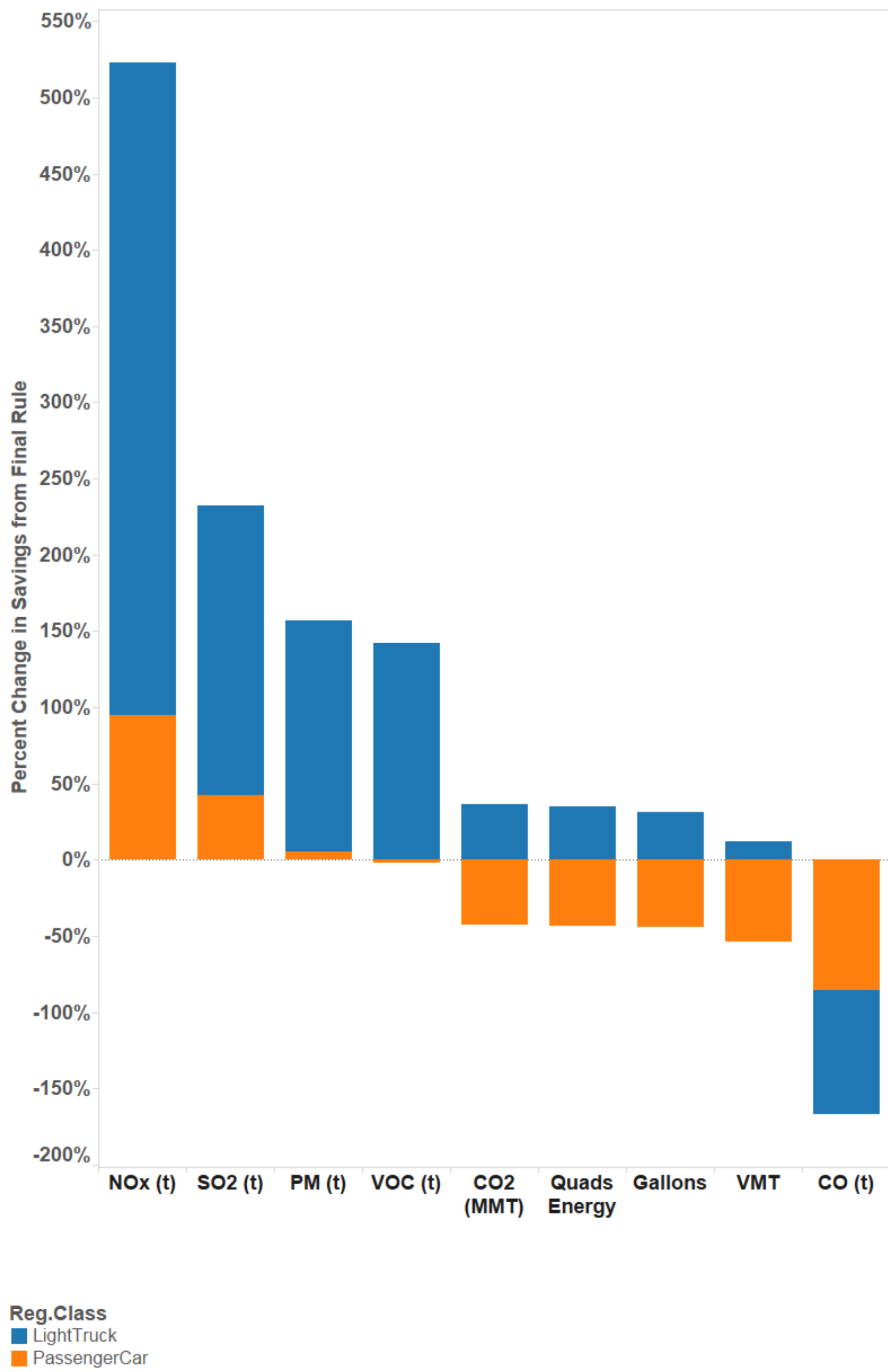

Figure 13.42 Comparison of Environmental And Physical Effects, Draft TAR and 2012 Final Rule

Of particular note in Figure 13.42is the magnitude of the difference in emissions savings for the conventional tailpipe pollutants (NOx and PM). Since the 2012 final rule analysis was conducted, additional tailpipe standards have been implemented that reduce the long-term emissions of these pollutants, and the increase in total VMT relative to the 2012 analysis increases the opportunity to reduce emissions. While the additional VMT associated with the rebound effect does increase the emissions of conventional pollutants from vehicle tailpipes, the reduction in upstream emissions from avoided fuel consumption is significantly larger - and produces social benefits.

Another impact that requires consideration is the impact CAFE standards may have on societal safety, as manufacturers reduce the mass of vehicles to improve fuel economy and vehicle owners increase their travel demand as a result of lower operating costs. Figure 13.43 shows the additional fatalities attributable to the Augural Standards for passenger cars and light trucks (by color). As discussed in Chapter 8 of the Draft TAR, reducing the mass of large light trucks generally has a beneficial impact on societal safety, while the mass reduction in small passenger cars has a negative effect. Both classes are projected to increase the number of miles driven as fuel economy increases (compared to the MY2015 vehicle), however, for light trucks, the increase in exposure to crashes is mitigated by the fact that reducing the mass of those vehicles reduced the severity of the crashes.

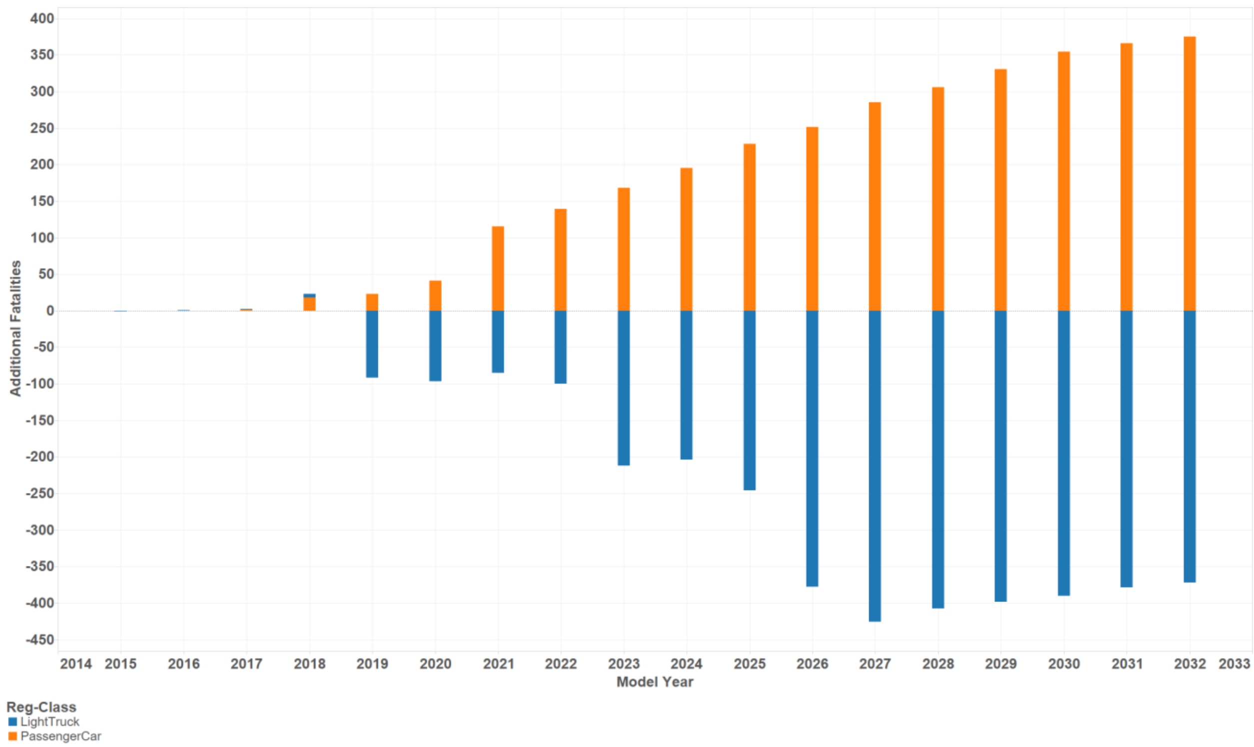

Figure 13.43 Societal Safety Effects for the Augural Standards (relative to MY2021 standards)

As Figure 13.43 shows, the number of fatalities associated with passenger cars under the Augural Standards grows over time as expected (because this figure measures the incremental impacts of the Augural Standards), but the bars below the x-axis represent fatalities avoided by changes to light trucks. The amount of mass reduction that can be applied to passenger cars has been limited in the analysis to achieve overall neutral societal safety, thus showing a pathway manufacturers could use to comply with the Augural Standards that has small net reductions in fatalities over the period when considering both mass reduction and increased VMT.

13.3.4 Overall Benefits and Costs

Table 13.25 summarizes the costs and benefits associated with the implementation of the Augural Standards for MYs 2022 – 2025, relative to the continuation of the MY 2021 standard over the same period (through MY 2028). The social costs associated with the program are primarily a direct result of technology applied to new vehicles to reach compliance with the standards, and appears in the table as technology cost and maintenance cost (resulting from the incremental cost of maintaining more expensive and complicated technology – though in this analysis it is mostly attributable to the cost of replacing low rolling resistance tires over a vehicle's life). In addition to these "cash" costs, are the social costs of the additional travel that results when the cost of driving is reduced as a result of increases in fuel efficiency. These have been grouped together for presentation (though calculated separately), and represent the cost to society of increased vehicular fatalities, crashes (that do not result in fatalities), congestion, and road noise.

The primary benefit of CAFE standards accrue as a result of avoided fuel expenditures by new car and truck buyers. This single category of benefits is sufficient to ensure that the Augural Standards result in net benefits, though it is not the only benefit to society that accrues primarily to buyers of new vehicles. Like the value of fuel savings, other significant social benefits accrue to new car and truck buyers, in particular the value of time associated with less frequent refueling events and the value of additional travel that buyers of more efficient vehicles receive. The latter serves to reduce fuel savings (since the additional driving consumes fuel), but the value of that travel to the individual exceeds the value of the gallons that would have been saved by foregoing the additional travel. Three categories of benefits are the result of reducing externalities that impact society as a result of vehicular travel. Energy security represents the economic risk associated with dependence on oil and exposure to price shocks, the social cost of carbon emissions estimate the long-term economic impact of global climate change, and the conventional pollutant category represents the health savings from reducing exposure to conventional pollutants emitted by vehicle tailpipes and throughout other parts of the fuel production and supply cycle. All costs and benefits are discounted at 3 percent from the year in which they occur.

As the table shows, pre-tax fuel savings are about 15 percent higher for light trucks in this analysis. The projected market share of light trucks is closer to half the market, and trucks have greater opportunities to save fuel both because they start from a lower level of fuel economy and are driven more, on average. While the sum of benefits accruing to buyers of new cars and trucks significantly exceeds the additional cost of new technology (and maintenance) borne by those consumers, the benefits associated with social externalities (only) do not. This was true for the analysis supporting the 2012 final rule CAFE standards as well.

Table 13.25 Estimated Present Value of Costs, Benefits and Net Benefits ($b) Over the Lifetimes of MYs 2016-2028 Vehicles Using 3 Percent Discount Rate (2013$)

	MY 2022 - MY 2025 Augural Standards		
	Light Truck	Passenger Cars	Total
Social Costs			
Technology Cost	42	45	88
Maintenance Cost	2	2	5
Crashes, Fatalities, Congestion, Noise	-3	9	6
Social Benefits			
Pre Tax Fuel Savings	64	56	122
Refueling Time Savings	3	3	6
Energy Security	5	4	9
Social Cost of Carbon Emissions [1]	14	12	27
Increased Mobility	5	4	9
Conventional Pollutants	6	5	11
Net Benefits	55	28	85

[1] [Social cost of carbon to be added]

Sensitivity of Net Benefits to Key Inputs

NHTSA examined how alternative assumptions about critical inputs to the simulation would change outcomes of interest. Table 13.22 describes the range of assumptions considered for each sensitivity case as well as the aspects of the CAFE compliance and effects simulation that are impacted by the assumption. The effects on net benefits are shown below.

Figure 13.44 is type of bar plot often referred to as a “tornado plot,” due to the shape it creates when sensitivities are ranked by their degree of influence on an outcome. It illustrates the change in net benefits attributable to the Augural Standards that results from using the alternative assumptions described in Table 13.22. The end points of each bar indicate the magnitude and direction of the change in net benefits that results from applying the alternative assumption represented by the color of the bar, where blue represents the low value and gray the high value described in Table 13.22for each of the assumptions listed on the left hand side. The reference point is defined as the sum of benefits and costs over model years 2016 to 2030, relative to the continuation of the MY2021 CAFE standards.

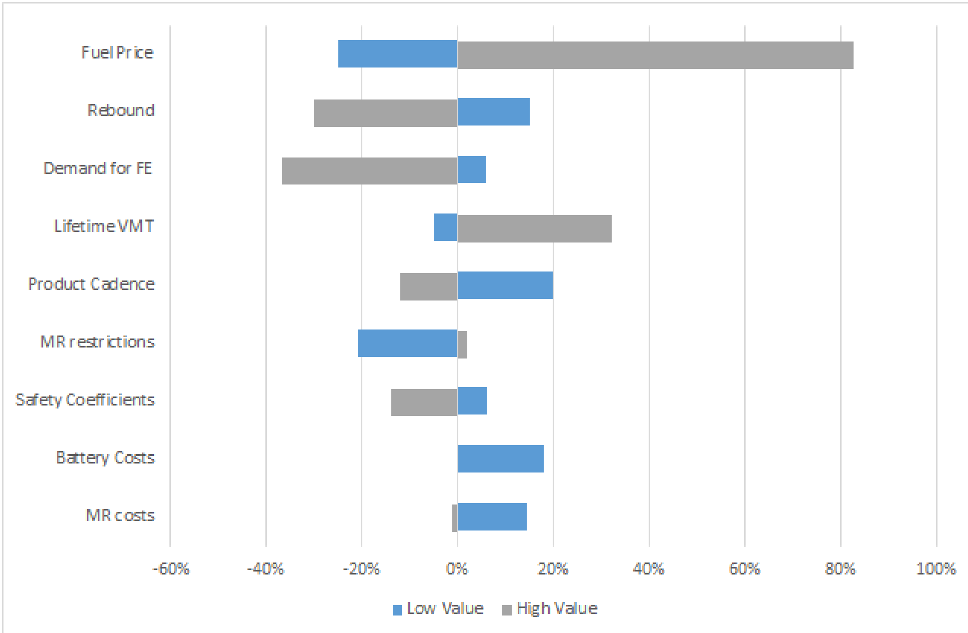

Figure 13.44 Influence of Alternative Assumptions on Net Benefits Attributable to Augural Standards

As in the preceding discussion, we see that assumed fuel prices have the largest influence on the net benefits attributable to the Augural Standards in the Draft TAR analysis. While the low oil price case reduces net social benefits by nearly 30 percent, the high oil price case increases net benefits by over 80 percent. In general, the sensitivity cases all move in intuitive directions. For example, lower costs for mass reduction and battery technologies increase net benefits (while higher mass reduction costs reduce them, but by a trivial magnitude). Like fuel price, rebound impacts the benefits of the program in a way that would be present if we considered net benefits relative to the 2012 final rule baseline. While assuming no rebound effect increases net benefits by about 15 percent, assuming a high rebound effect reduces them by 30 percent.

As we saw in the summary of industry impacts, the assumed consumer demand for fuel economy does not significantly impact total technology cost (across both the baseline and Augural Standards) but it does influence the amount of additional cost, and benefit, that can be attributed to the Augural Standards. If manufacturers assume that consumers will continue to value additional fuel saving technology, even after a manufacturer has reached compliance with CAFE standards, more of that technology will appear in the baseline absent further increases in stringency, and the fuel savings associated with those technologies will net out of the baseline.

As we also saw in the discussion of sensitivity to industry outcomes, product cadence may play an important role. The figure shows that a longer assumed cadence, which has the potential to reduce manufacturers' opportunities to comply with an increase in standards during the year in which it occurs, is likely to result in additional technology into products redesigned in earlier model years. Similarly, shorter cadence increases the opportunities for manufacturers to respond to increasingly stringent standards in the model years where the increases occur – forcing more of the technology cost, and fuel savings benefit, into the model years covered by the Augural Standards.

The alternative assumptions about both mass reduction application and safety coefficients have the directional impact on net benefits that one should expect. Including up to 20 percent mass reduction for passenger cars, reduces net benefits by about 20 percent due to the impact on overall societal safety. In contrast, allowing no mass reduction on passenger cars has a much smaller impact on net benefits. Applying values for the safety coefficients in the 5th and 95th percentile of their confidence interval produces the expected impact on fatalities, which results in changes to net benefits in the 10 – 15 percent range. The combination of these two factors should continue to emphasize the degree to which safety is an important consideration of the CAFE program, and the expected social benefits associated with CAFE standards.