A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies

Revised Final Report

United States
Environmental Protection
Agency

A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies

Revised Final Report

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

Prepared for EPA by
Ricardo, Inc.
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NOTICE

This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments.

EPA United States
Environmental Protection
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Updates to "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies"

The over arching goal for this study was to provide very accurate technology assessments through detailed simulations of various technology packages on CO2, fuel economy, and performance. Given such a goal, Ricardo is hereby issuing a refinement to the previously released report dated 12/21/07 as minor changes have been made that affect the fuel economy benefits by approximately 1.5%. These updates are described below and are comprised of one change to simulations involving cam phasing with cylinder deactivation and five corrections to back up tables.

Simulation Change

- Cylinder Deactivation combined with Cam Phasing

The cam phasing benefit was modified to apply the BMEP level appropriate for cylinder deactivation mode. Previously the cam phasing benefit map associated with all cylinders operating was applied instead of the reduced benefits accruing to cam phasing when in deactivation mode. The larger vehicle classes powered by V6 or V8 engines have technology packages with cylinder deactivation that are affected: Full Size Car (Package 16), Large MPV (Packages 16 and 6b), and Truck (Packages 9 and 12). This change affects the following tables:

  - Table 7-1, all 3 rows. In addition, the first row of this table, for Full Size Car package 16, had calculation errors in the FTP75, HWFET, and Combined Benefit cells that have been corrected.
  - Final Results Tables 7-14 through 7-19
  - Appendix Tables A-5 through A-10
  - Executive Summary Tables 1-8 through 1-10
  - On page 80 of the report the fuel economy benefits were corrected to match the values in Table 7-1 that range from 14 – 19%. The report previously stated the range as 15 – 21%.

Corrections to Back-Up Tables Which Do Not Affect Results Stated in Final Results Tables

- Correction to Tables 2-1, 2-2 and 4-1
  - A typo in the description of the Full Size Car engine was corrected. The engine is a SOHC, not DOHC as previously reported.
  - VVT was added to the description of Truck engine.

- Correction to Tables 1-6, 2-3, 7-10, 7-11, A-1 and A-2

A typo in the description of the Standard Car baseline engine was corrected. The engine has DCP, not ICP as previously reported.

- Correction to Tables 1-7, 2-4, 7-12, 7-13, A-3 and A-4

DCP was added to the description of the Small MPV baseline engine.

- Shift map correction to Large MPV package 4

A shift map resulting in better FE and consistent with the aggressive shift strategy as stated in Section 3.5 of the report was used. The previous shift map had baseline shift limits as stated earlier in Section 3.5. Table 7-2 changed, as did the associated text on page 81.

- GDI map correction applied to Full Size Car package Y1

The GDI map was applied consistently with Final Package configuration resulting in reduction in FE. The previous GDI map had incremental EGR benefit erroneously included. Table 7-3 and Figure 7-1 changed, as did the associated text on page 81.

- Table 7-4 correction

Table 7-4 fuel economy values are correctly reported. Previously the values were erroneously copied over from Table 7-3.

- Table 7-5 correction

A typo was corrected (DCCL changed to DVVL) in the second row of Table 7-5.

RICARDO

A STUDY OF POTENTIAL EFFECTIVENESS OF CARBON DIOXIDE REDUCING VEHICLE TECHNOLOGIES

Release date: 26 June 2008

THIS PROJECT WAS FUNDED UNDER SUBCONTRACT 06003-08 BY PERRIN QUARLES ASSOCIATES, INC. UNDER CONTRACT EP-C-06-003, WORK ASSIGNMENT 1-14 TO THE U.S. ENVIRONMENTAL PROTECTION AGENCY

THE FOLLOWING ORGANIZATIONS CONTRIBUTED TO THIS STUDY:

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RICARDO, PLC
PERRIN QUARLES ASSOCIATES, INC.
THE U.S. ENVIRONMENTAL PROTECTION AGENCY

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1.0 EXECUTIVE SUMMARY

Ricardo has been subcontracted by Perrin Quarles Associates, Inc. (PQA) under contract to the EPA to carry out an objective and scientific analysis of the influence of certain technology packages on automotive CO_2 emissions and vehicle performance.
The scope of the study was to determine the quantitative impact of technology combinations, or packages, when applied to baseline vehicles. The EPA selected the vehicle classes and the technology packages which were applied, as well as a baseline comparator vehicle for each class. Vehicle performance metrics were considered simultaneously with CO_2 emissions in order to indicate the potential impact on consumer acceptability. Vehicle performance metrics were considered an important part of the study as these can significantly influence the desirability of a vehicle to car buyers.

Ricardo's role was to carry out the analysis of the technologies. The report contains the description of the approach taken and the simulation results obtained. Significant CO_2 reductions are predicted from the combinations of powertrain and vehicle technologies. Many of these technologies could add significant cost to vehicles; however, cost analysis was beyond the scope of this study. Also, there is no Ricardo discussion or opinion on the results obtained nor any recommendations on the level of CO_2 reduction that could be obtained in practice from future vehicles. The intended purpose of this study is to serve as an input to the EPA in its rule-making effort relating to the potential impact of specific technology packages on fuel economy/CO_2 and vehicle performance. Further, while baseline vehicle comparators representing vehicle platforms were used to define the performance and fuel economy/CO_2 impacts, this report should not be interpreted as stating the actual impact on these baseline comparator vehicles.

A forward-looking, millisecond-by-millisecond, physics-based modeling approach was deployed. This encompassed simulation from the driver's foot to torque at the wheels and included detailed sub-models for influences such as turbocharger lag and engine warm-up. Ricardo used its unique proprietary test and analytical data for future engine, transmission, and vehicle technologies. Ricardo also ensured that the technologies were appropriately characterized into simulation, including any limitations.

Under direction of the EPA, one CO_2 improvement option was not included in the simulation, but instead was applied to the simulation results. This factor was friction reduction as might be obtained by low-viscosity oils and/or friction reducing components. A fuel economy benefit of 2.5% was applied to the simulation results and could be construed to be indicative of the potential for further CO_2 reductions from friction reduction. Furthermore, although vehicle weight has a significant impact on CO_2 output, this study was focused on the impact of powertrain technologies, vehicle aerodynamic drag force, tire rolling resistance and friction reduction; a weight change to the vehicles was not considered in this study.

The scope of the work focused on five different vehicle platforms representing the major vehicle segments. These five platforms were:

Standard Car	(for example, Toyota Camry)
Small MPV	(for example, Saturn Vue)
Full size car	(for example, Chrysler 300)
Large MPV	(for example, Dodge Grand Caravan)
Truck	(for example, Ford F150)

1.1 BASELINE RESULTS

For each vehicle class, a typical production vehicle was selected as a comparator and a baseline model was created that would represent the vehicle class and also be the starting point for addition of the technology packages. The unadjusted results for the EPA city, highway, and combined cycles as simulated for each of the baseline vehicle classes are shown in Figure 1-1.

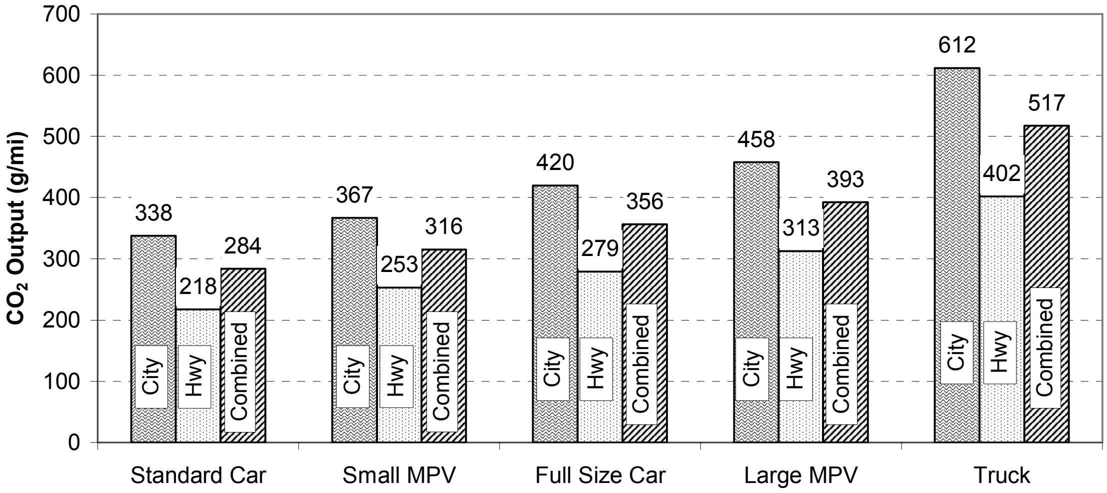


Figure 1-1: Comparison of simulated CO_2 output for the baseline vehicle classes

1.2 TECHNOLOGIES CONSIDERED

A number of technologies were considered for this study.

Engine technologies included:

- Variable Valvetrain
  - Cam phasing, DCP and CCP
  - Variable valve lift, CVVL
  - Discrete cam profile switching, DVVL
  - Camless
- Homogeneous Charge Compression Ignition combustion, HCCI
- Cylinder deactivation
- Gasoline Direct Injection, GDI
- Turbocharging / downsizing
- Diesel

Transmission technologies included:

- Advanced 6-speed automatic, AT
- Dual-clutch, DCT, both wet and dry clutch
- Continuously variable, CVT

Accessory technologies included:

- 42V stop-start system

- Electric accessories, including electric water pump (ePump) and electric power steering (ePS) and fast engine warm up
- High efficiency alternator (heAlt)

Vehicle technologies included:
- Aerodynamic drag force reduction
- Tire rolling resistance reduction

1.3 TECHNOLOGY PACKAGES

The EPA identified a number of technology packages of engine, transmission, and vehicle technologies that would be assessed for each vehicle platform. The number of technology packages totaled twenty-six. Each package was also given a subjective rating in terms of its production readiness. The ratings used were: already in production now or will be in production within 5 years, and production within 5-10 years. The corresponding terms used are "5 years" and "10 years", respectively. The technology packages with the associated vehicle and readiness were as follows:

Table 1-1: Technology Packages for Standard Car

Pkg	Engine	Valvetrain	Transmission	Accessories	Readiness
Z	I4, PFI	CCP DVVL	6-spd DCT, dry clutch	42V stop-start ePS ePump (42V)	5 years
1	I4, GDI	DCP DVVL	CVT	ePS ePump (12V) heAlt	5 years
2	I4, GDI	DCP	6-spd AT	42V stop-start ePS ePump (42V)	5 years

Table 1-2: Technology Packages for Small MPV

Pkg	Engine	Valvetrain	Transmission	Accessories	Readiness
Z	I4, PFI	CCP DVVL	6-spd DCT, wet clutch	42V stop-start ePS ePump (42V)	5 years
1	I4, GDI	DCP DVVL	CVT	ePS ePump (12V) heAlt	5 years
2	I4, GDI	DCP	6-spd AT	42V stop-start ePS ePump (42V)	5 years
5	I4, Diesel		6-spd DCT, wet clutch	ePS ePump (12V) heAlt	5 years
15	I4, GDI Turbo/down-size	DCP	6-spd DCT, wet clutch	ePS ePump (12V) heAlt	5 years
15a	I4, GDI	Camless	6-spd DCT, wet clutch	ePS ePump (12V) heAlt	10 years
15b	I4, GDI	HCCI	6-spd DCT, wet clutch	ePS ePump (12V) heAlt	10 years

Table 1-3: Technology Packages for Full Size Car

Pkg	Engine	Valvetrain	Transmission	Accessories	Readiness
4	I4, GDI Turbo/down-size	DCP	6-spd AT	ePS ePump (12V) heAlt	5 years
5	I4/I5 Diesel		6-spd DCT, wet clutch	ePS ePump (12V) heAlt	5 years
6a	Small V6, GDI	DCP CVVL	6-spd DCT, wet clutch	ePS ePump (12V) heAlt	5 years
16	Large V6, GDI	CCP Deac	6-speed AT	42V stop-start ePS ePump (42V)	5 years
Y1	Large V6, GDI	Camless	6-speed DCT, wet clutch	ePS ePump (12V) heAlt	10 years
Y2	Large V6, GDI	HCCI	6-speed DCT, wet clutch	ePS ePump (12V) heAlt	10 years

Table 1-4: Technology Packages for Large MPV

Pkg	Engine	Valvetrain	Transmission	Accessories	Readiness
4	I4, GDI Turbo/down-size	DCP	6-speed AT	ePS ePump (12V) heAlt	5 years
6b	Small V6, GDI	CCP Deac	6-spd DCT, wet clutch	ePS ePump (12V) heAlt	5 years
16	Large V6, GDI	CCP Deac	6-speed AT	42V stop-start ePS ePump (42V)	5 years

Table 1-5: Technology Packages for Truck

Pkg	Engine	Valvetrain	Transmission	Accessories	Readiness
9	V8, GDI	Deac	6-spd DCT, wet clutch	42V stop-start ePS ePump (42V)	5 years
10	Large V6, GDI Turbo/downsize	DCP	6-spd DCT, wet clutch	ePS ePump (12V) heAlt	5 years
11	Large V6 Diesel		6-spd DCT, wet clutch	ePS ePump (12V) heAlt	5 years
12	V8, GDI	CCP Deac	6-spd AT	42V stop-start ePS ePump (42V)	5 years
17	V8, GDI	DCP DVVL	6-spd AT	ePS ePump (12V) heAlt	5 years
X1	V8, GDI	Camless	6-spd DCT, wet clutch	ePS ePump (12V) heAlt	10 years
X2	V8, GDI	HCCI	6-spd DCT, wet clutch	ePS ePump (12V) heAlt	10 years

1.4 VEHICLE / TECHNOLOGY PACKAGE RESULTS

Each combination of vehicle and technology package was simulated for the effect on fuel economy and performance. A friction-reduction factor was applied to the fuel economy values and CO_2-equivalent output was then calculated. Results for the technology packages are shown below for each vehicle class. Technology packages that require a 5 to 10 year production readiness period are listed separately at the bottom of the tables to distinguish their lower level of technical maturity. The tables in this section list the initial performance results as described in Section 2.10.3 for each baseline vehicle and technology package; the complete listing of performance results is shown in the Appendix.

Table 1-6: Standard Vehicle Class CO_2 Emissions

Standard Car Vehicle Class

Technology Package Description									CO_2						Performance							
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW	
									g/mi	g/mi	g/mi	%	%	%	sec	sec	sec	sec	mph	meters	%	gear
Base-line	2.4L-4V I4 DCP	AT 5spd FDR 3.39	N	Mech	Bag1	base	base	N	338	217	284	-	-	-	3.2	8.7	3.4	5.4	28.3	19.2	13.8	3rd
Z	2.4L-4V I4 DVVL + CCP	DCT 6spd FDR 2.96	Y	ePS ePump	Y	-20%	-10%	Y	250	170	214	26%	22%	25%	3.8	8.8	3.1	4.7	22.4	12.7	15.3	3rd
		DCT 6spd FDR 3.07							250	170	214	26%	22%	25%	3.5	7.9	2.9	4.3	25.1	15.3	16.0	3rd
		DCT 6spd FDR 3.23							250	172	215	26%	21%	24%	3.4	7.6	2.8	4.3	26.2	16.0	16.7	3rd
		DCT 6spd FDR 3.40							249	174	215	26%	20%	24%	3.3	7.6	2.8	4.3	27.2	16.7	17.5	3rd
1	2.4L-4V I4 DVVL + DCP GDI	CVT FDR 6.23	N	ePS ePump heAlt	Y	-20%	-10%	Y	297	200	253	12%	8%	11%	3.7	9.1	3.2	5.0	24.9	16.3	17.9	-
		CVT w/ revised ratio FDR 5.00							295	198	251	13%	9%	11%	3.7	9.2	3.3	5.1	24.8	16.2	17.9	-
		CVT w/ revised ratio FDR 5.25							295	201	253	13%	8%	11%	3.6	9.0	3.3	4.9	25.5	16.7	17.9	-
		CVT w/ revised ratio FDR 5.50							296	204	255	12%	6%	10%	3.5	8.9	3.3	4.9	26.3	17.4	17.9	-
		CVT w/ revised ratio FDR 6.00							298	211	259	12%	3%	9%	3.3	8.6	3.2	4.9	27.9	18.6	17.9	-
2	2.4L-4V I4 DCP GDI	AT 6spd FDR 2.96	Y	ePS ePump	Y	-20%	-10%	Y	277	180	233	18%	17%	18%	3.4	8.8	3.3	5.3	26.7	16.8	14.8	3rd

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 1-7: Small MPV Vehicle Class CO_2 Emissions

Small MPV Vehicle Class

Technology Package Description									CO_2						Performance							
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW	
									g/mi	g/mi	g/mi	%	%	%	sec	sec	sec	sec	mph	meters	%	gear
Base-line	2.4L-4V I4 DCP	AT 4spd FDR 3.91	N	Mech except ePS	Bag1	base	base	N	367	253	316	-	-	-	3.8	10.4	3.7	6.0	24.6	16.7	14.8	2nd
Z	2.4L I4 DVVL + CCP	DCT 6spd FDR 3.10	Y	ePS ePump	Y	-20%	-10%	Y	272	208	243	26%	18%	23%	4.4	10.4	3.7	6.1	18.8	10.8	16.7	2nd
1	2.4L I4 DVVL + DCP GDI	CVT FDR 5.8	N	ePS ePump heAlt	Y	-20%	-10%	Y	313	231	276	15%	9%	13%	4.7	10.3	3.4	5.2	18.7	12.0	16.7	-
		CVT w/ revised ratio FDR 4.64							310	227	273	16%	10%	14%	4.7	10.3	3.4	5.2	18.7	12.0	16.7	-
		CVT w/ revised ratio FDR 4.90							309	229	273	16%	10%	13%	4.5	10.3	3.4	5.2	19.3	12.3	16.7	-
		CVT w/ revised ratio FDR 5.15							309	231	274	16%	9%	13%	4.3	10.0	3.4	5.2	20.3	13.0	16.7	-
		CVT w/ revised ratio FDR 5.50							310	234	276	16%	7%	13%	4.1	9.7	3.4	5.2	21.6	13.8	16.7	-
2	2.4L I4 DCP GDI	AT 6spd FDR 2.8	Y	ePS ePump	Y	-20%	-10%	Y	290	211	255	21%	17%	19%	3.8	10.7	4.5	6.9	24.5	16.1	16.9	2nd
5	1.9L I4 Diesel with aftertreatment	DCT 6spd FDR 3.00	N	ePS ePump heAlt	Y	-20%	-10%	Y	282	205	247	23%	19%	22%	3.9	10.4	3.9	6.3	24.1	12.9	13.1	3rd
15	1.5L I4 Turbo DCP GDI	DCT 6spd FDR 3.2	N	ePS ePump heAlt	Y	-20%	-10%	Y	272	211	244	26%	17%	23%	4.6	10.1	3.6	4.9	16.6	8.9	12.9	3rd
		DCT 6spd FDR 3.36							272	211	245	26%	17%	22%	4.4	9.8	3.3	5.2	17.8	9.5	13.6	3rd
		DCT 6spd FDR 3.52							272	212	245	26%	16%	22%	4.3	9.6	3.2	5.2	18.9	10.1	14.1	3rd
		DCT 6spd FDR 3.68							273	213	246	26%	16%	22%	4.1	9.5	3.2	5.2	20.0	10.7	14.6	3rd
Low Technology Readiness - 10 Years																						
15a	2.4L I4 Camless GDI	DCT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-20%	-10%	Y	262	193	231	29%	24%	27%	4.3	10.3	3.7	6.1	19.6	11.7	16.6	2nd
15b	2.4L I4 HCCI GDI	DCT 6 spd FDR 3.1	N	ePS ePump heAlt	Y	-20%	-10%	Y	270	197	237	26%	22%	25%	4.3	10.3	3.7	6.1	19.6	11.7	16.6	2nd

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 1-8: Full Size Car Vehicle Class CO_2 Emissions

Full Size Car Vehicle Class

Technology Package Description									CO_2						Performance							
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW	
									g/mi	g/mi	g/mi	%	%	%	sec	sec	sec	sec	mph	meters	%	gear
Base-line	3.5L-4V V6	AT 5spd FDR 2.87	N	Mech	Bag1	base	base	N	420	279	356	-	-	-	2.6	6.7	2.3	3.8	33.7	24.6	24.6	2nd
4	2.2L I4 Turbo DCP GDI	AT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y	346	236	296	18%	15%	17%	2.6	6.6	2.3	3.4	33.7	22.0	25.6	2nd
5	2.8L I4/5 Diesel with aftertreatment	DCT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y	316	221	273	25%	21%	23%	2.6	7.1	2.7	4.3	33.8	21.7	18.5	4th
		DCT 6spd 6.55 span FDR 3.08							315	221	273	25%	21%	24%	2.5	7.1	2.7	4.3	34.3	22.4	18.5	4th
	2.8L I4/5 US Diesel with aftertreatment	DCT 6spd 6.55 span FDR 3.08							340	220	286	19%	21%	20%	2.5	7.1	2.7	4.3	34.3	22.4	18.5	4th
6a	3.0L V6 DCP + CVVL GDI	DCT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y	334	234	289	20%	16%	19%	3.3	7.3	2.3	3.3	26.8	16.8	26.1	2nd
		DCT 6spd FDR 3.20							338	237	293	19%	15%	18%	3.1	7.1	2.3	3.4	28.6	17.8	26.1	2nd
		DCT 6spd 6.55 span FDR 3.08							334	234	289	20%	16%	19%	3.1	7.0	2.3	3.5	28.7	17.9	25.6	2nd
16	3.5L V6 CCP + Deac GDI	AT 6spd FDR 2.7	Y	ePS ePump	Y	-20%	-10%	Y	301	205	257	28%	27%	28%	2.7	6.8	2.5	3.6	33.3	21.8	27.2	2nd
Low Technology Readiness - 10 Years																						
Y1	3.5L V6 Camless GDI	DCT 6spd FDR 2.80	N	ePS ePump heAlt	Y	-20%	-10%	Y	278	199	242	34%	29%	32%	3.1	6.8	2.2	3.2	29.3	17.9	28.7	2nd
Y2	3.5L V6 HCCI GDI	DCT 6spd FDR 2.80	N	ePS ePump heAlt	Y	-20%	-10%	Y	290	197	248	31%	29%	30%	3.1	6.8	2.2	3.2	29.3	17.9	28.7	2nd

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 1-9: Large MPV Vehicle Class CO_2 Emissions

Large MPV Vehicle Class

Technology Package Description									CO_2						Performance							
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW	
									g/mi	g/mi	g/mi	%	%	%	sec	sec	sec	sec	mph	meters	%	gear
Base-line	3.8L-2V V6	AT 4spd FDR 3.43	N	Mech	Bag1	base	base	N	458	313	393	-	-	-	3.3	9.3	3.5	5.6	27.5	16.9	17.7	2nd
4	2.1L I4 Turbo DCP GDI	AT 6spd FDR 3.17	N	ePS ePump heAlt	Y	-20%	-10%	Y	357	256	312	22%	18%	21%	3.2	8.0	2.8	4.3	27.8	16.5	17.1	3rd
6b	3.0L V6 CCP + Deac GDI	DCT 6spd FDR 3.17	N	ePS ePump heAlt	Y	-20%	-10%	Y	335	245	295	27%	22%	25%	3.9	8.5	2.8	4.2	21.3	11.9	16.8	3rd
		DCT 6spd FDR 3.72							333	248	295	27%	21%	25%	3.5	8.1	2.7	4.2	24.5	13.6	19.7	3rd
		DCT 6spd FDR 3.00							338	243	295	26%	22%	25%	4.1	8.7	2.8	4.1	20.1	11.3	15.5	3rd
	2.7L V6 CCP + Deac GDI	DCT 6spd FDR 3.72							323	244	287	30%	22%	27%	3.8	8.9	3.0	4.8	21.7	12.1	17.4	3rd
16	3.8L V6 CCP + Deac GDI	AT 6spd FDR 2.7	Y	ePS ePump	Y	-20%	-10%	Y	325	225	280	29%	28%	29%	3.3	9.3	3.4	5.6	27.1	15.6	17.0	2nd

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 1-10: Truck Vehicle Class CO_2 Emissions

Truck Vehicle Class

Technology Package Description									CO_2						Performance							
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	60 MPH Grade Capability at GCW	
									g/mi	g/mi	g/mi	%	%	%	sec	sec	sec	sec	mph	meters	%	gear
Base-line	5.4L-3V V8 CCP	AT 4spd FDR 3.73	N	Mech	Bag1	base	base	N	612	402	517	-	-	-	2.6	7.7	3.0	4.6	33.6	23.3	8.8	2nd
6-Spd AT	5.4L-3V V8 CCP	AT 6spd FDR 3.60	N	Mech	Bag1	base	base	N	586	396	500	x	x	x	2.3	7.5	2.9	5.0	35.9	26.2	8.5	3rd
9	5.4L-3V V8 CCP + Deac GDI	DCT 6spd FDR 3.3	Y	ePS ePump	Y	-10%	base	Y	432	315	379	29%	22%	27%	2.7	7.8	2.8	4.6	32.7	21.1	8.4	3rd
10	3.6L V6 Turbo DCP GDI	DCT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-10%	base	Y	404	319	366	34%	21%	29%	2.9	6.7	2.2	3.5	31.5	19.3	12.3	2nd
		DCT 6spd FDR 3.26							416	321	373	32%	20%	28%	2.8	6.4	2.2	3.6	32.6	19.8	12.5	2nd
		DCT 6spd FDR 3.41							418	323	376	32%	19%	27%	2.7	6.4	2.2	3.6	33.5	20.5	13.0	2nd
		DCT 6spd FDR 3.57							421	325	378	31%	19%	27%	2.6	6.3	2.2	3.6	35.5	21.4	12.9	2nd
11	4.8L V6 Diesel with aftertreatment	DCT 6spd FDR 3.15	N	ePS ePump heAlt	Y	-10%	base	Y	444	326	391	27%	19%	24%	2.7	7.7	2.7	4.7	32.5	20.4	10.2	3rd
12	5.4L-3V V8 CCP + Deac GDI	AT 6spd FDR 3.1	Y	ePS ePump	Y	-10%	base	Y	459	328	400	25%	18%	23%	2.4	7.5	2.9	4.9	35.6	25.2	10.7	2nd
17	5.4L V8 DVVL + DCP GDI	AT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-10%	base	Y	492	333	420	20%	17%	19%	2.2	7.1	2.7	4.5	37.1	27.3	10.7	2nd
Low Technology Readiness - 10 Years																						
X1	5.4L V8 Camless GDI	DCT 6spd FDR 3.35	N	ePS ePump heAlt	Y	-10%	base	Y	422	314	374	31%	22%	28%	2.7	7.7	2.8	4.6	32.8	21.2	8.6	3rd
X2	5.4L V8 HCCI GDI	DCT 6spd FDR 3.35	N	ePS ePump heAlt	Y	-10%	base	Y	425	311	374	31%	23%	28%	2.7	7.7	2.8	4.6	32.8	21.2	8.6	3rd

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

2.0 INTRODUCTION

The growing concern over greenhouse gas (GHG) emissions has spawned global action aimed at making significant future reductions. One of the identified sources of GHG production is the automotive internal combustion engine, which accounts for roughly 30% of all GHG emissions in the United States [1]. The EPA's Office of Transportation and Air Quality (OTAQ) was directed to establish a Federal GHG emissions rule that would help President George W. Bush achieve his "20-in-10" goal for the nation. This project forms part of the technological feasibility analysis to support those rulemaking efforts by quantifying the possible reductions in greenhouse gases, and specifically carbon dioxide (CO_2), from passenger-car and light-truck vehicles.

Ricardo, Inc., executed this project as an independent and objective analytical study under subcontract to Perrin Quarles Associates, Inc. (PQA) for the US EPA. The goal of the study was the computer simulation of engine, drivetrain, and vehicle technologies for greenhouse gas emissions reduction and considered passenger cars for the 2010-2017 model years (MY) and light trucks for the 2012-2017 MY timeframe. Ricardo, Inc., is the US arm of Ricardo PLC, a global automotive consultancy with nearly 100 years of specialized engineering expertise and technical experience in internal combustion engines, transmissions, and automotive vehicle development. This project was performed between July and October of 2007.

2.1 THE NEED TO CONSIDER VEHICLE PERFORMANCE AS WELL AS CARBON DIOXIDE EMISSIONS

Today's automobile brings multiple benefits to its owner and is not just a means of transportation. People buy their cars based on a number of different attributes beyond styling and brand name. These attributes include, but are not limited to:

- The perceived performance of the vehicle, from its initial pull away acceleration to its ability to quickly merge into and out of traffic flow.
- The towing capacity .
- The responsiveness of the vehicle to changes in accelerator pedal position.
- The level of refinement of the vehicle's driving behavior, which includes minimal vibrations transmitted to the driver and passengers, low noise from the powertrain, and elimination of excessively noticeable numbers of gear changes.

These factors are often overlooked in studies such as this, but they can be of vital importance to the desirability of automobiles. The original equipment manufacturers (OEMs) expend significant engineering efforts during the development of new vehicles to ensure the key attributes will meet the demands of their buyers. Changes to vehicle propulsion systems to reduce CO_2 will affect these attributes as well. Hence it is important for studies on automotive CO_2 reduction to try to comprehend the impact on all the key vehicle attributes.

2.2 OBJECTIVES

The aim of this study was to provide an objective, scientific analysis of the opportunity for automotive CO_2 reduction. To be scientific, a physics-based modeling approach was used that enabled detailed simulation of the vehicle. To be objective, performance metrics were identified collaboratively with the EPA that could be outputs of the simulation model and would characterize some key vehicle attributes. Uncertainties resulting from the analytical method are negligible, and in most cases the input data have a relatively small error band. The largest source of uncertainty in the results is due to the possible variations in applying the technologies to a vehicle (i.e. differences in actual specification, design, control, and calibration.) These differences of implementation are much greater than can be projected for a vehicle class.

There have been several studies in the past that have evaluated the influence of individual technologies on reducing automotive CO_2. However, the benefit of these technologies will vary depending on the other technologies with which they are being combined as well as the specific vehicle platform to which the technology is being applied. For example, the percentage benefit in reducing CO_2 of an advanced gasoline technology such as cylinder deactivation will be different when applied on a truck compared to a small car. Also, certain technologies may not be readily applied to some vehicles due to constraints of the technology. To overcome the limitations of previous studies, an objective of the present study was to simulate the influence of prescribed technology combination (packages) when applied to specific vehicle applications.

2.3 SIMULATION APPROACH

The modeling approach was a forward-looking, physics-based representation of the whole vehicle. The model simulates what happens to the vehicle when the driver applies the accelerator and/or brake pedal in order to achieve a certain vehicle speed at a certain time. The model operates on a millisecond-by-millisecond basis and predicts the vehicle CO_2 and actual speed with time as the driver tries to drive a certain vehicle speed trace (duty cycle). The model physics includes torques and inertias as well as detailed sub-models for the influence of factors such as turbo-lag and engine friction reduction as the lubricating oil warms up from a cold start.

The key to successful modeling is good data representing the automotive technologies. This is referred to as input materials. Ricardo has detailed proprietary data for future engine, transmission and vehicle systems, obtained from its production development and research work as an engine, transmission and vehicle technology partner to OEMs worldwide.

This detailed simulation forms the appropriate basis for investigating the influence of technology packages on vehicle attributes including CO_2 and is typical of the way the automotive industry undertakes its analytical assessment of vehicle performance.

2.4 ECONOMIC ANALYSIS

The technology packages studied have more component content than today's gasoline engines. Many of the components will be new to the market and will, at least initially, be at lower volumes than today's components.

Therefore the manufacture and assembly costs of these technology packages will be more than the gasoline engine cost of today. The economic impact of these technologies is of key importance when it comes to governmental rulemaking on CO_2 reductions. However, the economic impact of the technologies studied was not part of the Ricardo scope. To facilitate economic studies that may be carried out, Ricardo has provided a brief description of the individual technologies considered in the study.

2.5 TECHNOLOGY READINESS

The technology packages identified are in various states of development towards production. For example, direct injection, stoichiometric gasoline engines are in production today, whereas homogenous charge compression ignition (HCCI) engines are still being researched on test beds and very early prototype vehicles. The actual state of development for specific technologies will vary from manufacturer to manufacturer. To complement the assessment, Ricardo has provided a subjective assessment of the readiness of the technologies for production.

2.6 SCOPE OF WORK

The technical analyses yielded simulation results of fuel economy and equivalent CO_2 output for various passenger vehicle classes and combinations of advanced technologies in order to quantify the effect of combined technologies on a vehicle. Vehicle weight changes were not included in this study. The effects of these combinations of technologies on specific vehicle performance criteria were also evaluated. Only the fuel economy/equivalent CO_2 output and vehicle performance parameters were considered in the scope of this study and no cost or warranty/durability information was included or investigated. However, subjective aspects like acceptable drivability, idle stability, and NVH performance were taken into account when employing certain advanced technologies and their combinations. Additional details are discussed in the relevant sections.

2.7 REPRESENTATIVE VEHICLE CLASSES AND BASELINE VEHICLES

This analysis was intended to build upon and improve existing literature investigating the GHG reduction potential of new vehicle technologies. Similar to previous studies [2 & 3], the EPA identified five vehicle classes to be representative of the overall population of cars and light trucks in the US operational passenger vehicle fleet. These classes were: Standard Car, Small Multi-Purpose Vehicle (MPV), Full Size Car, Large MPV, and Truck. The EPA also chose a specific representative vehicle for each of the five classes: the Toyota Camry for the Standard Car, the Saturn Vue for the Small MPV, the Chrysler 300 for the Full Size car, the Dodge Grand Caravan for the Large MPV, and the Ford F150 for the Truck. Published data for these specific vehicles are listed in the table below. The fuel economy (FE) values are as reported in the EPA Test Car List.

Table 2-1: Baseline Vehicles Description – EPA Fuel Economy

Baseline Vehicles										
Vehicle Class	**Representative Vehicle**	**Engine**	**Trans.**	**Drivetrain**	**Curb Weight (lb)**	**ETW (lb)**	**GCW (lb)**	**EPA City FE (mpg)**	**EPA Highway FE (mpg)**	**EPA Combined FE (mpg)**
Standard Car	Toyota Camry	2.4L I4 DOHC 4 valve VVT	5 spd Auto	FWD	3108	3625	N/A	26.7	42.2	32.0
Small MPV	Saturn Vue	2.4L I4 DOHC 4 valve VVT	4 spd Auto	FWD	3825	4000	N/A	23.8	36.7	28.3
Full Size Car	Chrysler 300	3.5L V6 SOHC 4 valve	5 spd Auto	RWD	3721	4000	N/A	20.9	34.1	25.3
Large MPV	Grand Caravan	3.8L V6 OHV 2 valve	4 spd Auto	FWD	4279	4500	N/A	19.5	31.9	23.6
Truck	Ford F150	5.4L V8 SOHC 3 valve VVT	4 spd Auto	4WD	5470	6000	14000	15.5	22.7	18.1

Table 2-2: Baseline Vehicles Description – EPA CO_2-Equivalent

Baseline Vehicles										
Vehicle Class	**Representative Vehicle**	**Engine**	**Trans.**	**Drivetrain**	**Curb Weight (lb)**	**ETW (lb)**	**GCW (lb)**	**EPA City CO_2^* (g/mi)**	**EPA Highway CO_2^* (g/mi)**	**EPA Combined CO_2^* (g/mi)**
Standard Car	Toyota Camry	2.4L I4 DOHC 4 valve VVT	5 spd Auto	FWD	3108	3625	N/A	340.3	215.3	284.0
Small MPV	Saturn Vue	2.4L I4 DOHC 4 valve VVT	4 spd Auto	FWD	3825	4000	N/A	381.8	247.6	321.1
Full Size Car	Chrysler 300	3.5L V6 SOHC 4 valve	5 spd Auto	RWD	3721	4000	N/A	434.8	266.5	359.2
Large MPV	Grand Caravan	3.8L V6 OHV 2 valve	4 spd Auto	FWD	4279	4500	N/A	466.0	284.9	385.0
Truck	Ford F150	5.4L V8 SOHC 3 valve VVT	4 spd Auto	4WD	5470	6000	14000	586.3	400.3	502.0

* CO_2-equivalent values are based on FE values from Table 2.1 and gasoline conversion factor stated in Section 2.10.2 of this report

2.8 TECHNOLOGY PACKAGES

The aim of this study was to project what the effects of current advanced technologies and future technologies would be on CO_2 levels for each of the identified vehicle classes when used in specific combinations. It is important to note that the effect of the whole combination is the key, since the result of multiple technologies applied to a specific vehicle may not simply be additive when compared individually to the baseline, and in most cases, is less effective than the sum of the individual component technologies in that combination.

The EPA identified a number of combinations of vehicles and technology packages to be simulated in this part of the project. In addition to these cases, final drive ratio sweeps were also performed for certain configurations to determine the sensitivities involved. The various vehicle and technology package simulations are listed below:

Table 2-3: Standard Car Vehicle Class Technology Packages

Standard Car Vehicle Class								
Technology Package Description								
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier
Base-line	2.4L-4V I4 DCP	AT 5spd FDR 3.39	N	Mech	Bag1	base	base	N
Z	2.4L-4V I4 DVVL + CCP	DCT 6spd FDR 2.96	Y	ePS ePump	Y	-20%	-10%	Y
		DCT 6spd FDR 3.07						
		DCT 6spd FDR 3.23						
		DCT 6spd FDR 3.40						
1	2.4L-4V I4 DVVL + DCP GDI	CVT FDR 6.23	N	ePS ePump heAlt	Y	-20%	-10%	Y
		CVT w/ revised ratio FDR 5.00						
		CVT w/ revised ratio FDR 5.25						
		CVT w/ revised ratio FDR 5.50						
		CVT w/ revised ratio FDR 6.00						
2	2.4L-4V I4 DCP GDI	AT 6spd FDR 2.96	Y	ePS ePump	Y	-20%	-10%	Y

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 2-4: Small MPV Vehicle Class Technology Packages

Small MPV Vehicle Class

Technology Package Description

EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier
Base-line	2.4L-4V I4 DCP	AT 4spd FDR 3.91	N	Mech except ePS	Bag1	base	base	N
Z	2.4L I4 DVVL + CCP	DCT 6spd FDR 3.10	Y	ePS ePump	Y	-20%	-10%	Y
1	2.4L I4 DVVL + DCP GDI	CVT FDR 5.8	N	ePS ePump heAlt	Y	-20%	-10%	Y
		CVT w/ revised ratio FDR 4.64						
		CVT w/ revised ratio FDR 4.90						
		CVT w/ revised ratio FDR 5.15						
		CVT w/ revised ratio FDR 5.50						
2	2.4L I4 DCP GDI	AT 6spd FDR 2.8	Y	ePS ePump	Y	-20%	-10%	Y
5	1.9L I4 Diesel with aftertreatment	DCT 6spd FDR 3.00	N	ePS ePump heAlt	Y	-20%	-10%	Y
15	1.5L I4 Turbo DCP GDI	DCT 6spd FDR 3.2	N	ePS ePump heAlt	Y	-20%	-10%	Y
		DCT 6spd FDR 3.36						
		DCT 6spd FDR 3.52						
		DCT 6spd FDR 3.68						
Low Technology Readiness - 10 Years								
15a	2.4L I4 Camless GDI	DCT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-20%	-10%	Y
15b	2.4L I4 HCCI GDI	DCT 6 spd FDR 3.1	N	ePS ePump heAlt	Y	-20%	-10%	Y

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 2-5: Full Size Car Vehicle Class Technology Packages

Full Size Car Vehicle Class

Technology Package Description

EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier
Base-line	3.5L-4V V6	AT 5spd FDR 2.87	N	Mech	Bag1	base	base	N
4	2.2L I4 Turbo DCP GDI	AT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y
5	2.8L I4/5 Diesel with aftertreatment	DCT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y
		DCT 6spd 6.55 span FDR 3.08						
	2.8L I4/5 US Diesel with aftertreatment	DCT 6spd 6.55 span FDR 3.08						
6a	3.0L V6 DCP + CVVL GDI	DCT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y
		DCT 6spd FDR 3.20						
		DCT 6spd 6.55 span FDR 3.08						
16	3.5L V6 CCP + Deac GDI	AT 6spd FDR 2.7	Y	ePS ePump	Y	-20%	-10%	Y
Low Technology Readiness - 10 Years								
Y1	3.5L V6 Camless GDI	DCT 6spd FDR 2.80	N	ePS ePump heAlt	Y	-20%	-10%	Y
Y2	3.5L V6 HCCI GDI	DCT 6spd FDR 2.80	N	ePS ePump heAlt	Y	-20%	-10%	Y

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 2-6: Large MPV Vehicle Class Technology Packages

Large MPV Vehicle Class

Technology Package Description

EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier
Base-line	3.8L-2V V6	AT 4spd FDR 3.43	N	Mech	Bag1	base	base	N
4	2.1L I4 Turbo DCP GDI	AT 6spd FDR 3.17	N	ePS ePump heAlt	Y	-20%	-10%	Y
6b	3.0L V6 CCP + Deac GDI	DCT 6spd FDR 3.17	N	ePS ePump heAlt	Y	-20%	-10%	Y
		DCT 6spd FDR 3.72						
		DCT 6spd FDR 3.00						
	2.7L V6 CCP + Deac GDI	DCT 6spd FDR 3.72						
16	3.8L V6 CCP + Deac GDI	AT 6spd FDR 2.7	Y	ePS ePump	Y	-20%	-10%	Y

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 2-7: Truck Vehicle Class Technology Packages

Truck Vehicle Class								
Technology Package Description								
EPA Package Identifier	**Engine**	**Transmission**	**42V Stop-Start**	**Accessories**	**Warm-up Model**	**Aero Drag**	**Rolling Resistance**	**Frictional Multiplier**
Base-line	5.4L-3V V8 CCP	AT 4spd FDR 3.73	N	Mech	Bag1	base	base	N
6-Spd AT	5.4L-3V V8 CCP	AT 6spd FDR 3.60	N	Mech	Bag1	base	base	N
9	5.4L-3V V8 CCP + Deac GDI	DCT 6spd FDR 3.3	Y	ePS ePump	Y	-10%	base	Y
10	3.6L V6 Turbo DCP GDI	DCT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-10%	base	Y
		DCT 6spd FDR 3.26						
		DCT 6spd FDR 3.41						
		DCT 6spd FDR 3.57						
11	4.8L V6 Diesel with aftertreatment	DCT 6spd FDR 3.15	N	ePS ePump heAlt	Y	-10%	base	Y
12	5.4L-3V V8 CCP + Deac GDI	AT 6spd FDR 3.1	Y	ePS ePump	Y	-10%	base	Y
17	5.4L V8 DVVL + DCP GDI	AT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-10%	base	Y
Low Technology Readiness - 10 Years								
X1	5.4L V8 Camless GDI	DCT 6spd FDR 3.35	N	ePS ePump heAlt	Y	-10%	base	Y
X2	5.4L V8 HCCI GDI	DCT 6spd FDR 3.35	N	ePS ePump heAlt	Y	-10%	base	Y

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

It must also be noted that the reduced engine friction, lower rolling resistance tires, and reduced aerodynamic drag were applied to each of the vehicle/technology package combinations as prescribed by the EPA. Specific technology actions were not identified to obtain these improvements.

2.9 TECHNOLOGY SENSITIVITY CASE STUDIES

While the effects of the various vehicle and technology *packages* identified above on CO_2 output was the primary aim of the study, investigations of how much each individual technology affected vehicle fuel economy were also undertaken. Thus, incremental technology sensitivity studies were performed and are discussed in Section 7.2.

2.10 TEST CYCLES AND PERFORMANCE CRITERIA

2.10.1 Test Cycles

The test cycles considered for fuel economy and equivalent CO_2 output were the EPA FTP Urban Dynamometer Driving Schedule and HWFET Highway Test Driving Schedule, with all analyses being performed at the EPA vehicle equivalent test weight (ETW) for each of the identified base vehicles.

2.10.2 Fuel Economy and CO_2 Equivalency

Standard fuels were used for gasoline and diesel engines, respectively, and equivalent CO_2 output values were derived by applying a known factor for each fuel type to the fuel economy (FE) results. For this analysis, GHG emissions per gallon of fuel consumed were provided by the EPA as follows:

Table 2-8: GHG CO_2-equivalent Emissions Factor

Fuel Type	GHG Emissions Factor (g CO_2-equiv./ gallon of fuel)
Gasoline	9,087
Diesel	10,097

The CO_2-equivalent output can then be calculated from the vehicle fuel economy (FE) values using the fuel-appropriate factor above and the equation:

$$CO_{2\text{-equiv}} \text{ (g/mile)} = \text{GHG Emissions Factor / FE (miles/gal)}$$

2.10.3 Vehicle Performance Criteria

As described earlier, vehicle performance criteria are also an important consideration for studies investigating CO_2 reductions. A number of different criteria are used throughout the industry and the opinion on the importance of the specific criteria varies between industry, environmental groups, and government agencies.

For this study, the following performance criteria were initially proposed; the EPA intended to maintain roughly equivalent overall performance levels to the base vehicles and was willing to consider tradeoffs among these performance parameters:

- Wide-open-throttle (WOT) accelerations from rest:
    - 0 – 30 MPH time
    - 0 – 60 MPH time
- WOT accelerations from a set vehicle speed (representing passing or freeway merging maneuvers):
    - 30 – 50 MPH time
    - 50 – 70 MPH time
- Vehicle speed and distance traveled after a three-second WOT acceleration from rest.
- Grade capability at 70 mph for the Standard Car, Small MPV, Large Car, and Large MPV
- Grade capability at 60 mph for the Truck at Gross Combined Weight (GCW)

All simulations, apart from the Truck GCW case, were performed at the EPA Equivalent Test Weight (ETW) for the vehicle as listed in the tables.

Also, grade capability is defined as the steepest grade that the vehicle is capable of climbing at a given speed and weight, regardless of gear. The results for this metric report both the grade (%) and gear.

During the course of the study, Ricardo suggested the following additional metrics to increase the amount of information available:

- Wide-open-throttle (WOT) accelerations from rest:
    - 0 – 10 MPH time
    - 0 – 50 MPH time
    - 0 – 70 MPH time
- Top-gear grade capability (or torque reserve) at 60 mph and 70 mph for all vehicle classes
- Top-gear grade capability (or torque reserve) at 60 MPH for the Truck at GCW

Again, all simulations, apart from the Truck GCW case, were performed at the EPA Equivalent Test Weight (ETW) for the vehicle as listed in the tables.

Also, top-gear grade capability is defined as the steepest grade that the vehicle is capable of climbing at a given speed and weight in top gear only, which is an indication of torque reserve (the excess torque available from the engine at part-throttle conditions).

Only the initial performance metrics are included in the tables presented in Sections 1 and 7. The same vehicle technology package, fuel economy, and CO_2 data, accompanied by the complete set of performance results (initial and additional), are shown in the tables in the Appendix.

The 0 – 10 MPH and 0 – 30 MPH time criteria along with vehicle speed and distance traveled after 3 seconds are all indicators of vehicle launch. For buyers, a good launch can be a significant factor distinguishing the performance of one vehicle from another.

It was recognized that certain advanced technologies, in particular DCTs and CVTs, would necessarily have to sacrifice some of the initial launch (0 – 10 MPH) at WOT in order to achieve the fuel economy or CO_2 improvements that they can offer. This is due to the lack of a torque converter and the delay time for initial clutch engagement. However, under part-throttle conditions, the control of these advanced transmissions has made the launch performance virtually indistinguishable from an automatic transmission with a torque converter.

The 0 – 50 MPH, 0 – 60 MPH, and 0 – 70 MPH times are often quoted by magazines as indicators of vehicle performance.

The 30 – 50 MPH and 50 – 70 MPH acceleration times are indicators of vehicle performance during freeway merges and overtaking, and are again seen as representation of performance that is important to car buyers.

The grade capability is another similar series of tests important to buyers that simulate the ability of the vehicle to maintain a given speed up a specific grade. The top-gear grade capability results indicate the maximum grade that the vehicle can climb at the stated speed in top gear (without a downshift). The heavier (GCW) test weight is used for the truck case to take account of towing needs of this vehicle.

This set of vehicle performance criteria is not an all-inclusive list, but is meant to be a good coverage of the factors important to vehicle buyers.

2.11 INPUT DATA AND MODELING APPROACH OVERVIEW

Since the intention of this study was to model existing and future vehicle technologies, not all of the necessary input data were publicly available. Thus, Ricardo obtained information from other commercial sources where appropriate and extensively used representative data from its own proprietary databases. Ricardo invests 5 – 7% of its annual sales revenue in collaborative research with industry partners on future engine, transmissions and vehicle technology. Hence, as a consultancy, Ricardo is uniquely placed to provide the required input materials.

All input data was reviewed extensively for completeness and accuracy and then used as representative inputs to the detailed models created for this study. No vehicle manufacturers were approached for any input data in order to maintain the complete independence and objectivity of this work.

Although there are a few software packages available to perform the simulation tasks, Ricardo chose MSC.EASY5™, a licensed commercially available package that allows detailed modeling of engines, transmissions, drivelines, vehicle systems (including tires and aerodynamics), and driver inputs. More in-depth descriptions of the input data and modeling activities are stated in Section 3 of this report.

To verify the validity of the models and input data, and to satisfy concerns of whether the projections for the advanced and future technologies and associated packages would be reasonable and accurate, the baseline vehicle results were compared with published data for the identified representative vehicles. The project team determined that there was no need to “calibrate” the models to match published data more closely since the initial results were considered to represent the published data with sufficient accuracy, and all the input values were reviewed and approved as being representative of real-world findings and built on experience with other similar simulation activities.

2.12 COMPILATION AND ANALYSIS OF RESULTS

Results are presented for the 5 baseline vehicle cases and the agreed technology packages in Sections 1, 4, and 7 and the Appendix of this document. The data tables list the outputs for fuel economy and CO_2 emissions as well as percentage changes from the baseline for each on the city and highway cycles and a combined cycle. Vehicle performance results for the identified metrics are also listed for each package and can be referenced to the baseline in absolute numbers. Each of the technology packages is also described in terms of its individual technologies and readiness for production.

This report does not draw any specific conclusions from the data. However, Ricardo believes that the simulation method and approach used to derive the results are consistent and correct and that the output information is an accurate projection for the vehicle, technologies, and combinations stated. Also, because different vehicles exhibit unique characteristics, care must be taken to properly apply the results of this study to other vehicles.

2.13 SECTION 2 REFERENCES

1. INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS: 1990-2005 (EPA430-R-07-002), U.S. Environmental Protection Agency Office of Transportation and Air Quality, April 2007
2. EFFECTIVENESS AND IMPACT OF CORPORATE AVERAGE FUEL ECONOMY (CAFE) STANDARDS, National Research Council, Washington, DC, National Academy Press, 2002
3. REDUCING GREENHOUSE GAS EMISSIONS FROM LIGHT-DUTY MOTOR VEHICLES, Northeast States Center for a Clean Air Future (NESCCAF), September 2004

3.0 VEHICLE MODEL

A full physical model was developed for each baseline vehicle using MSC.EASY5^{TM}. This is a commercially available software package that is used widely in the industry for vehicle system analysis. MSC.EASY5^{TM} enables a complete physical model of the vehicle. The torque reactions are simulated from the engine, through the transmission to the wheels. The model reacts to simulated driver inputs to the accelerator and/or brake pedals. This enables the actual vehicle acceleration to be determined. The model is divided into a number of subsystem models. Within each subsystem the model determines key component data such as torque, speeds, and heat rejection, and from these, algorithms are used to determine the appropriate subsystem efficiencies.

The vehicles were modeled using published information from various sources and Ricardo proprietary data.

Published vehicle data and [source]:

- Equivalent Test Weight (ETW) [EPA Vehicle Certification Database]
- Gross Vehicle Weight (GVW) [Manufacturer website]
- Gross Combined Weight (GCW) [Manufacturer website]
- Road load coefficients [EPA Vehicle Certification Database]
- Vehicle dimensions (length, width, height, wheelbase and track) [Manufacturer website]
- Tire size [Manufacturer website]
- Engine displacement, rated HP, rated torque and technology level [Manufacturer website]
- Transmission gear ratios [various websites]
- Final drive ratio [Manufacturer website and EPA Vehicle Certification Database]

Model inputs based on Ricardo proprietary data and experience:

- Transmission hydraulic losses and gear efficiency
- Torque converter efficiency and capacity factor
- Engine, transmission and driveline rotational inertia
- Driveline spin losses
- Transmission shift and torque converter lockup strategy
- Vehicle frontal area (A_f) and coefficient of drag (C_D)
- Tire rolling resistance
- Vehicle weight distribution and center of gravity

Key subsystem models include engine, engine accessories, transmission, torque converter, final drive differential, vehicle characteristics, vehicle driver, and 42V stop-start.

3.1 ENGINE MODEL

The engine model uses torque curves for full-load torque and closed-throttle motoring torque throughout the entire engine operating speed range. Full-load torque values were correlated to published power ratings for the baseline vehicle engines. Ricardo proprietary data was used to generate a map of fuel consumption rates covering the full range of engine speed and load values. This is used to calculate fuel usage at each operating point in the simulation. The torque and fuel rates are adapted from Ricardo proprietary test data from various engines for each simulation to the engine specifications required. Idle speed and maximum engine RPM are specified for each model. Full engine maps were also used to evaluate all advanced engine technologies (refer to Section 5 for data sources).

Some gasoline and all the diesel technologies use turbochargers. The steady-state performance of the engine will be different than the engine transient response due to the time it takes the turbocharger to spin up to its new operating speed. To simulate this effect, a turbo lag model was used for all the advanced technology packages that incorporate turbochargers. The lag was based on Ricardo experience and was dependent on engine size.

3.2 ENGINE MODEL – WARMUP

Fuel consumption during the first 505 seconds of the FTP drive cycle (bag #1) depends on how quickly the engine warms up, since a cold engine has higher oil viscosity and hence higher frictional losses. Also combustion can be sub-optimal when the engine is cold. It is typical in the industry to apply a "cold start factor" for the fuel economy achieved during bag #1 time of the FTP cycle. This factor is approximately 80% of the bag #3 fully warm part of the FTP.

For this study, the technology packages represent more efficient powertrains, which could reject less heat and hence have different engine warmup times compared to the baseline technologies. Therefore, to improve the accuracy of the predictions, a warmup model was incorporated to simulate the effects of going from a cold engine starting condition to a hot engine operating condition.

The engine thermal models are linked into a simplified vehicle cooling circuit model that accounts for coolant and oil thermal inertias. The warm up model predicts oil and coolant temperature change and from this determines engine friction change and its influence on fuel consumption.

Running the model showed approximately a 20% decrease in fuel economy for a cold engine compared to a hot engine, which correlated well to vehicle dynamometer test results.

The engine thermal model was sufficiently detailed to account for improvements to warm up times provided by electric water pumps and intelligent cooling systems as might be used on advanced vehicles.

3.3 ENGINE MODEL – CYLINDER DEACTIVATION

A cylinder deactivation model was used to evaluate the effect of running on half of the available cylinders during light throttle conditions. The remaining cylinders operate at a higher BMEP thus reducing pumping work and results in a lower total fuel rate. The model applies a BSFC modifier, based on Ricardo proprietary data, to the fuel rate when the engine is in deactivation mode. Deactivation was only used when the vehicle conditions are between certain limits:

1. minimal vehicle speed = 15 mph
2. minimal engine speed = 850 rpm
3. allowed gears: 4-speed transmission = 3rd & 4th , 5-speed transmission = 4th & 5th, 6-speed transmission = 4th, 5th & 6th
4. manifold pressures for deactivate-off and deactivate-on (to avoid on-off hunting).

3.4 ENGINE ACCESSORIES MODEL

Parasitic loads from the alternator were assumed constant over the drive cycles and were included in the engine model. Alternator efficiency of 55% was assumed for baseline vehicle simulations and 70% efficiency for the high efficiency alternator (heAlt) in all of the advanced technology package simulations to represent future alternator design improvements.

Power steering systems (full electric or electric hydraulic) were modeled as engine speed dependent and were included in the engine model for each baseline vehicle. The electric power steering systems assumed no engine parasitic loads on the EPA drive cycles and acceleration performance cycles, which require no steering input. All advanced package simulations included the benefit of electric power steering.

The Truck model also includes engine parasitic losses due to the belt-driven engine-cooling fan. The other vehicles were assumed to have electric radiator fans, with the load being drive-cycle dependent and added to the vehicle's base electrical load.

3.5 TRANSMISSION MODEL

Efficiencies for each gear ratio were calculated based on an empirical formula derived from several transmission and final drive gear tests. Different efficiency curves were mapped for planetary, dual-clutch (DCT with dry and wet clutches) and belt-driven CVT gearboxes. Hydraulic pumping losses were included in the efficiency calculations. Transmission efficiencies were calculated to represent the average of the leading edge for today's industry and not one particular manufacturer's design.

A shift map (upshift and downshift based on engine load and vehicle speed) was developed for each vehicle/engine/transmission combination using common industry design practices. A minimum engine speed after upshift of 1250 RPM was considered for the I4 engines (1200 RPM for V6 and 1150 RPM for V8) with considerations for gear hunting and WOT shifts at engine redline.

An "aggressive" shift schedule was used with the advanced technology vehicle packages that allowed the engine to operate at 100-150 RPM lower during some portions of the drive cycles. The NVH effect of this lower engine speed was considered but not quantified.

3.6 TORQUE CONVERTER MODEL

Torque converter characteristics curves for torque ratio and K-factor were generated using typical industry standards for efficiency. Each vehicle's torque converter characteristics for torque ratio and K-factor were tailored for the application based on Ricardo experience. Impeller and turbine rotational inertias are also input to the model.

A lockup clutch model was used with all torque converters and was of sufficient capacity to prevent clutch slip during all simulation conditions. Lockup was allowed in 3rd and 4th gears with the 4-speed automatics, 3rd/4th/5th gears with the 5-speed automatics, and 4th/5th/6th gears with the 6-speed automatics. During light throttle conditions a minimum engine operating speed of 1300 RPM for I4 engines (1200 RPM for V6 and 1000 RPM for V8) with the converter clutch locked was considered in developing the lock/unlock maps. A vibration damper or limited clutch slip (30-50 RPM) strategy was not modeled for the lockup clutch. These devices typically have a minor effect on fuel economy and manufacturers may choose to adopt these to minimize any driveability impacts of the torque converter lockup operation.

An "aggressive" torque converter lock/unlock schedule was used with the advanced technology vehicle packages that allowed the engine to operate at 100-150 RPM lower during some portions of the drive cycles. The vehicle refinement effect of this lower engine speed was considered but not quantified.

3.7 FINAL DRIVE DIFFERENTIAL MODEL

Baseline final drive ratios were taken from published information and driveline efficiencies and spin losses were assumed as typical industry standards. The spin losses of the 4-wheel-drive Truck front axle and transfer case were included in the model to simulate the fuel economy and performance of the 4-wheel-drive powertrain operating in 2-wheel-drive mode (similar to EPA procedure for emissions and fuel economy certification testing).

3.8 VEHICLE CHARACTERISTICS

Vehicle mass and dimensions for wheelbase and height are from published sources. Center of gravity and front/rear weight distribution are assumed as typical for the vehicle class.

Model inputs for Frontal Area (A_f) and Coefficient of Drag (C_D) were assumed to be typical of the vehicle class.

The wheel/tire model includes inputs for rolling radius, rotational inertia, slip at peak tire force, maximum friction coefficient, and tire rolling resistance coefficients.

3.9 DRIVER MODEL

Vehicle simulations for fuel economy were conducted over the EPA FTP75 (city) and HWFET (highway) drive cycles. The FTP75 cycle consists of three "bags" for a total of 11.041 miles. A ten minute engine-off soak is performed between bags 2 and 3 (after 1372 seconds of testing). A bag 1 correction factor of 80% was applied to the simulated "hot" fuel economy result of the baseline vehicles to approximate warm-up conditions of increased friction and sub-optimal combustion.

The vehicle model is forward facing and has a model for the driver. The driver looks at the required vehicle speed in the drive cycle and applies the throttle or brake pedal as needed to meet the required speed. This allows the modeling of the actual vehicle response to meet the target drive cycle.

The driver model contains the drive cycle time/velocity trace, controls for the throttle and brake functions and maintains vehicle speed to the desired set point. For WOT accelerations from zero vehicle velocity, the driver model controls the throttle to ramp-up the full load engine torque during the first second of the simulation. This more closely simulates actual vehicle engine/transmission calibrations and engine induction system lag. The model does not include launch delays that are inherent in the vehicle hardware and relies on the published engine output values.

3.10 STOP-START MODEL

As the stop-start system has significant complexity it is worth describing the modeling. A 42V starter / alternator can be used to restart the engine after an idle stop condition and to supply power to the Dual Voltage electrical system. Under normal driving conditions the starter / alternator functions similarly to the conventional alternator but is sized for 42V operation. When the vehicle is stationary, the engine coolant temperature determines the idle stop functionality. Below the desired coolant temperature set point, the idle stop function is disabled to maintain appropriate emissions regulation. Above the coolant temperature set point, the engine is turned off to decrease fuel consumption.

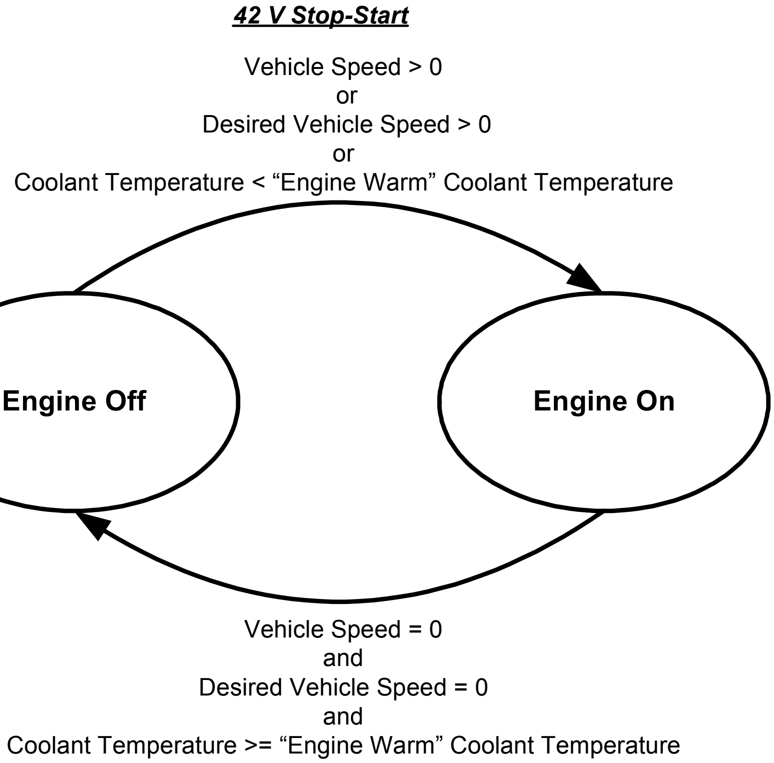


Figure 3-1: Basic Stop-Start Strategy

The 42V stop-start included the starter/alternator and a DC–DC converter. To power the 12V loads a conversion efficiency of the DC-DC was modeled as a constant 85%. As higher voltage was available, the stop/start technology also included electric pumps for engine oil and engine coolant. The model included electrical losses associated with the motors, conductors and power electronics. The efficiency of the electrical machines, defined as output power over input power, is shown in Figure 3-2. For a electrical motor the efficiency is the ratio of the shaft power (output) to electric power (input) and for a generator the efficiency is the ratio of electric power (output) to shaft power (input).

The starter / alternator was based on an electric motor drive system with a peak power output of 5kW. It is shown that the energy required to restart the engine is negligible compared to the total drive cycle energy. On the city drive cycle, the Small MPV experienced 18 stops, requiring less than 1kJ of total energy to restart the engine. This represents less than 0.2% of the total energy expended over the drive cycle.

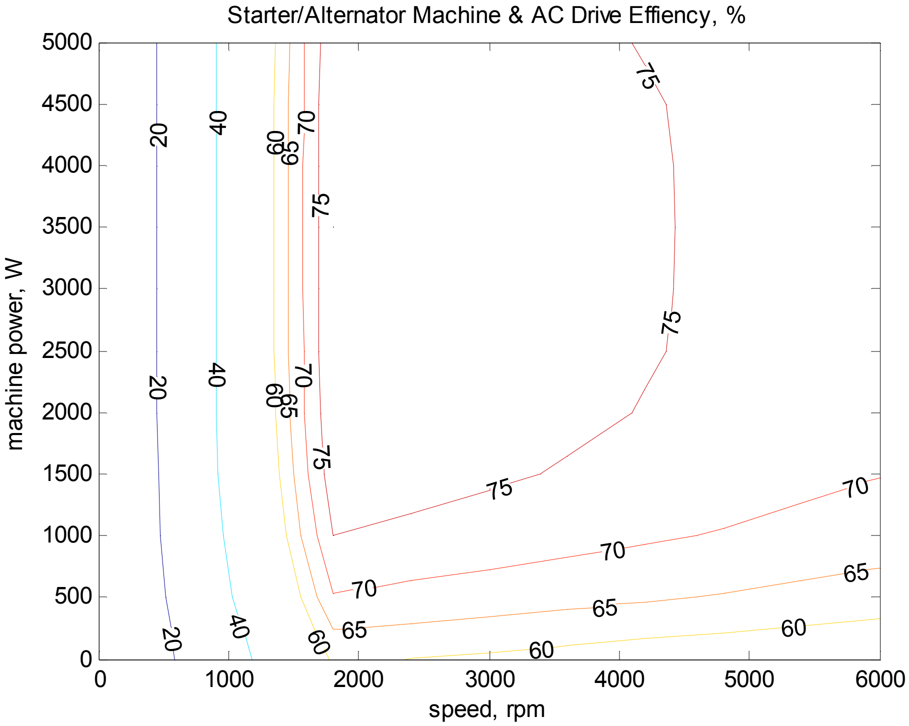


Figure 3-2: Starter / Alternator Machine & Air Conditioning Drive Efficiency

The oil pump and water pump hydraulic power requirements are based on typical restriction curves and design point requirements. The electric pumps are modeled as a reduction in parasitic losses resulting from decoupling the pump speed from the engine speed. The operating point of the electric pumps is determined from engine load and hydraulic power requirements. While a conventional pump power increases monotonically with speed, the flow rate does not because the pressure is regulated. Therefore, electric pumps can limit the power consumed at higher engine speeds to match the flow provided by a conventional pump. Figure 3-3 shows the electric pump power leveling off above a certain engine speed depending on the engine load.

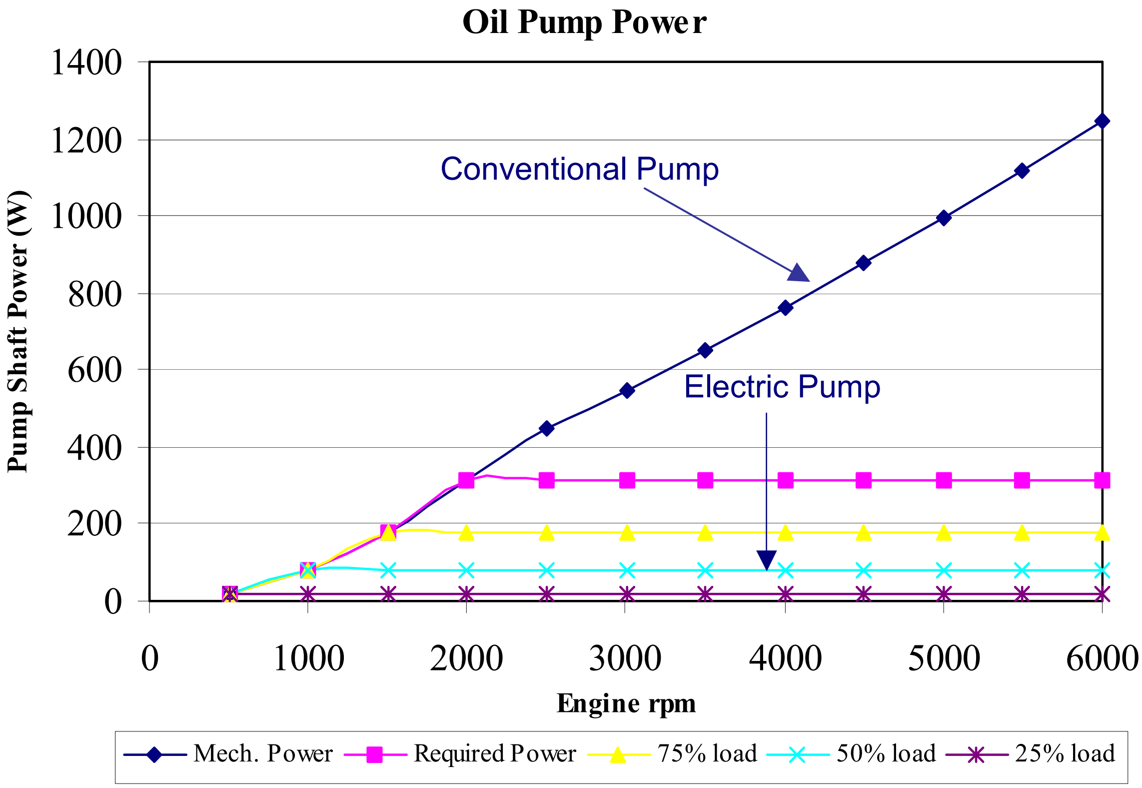


Figure 3-3: Electric Oil Pump Hydraulic Power Equipment

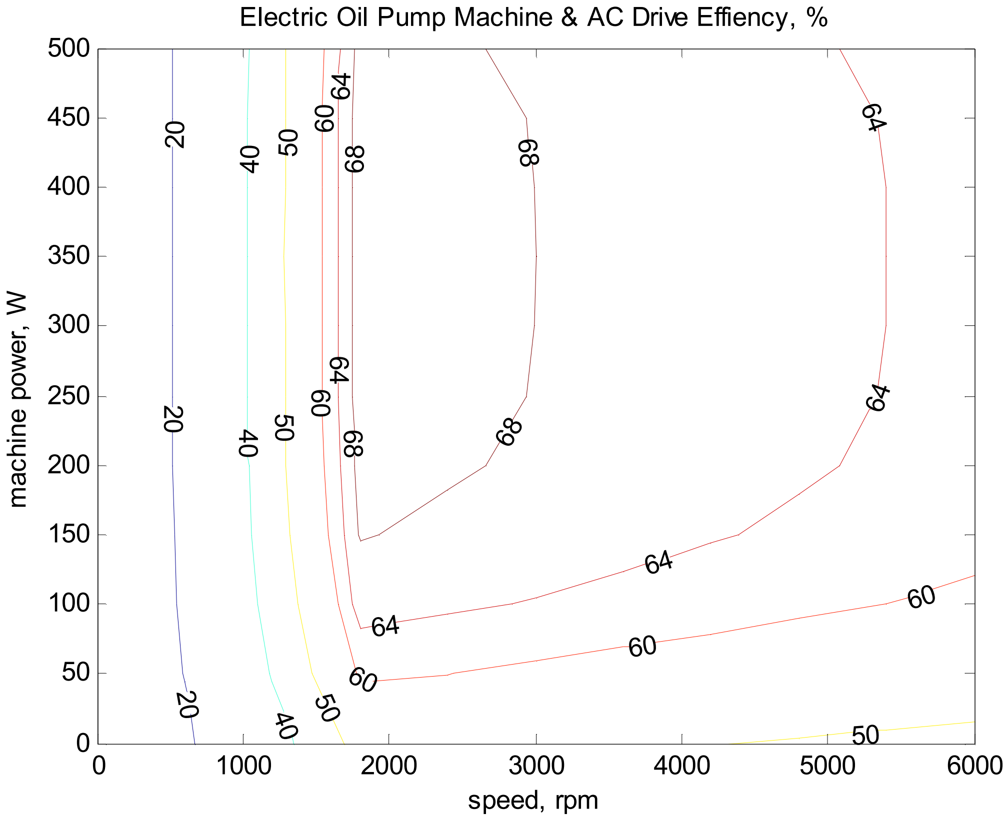


Figure 3-4: Electric Oil Pump Machine & Air Conditioning Drive Efficiency

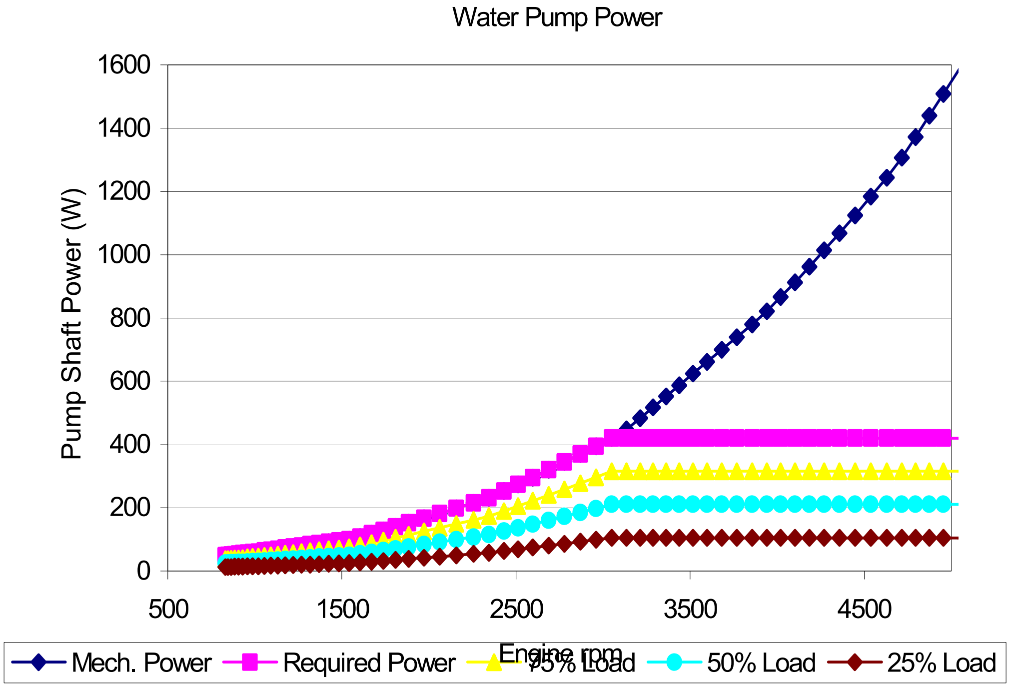


Figure 3-5: Electric Water Pump Hydraulic Power

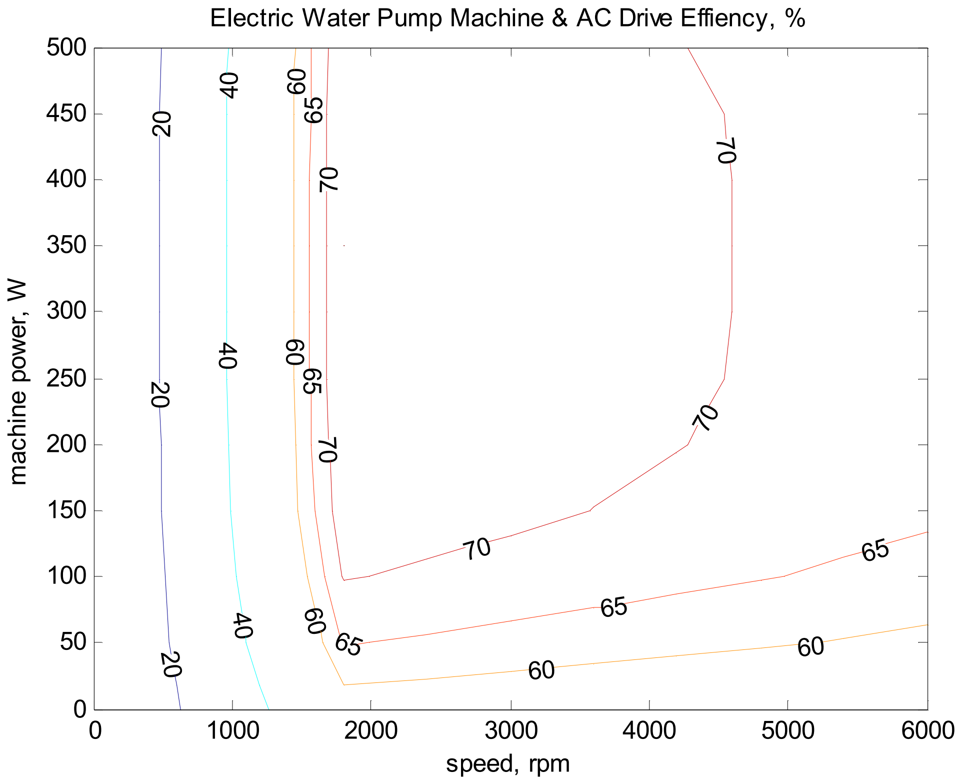


Figure 3-6: Electric Water Pump Machine & Air Conditioning Drive Efficiency

4.0 DISCUSSION OF BASELINE VEHICLE CLASS RESULTS AND COMPARISON WITH COMPARATOR VEHICLE

The modeling approach described in Section 3 was used in conjunction with input data compiled from public as well as Ricardo-proprietary sources to generate results for the representative baselines in each of the five vehicle classes identified by the EPA. The five vehicles classes and the representative vehicle chosen by EPA are provided below.

Table 4-1: Baseline Vehicles Description and EPA Fuel Economy

Baseline Vehicles										
Vehicle Class	**Representative Vehicle**	**Engine**	**Trans.**	**Drivetrain**	**Curb Weight (lb)**	**ETW (lb)**	**GCW (lb)**	**EPA City FE (mpg)**	**EPA Highway FE (mpg)**	**EPA Combined FE (mpg)**
Standard Car	Toyota Camry	2.4L I4 DOHC 4 valve VVT	5 spd Auto	FWD	3108	3625	N/A	26.7	42.2	32.0
Small MPV	Saturn Vue	2.4L I4 DOHC 4 valve VVT	4 spd Auto	FWD	3825	4000	N/A	23.8	36.7	28.3
Full Size Car	Chrysler 300	3.5L V6 SOHC 4 valve	5 spd Auto	RWD	3721	4000	N/A	20.9	34.1	25.3
Large MPV	Grand Caravan	3.8L V6 OHV 2 valve	4 spd Auto	FWD	4279	4500	N/A	19.5	31.9	23.6
Truck	Ford F150	5.4L V8 SOHC 3 valve VVT	4 spd Auto	4WD	5470	6000	14000	15.5	22.7	18.1

As a first step in validation of the model, the simulated road load for each baseline vehicle case was compared to the published EPA road load curve for the representative comparator vehicle. This data is as follows:

Table 4-2: Maximum Road Load Force Variation

Vehicle Class	Maximum Road Load Force Variation (model versus published EPA data)
Standard Car	-0.2%
Small MPV	+0.2%
Full Size Car	-0.4%
Large PMV	+1.2%
Truck	-2.4%

The following charts document the results of the simulations for the baseline cases as compared to the identified respective representative vehicles for the 5 classes used in this study. As mentioned in Section 2 of this report, any discrepancies between the simulation results and the actual vehicle data were attributed to the use of generic input data for that vehicle class instead of actual data for a specific vehicle. Specifically, the 0 – 60 MPH times will be affected by the method used to conduct the actual vehicle test as well as the reasons cited in Section 3.9. The baseline simulation results were required to represent the vehicle classes and not specific vehicles and formed a consistent basis for comparing the technology packages.

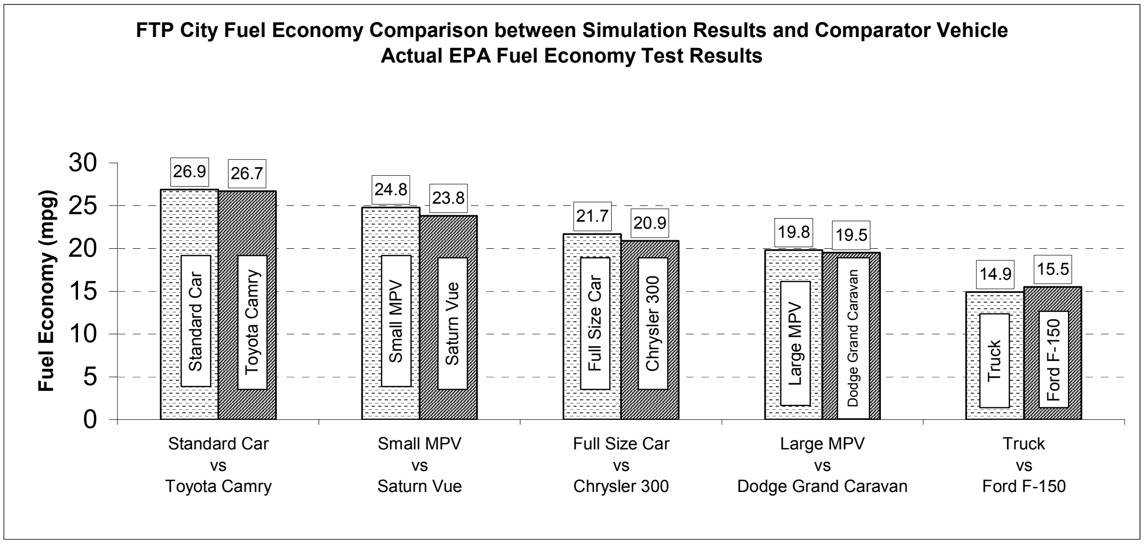


Figure 4-1: FTP City Fuel Economy Comparison between Simulation Results and Comparator Vehicle

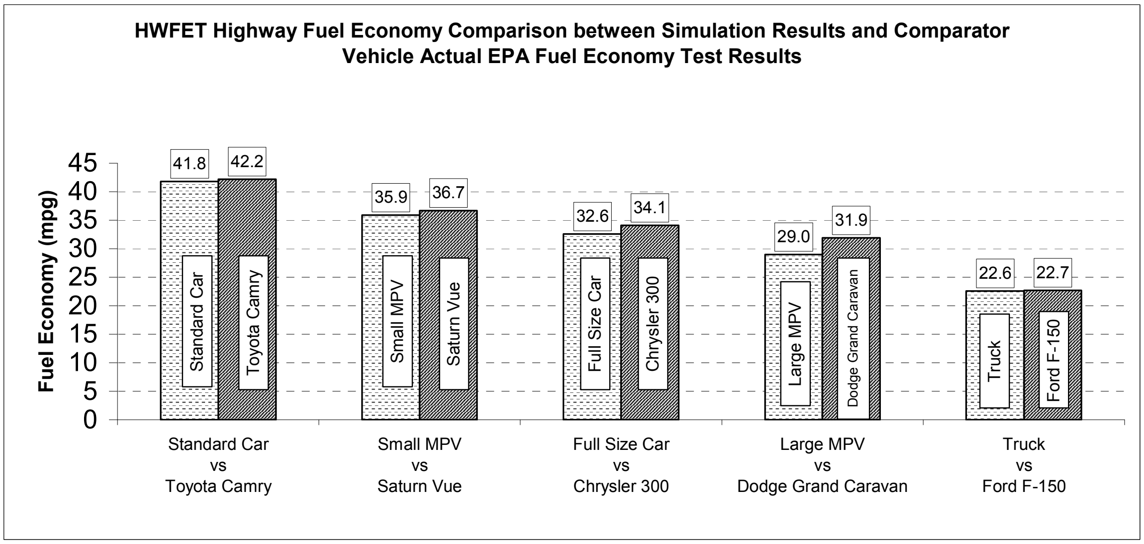


Figure 4-2: HWFET Highway Fuel Economy Comparison between Simulation Results and Comparator Vehicle

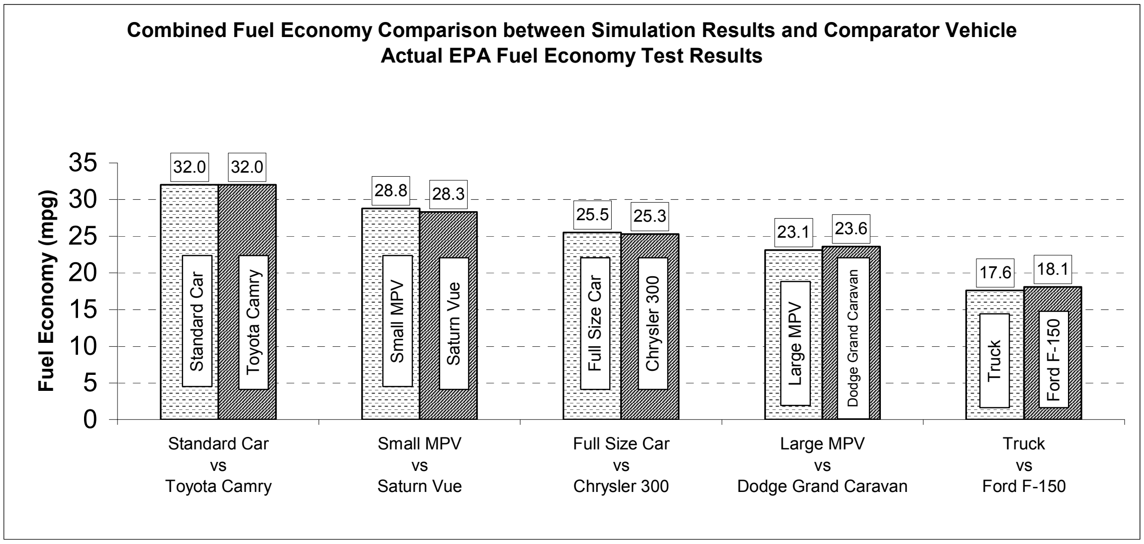


Figure 4-3: Combined Fuel Economy Comparison between Simulation Results and Comparator Vehicle

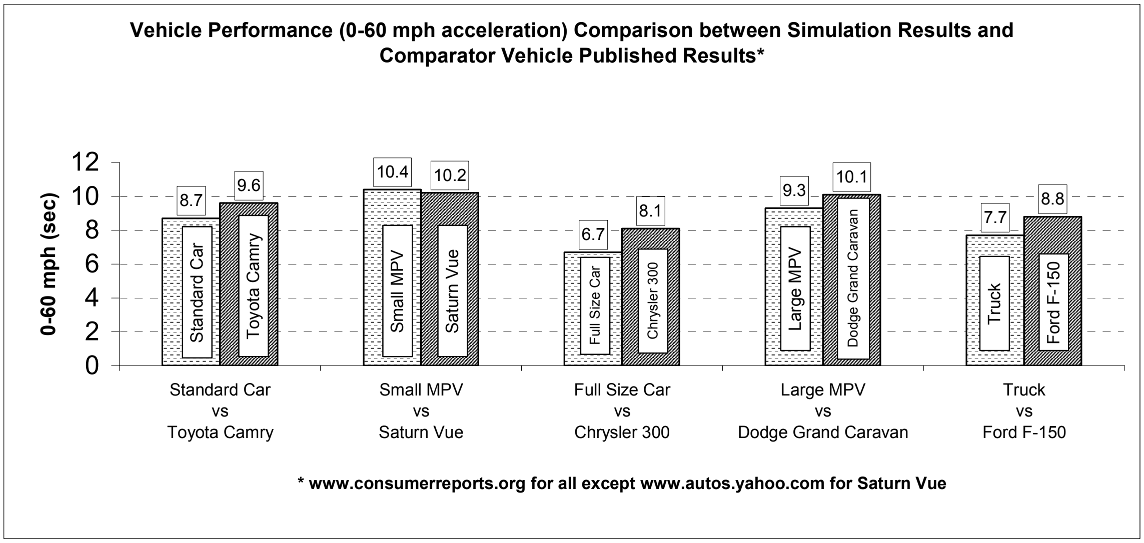


Figure 4-4: Vehicle Performance Comparison between Simulation Results and Comparator Vehicle

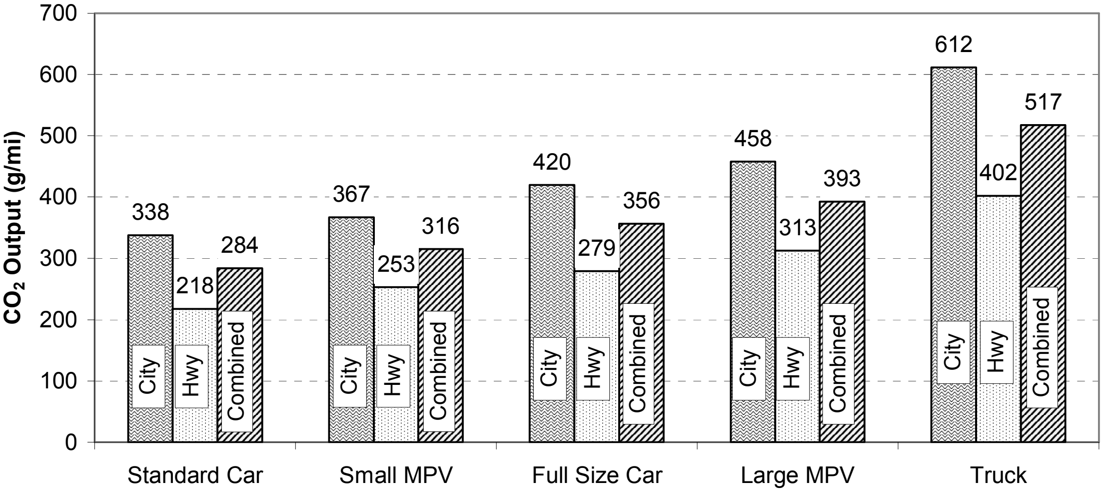


Figure 4-5: CO$_2$ Emissions Level Comparison of Simulation Results for all Baseline Vehicle Cases

5.0 INDIVIDUAL TECHNOLOGIES STUDIED

In this section the advanced technologies applied to the engine and the transmission are discussed. It should be noted that many of these technologies have the potential to change vehicle weight and therefore further impact vehicle fuel economy and CO_2 output. However the weight changes inherent in most of these technologies was assumed to fall within a band of 125lb as defined by the Engineering Test Weight classes.

5.1 ENGINE TECHNOLOGIES

5.1.1 Cam Phaser Systems - Variable Valve Timing (VVT)

A cam phaser actuator adjusts the camshaft angular position relative to the cam sprocket, and therefore, relative to the crankshaft position. The majority of applications use hydraulically actuated units, powered by engine oil pressure, and managed by a solenoid that controls the oil pressure supplied to the phaser. The figures below show the standard vane-type hydraulic cam phaser and an electrically actuated unit, which are beginning to appear in production. Typical angular adjustment range is 50–60 crankshaft degrees. There are a number of different implementation options:

- DCP (Dual Cam Phaser), where one cam phaser is used on each camshaft, giving independent control of inlet and exhaust valve timing
- ICP (Inlet Cam Phaser), where one cam phaser is used on the inlet camshaft only
- CCP (Coordinated Cam Phaser), where one cam phaser is used per engine, giving equal cam phase adjustment to inlet and exhaust camshafts.

Figure 5-1: Hydraulic vane-type cam phaser

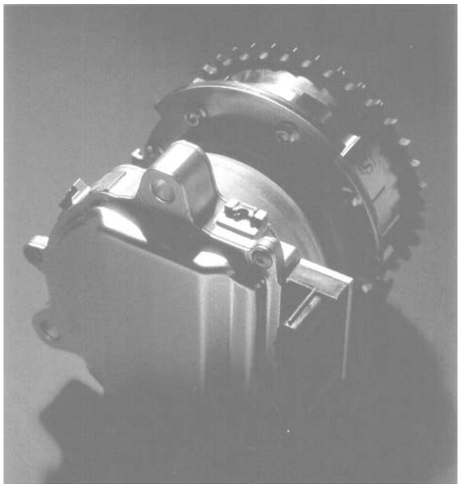


Figure 5-2: Electrically actuated cam phaser

5.1.1.1 Advantages

Compared to fixed valve timing, use of variable cam phasing gives an improvement in full-load volumetric efficiency, particularly at low speed, resulting in increased torque output. In turbocharged engines, particularly direct-injection turbocharged engines, use of variable cam phasing gives improved scavenging at full load, resulting in improved octane requirement and higher torque.

At low load, use of variable cam phasing gives a reduction in pumping losses, resulting in improved low-load fuel consumption. The economy benefit depends on the residual tolerance of the combustion system. Additional benefits are seen at idle, where low valve overlap can be used to give improved combustion stability.

5.1.1.2 Disadvantages and Technical Risks

The only disadvantage of this technology is that there may be a need to increase the engine oil pump capacity.

Hydraulically actuated cam phasers are regarded as a mature technology with minimal technical risk. Electrically actuated cam phasers are relatively new, but are now in volume production with Toyota, which suggests that any technical issues have been resolved.

To deliver the full potential benefits, the phaser system must be optimized for fast transient response (> 100 degrees crank angle per second).

5.1.1.3 Source of Engine Brake Specific Fuel Consumption (BSFC) Maps

Since cam phasers are becoming widely used in production, data was readily available from Ricardo benchmark data.

5.1.2 Variable Valve Lift Systems

5.1.2.1 Continuously Variable Valve Lift (CVVL)

In CVVL systems, maximum valve lift is varied by means of a mechanical linkage, driven by an actuator controlled by the engine Electronic Control Unit (ECU). Cam period and phasing vary as the maximum lift is changed, with the relation depending on the geometry of the mechanical system. CVVL is applied in addition to cam phase control. The BMW “Valvetronic“ system, as shown in the figure below, is the best known production CVVL system, giving a lift range of 0.25–9.4 mm. This allows the engine to be completely valve-throttled.

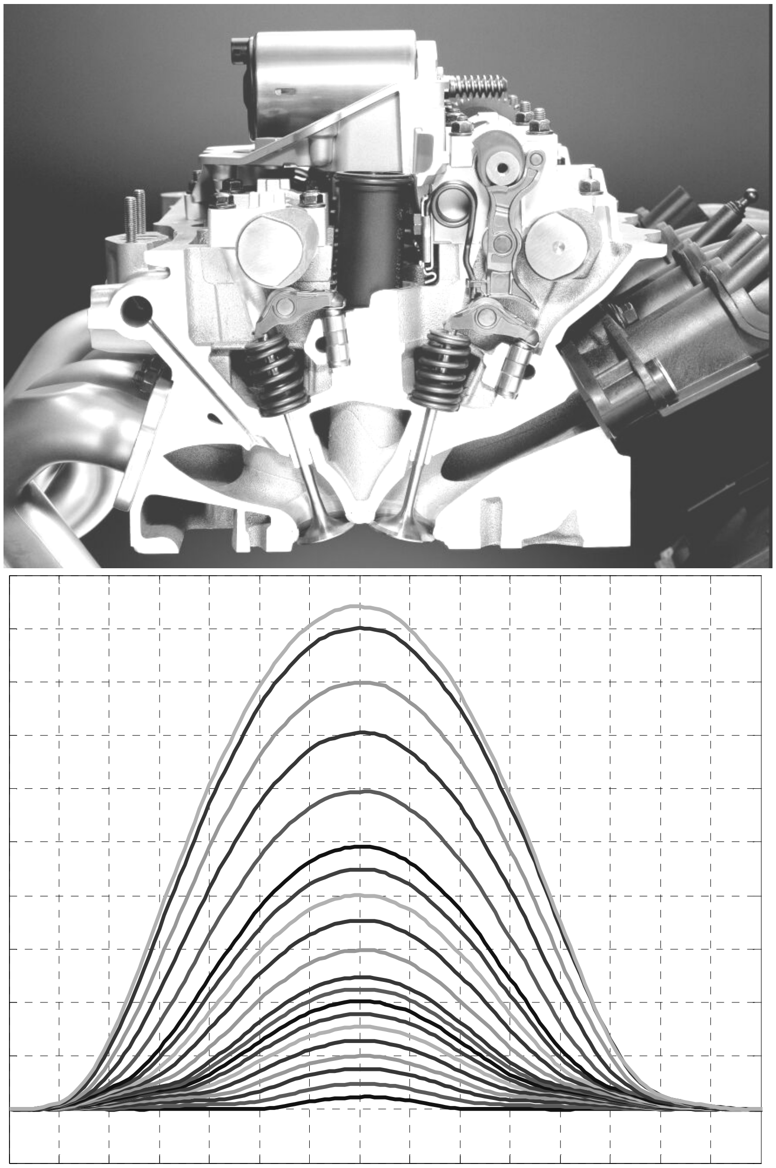


Figure 5-3: BMW “Valvetronic” continuously variable inlet valve lift system and valve lift profiles available with it

5.1.2.2 Discrete Variable Valve Lift (DVVL)

DVVL systems allow the selection between 2 or 3 separate cam profiles by means of a hydraulically actuated mechanical system. DVVL is normally applied together with cam phase control. One example is the INA system for direct-attack valvetrains, as shown. DVVL is also known as Cam Profile Switching (CPS).

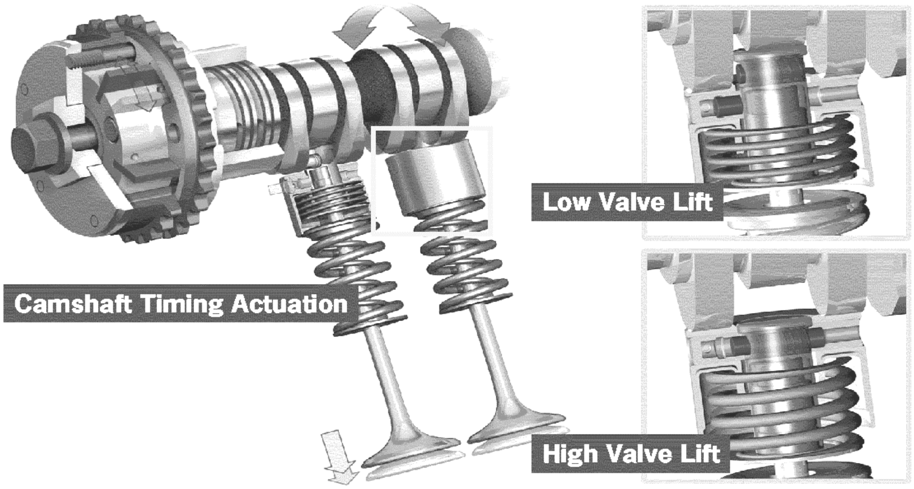


Figure 5-4: INA DVVL system for direct-attack valvetrains

5.1.2.3 Advantages Compared to CAM Phasers Only

Variable valve lift gives a further reduction in pumping losses compared to what can be obtained with cam phase control only, with CVVL giving greater benefit than DVVL. There may also be a small reduction in valvetrain friction when operating at low valve lift. This results in improved low-load fuel consumption for cam phase control with variable valve lift compared to cam phase control only. Most of the fuel economy benefit is achieved with variable valve lift on the inlet valves only.

In terms of fuel economy benefit versus system cost, variable lift systems on the inlet valves only are seen as a cost-effective technology when applied in addition to cam phase control.

5.1.2.4 Disadvantages and Technical Risks

In Ricardo's experience, it is more difficult to achieve good cylinder-to-cylinder airflow balance at low load with a CVVL valve-throttled engine due to the sensitivity of airflow to small differences in lift caused by production component tolerances. BMW has reported mixture quality issues with CVVL and port fuel injection, requiring a compromise on pumping work reduction to ensure good mixture quality. With CVVL, a small amount of throttling is necessary to maintain brake servo operation, unless a separate vacuum pump is used. BMW maintains 50 mbar inlet manifold depression on its "Valvetronic" engines to allow the brake servo to function.

Tumble air motion generated by the inlet port is not available in the cylinder at low valve lift, which has an effect on combustion characteristics. The high gas velocities at the valve seat generate high turbulence levels, but most of this has decayed by the time of ignition.

DVVL is a mature technology with low technical risk.

CVVL system designs are unique to each OEM and it is therefore not possible to generalize about technical risk. BMW has the most production experience and has sold port injection "Valvetronic" engines since 2001. The most recent introduction of "Valvetronic" is on the BMW/PSA 1.6-liter, 4-cylinder, port injection "Prince" engine.

With CVVL systems, engine transient response will be limited by rate of change of maximum valve lift. 100 ms response time from minimum to maximum lift is available from the BMW system.

5.1.2.5 Source of Engine BSFC Maps

5.1.2.5.1 CVVL

The CVVL BSFC benefit map was based on measured test bed data from a Ricardo research engine and BMW published data for its “Valvetronic” engine [1-4]. The specification of the research engine is as follows:

- European 4 cylinder
- 4 valves per cylinder
- Bore of 84mm
- Stroke of 90mm
- Compression Ratio of 10.5 :1
- Port fuel injection
- Dual variable cam phasers with 60 degree crank angle range
- The engine was fitted with a new cylinder head designed and manufactured by Ricardo, incorporating the BMW ‘Valvetronic‘ mechanical variable lift and period system for both intake and exhaust valves.

5.1.2.5.2 DVVL

The DVVL BSFC benefit map is based on Ricardo test data from a North American V6, using alternative camshafts to simulate the benefit of a cam profile switching system.

5.1.3 Cylinder Deactivation

Cylinder deactivation is a fuel economy technology that is in use today in the North American market. It can be found on several vehicles under various trade names such as Multiple Displacement System (MDS) and Active Fuel Management (AFM). Cylinder deactivation has to date been applied to V6, V8, and V12 engines.

The concept of cylinder deactivation targets reducing pumping losses by switching off, or deactivating, half of the engine cylinders. By deactivating half the cylinders, the remaining active cylinders are operating at twice the load that the engine would normally operate at if all cylinders were active. By definition therefore, those active cylinders have the throttle further open, thereby reducing the pump losses and improving fuel consumption.

Mitsubishi Motor Corporation introduced an early example of cylinder deactivation with its MIVEC system applied to a four-cylinder engine. This engine had a short-lived production run but demonstrated its feasibility. In the North American market, a significant percentage of the engines in production were based on a pushrod valvetrain. The simplicity of the architecture of pushrod valvetrains lends itself to cylinder deactivation, and thus, significant effort was directed to this technology on both V8 and V6 pushrod engines. General Motors Corporation and Chrysler Corporation have developed systems for their respective engine families. Applying cylinder deactivation to overhead camshaft engines is also possible but requires a more complex solution. Mercedes-Benz successfully applied this technology to its V8 and V12 engines.

Effective cylinder deactivation requires accurately timed disablement and re-enablement of both the intake and exhaust valves. In the case of a pushrod valvetrain, a revised hydraulic lifter is used which incorporates an oil-pressure-controlled locking pin. The pin can be either locked or unlocked to allow the pushrod to operate or not operate the valve. Below is an example of the layout for a pushrod valvetrain.

Figure 5-5: Pushrod Valvetrain

Overhead camshaft engines generally have greater challenges in deactivating valves, primarily due to the available package space and generally a four-valve-per-cylinder layout. Typically, there are two types of valve train: Type 1 a direct-acting bucket tappet, which is either hydraulically or mechanically lashed; Type 2 is a roller finger follower with a static hydraulic lash adjuster. In the case of a Type 1 configuration, a hydraulic tappet can allow “lost motion” by utilizing an oil-controlled locking pin, an example of which is shown below.

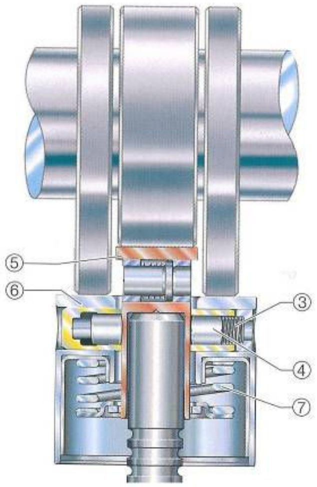


Figure 5-6: Oil-Controlled Locking Pin

Type 2 valvetrains can utilize two approaches. One has a collapsing rocker, where lost motion can be achieved by allowing the roller to move relative to the follower. This approach still uses a conventional lash adjuster. The other approach uses a conventional roller follower and has a lost motion lash adjuster similar to that used on the pushrod valvetrain layout. The figure below shows examples of a lost-motion Type 2 roller finger follower:

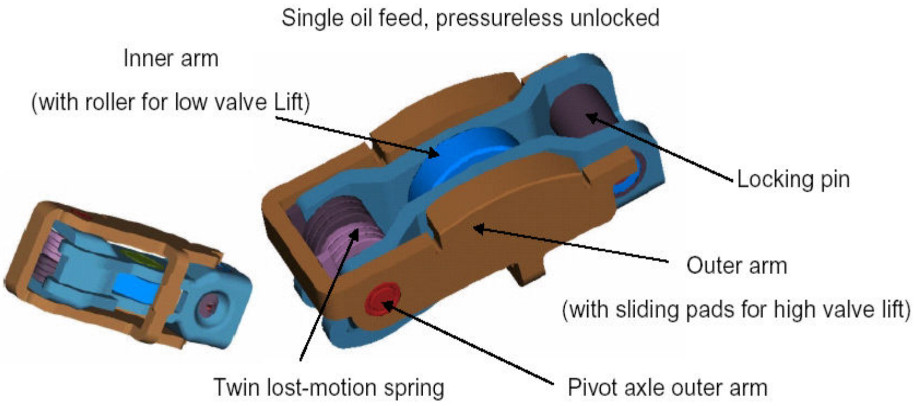


Figure 5-7: Symmetrical Roller Finger Follower (SRFF)

In the case of the Mercedes engine, the valvetrain was a 3-valve configuration. Therefore, a more complex solution was required, as shown below.

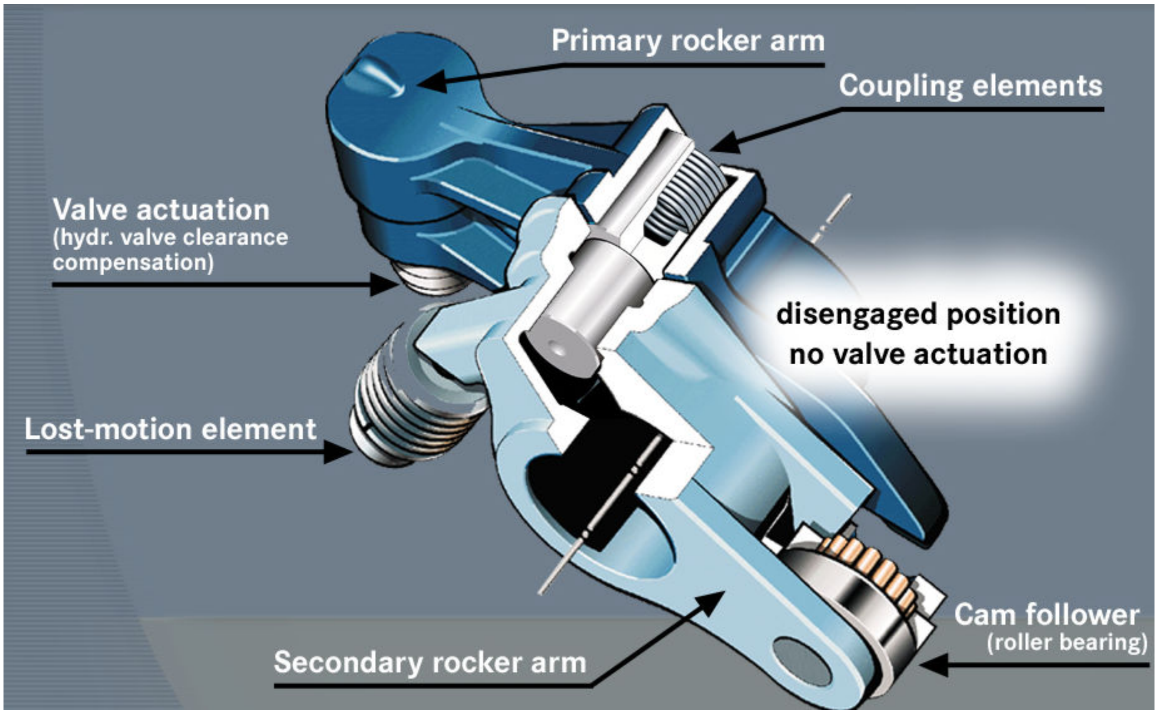


Figure 5-8: Mercedes 3-valve Configuration Follower

The sequencing of cylinder deactivation is important. Firstly, when deactivating half the number of cylinders, this has to be done in such a manner that an even firing interval is maintained. So in the case of a V8, the firing interval would increase from 90^o to 180^o. Depending on the firing order and configuration selected, either one bank of an engine will be deactivated (V6) or selected cylinders on both banks (V8). The control of the deactivation is by solenoid valves akin to those found on transmissions. The number of valves used is an area where extensive development has occurred in an attempt to minimize the total but still achieve satisfactory control. Four control valves are typical on a pushrod engine, whilst four per cylinder head is typical for an overhead cam engine.

5.1.3.1 Advantages

Cylinder deactivation control strategy is relatively simple. It relies on setting a maximum and minimum manifold absolute pressure with which it will deactivate the cylinders. There is potentially a significant fuel saving due to the reduced pumping losses as part load. The same engine displacement and maximum horsepower can be maintained.

5.1.3.2 Disadvantages and Technical Risks

Vehicle integration has been a challenge for cylinder deactivation. Issues with NVH dominate the list of implementation issues. Active engine mounts are needed to run deactivated at idle. Noise quality from both intake and exhaust has been problematic, and in some cases, had lead to active exhaust systems with an ECU-controlled valve. Deactivation is typically used in the highest two gears only. Other factors affecting real-world fuel consumption include vehicle power-to-weight ratio, drag coefficient, and available gear ratios. In many cases, it is difficult to maintain the vehicle in deactivated mode at 70 mph, which can lead to customer dissatisfaction with fuel consumption. As engine specific rating improves, the potential fuel consumption benefit reduces, or stated another way, as vehicle specific power rating improves, the potential fuel consumption benefit increases.

5.1.3.3 Source of Engine BSFC Maps

Production cylinder deactivation systems exist and Ricardo has benchmark data that can be appropriately scaled to various engine applications.

5.1.4 Gasoline Direct Injection

In gasoline direct-injection engines, fuel is injected into the cylinder rather than the inlet manifold or inlet port. Some changes to engine architecture are required compared to a port fuel injection engine. A typical homogeneous stoichiometric Direct Injection (DI) layout is shown below.

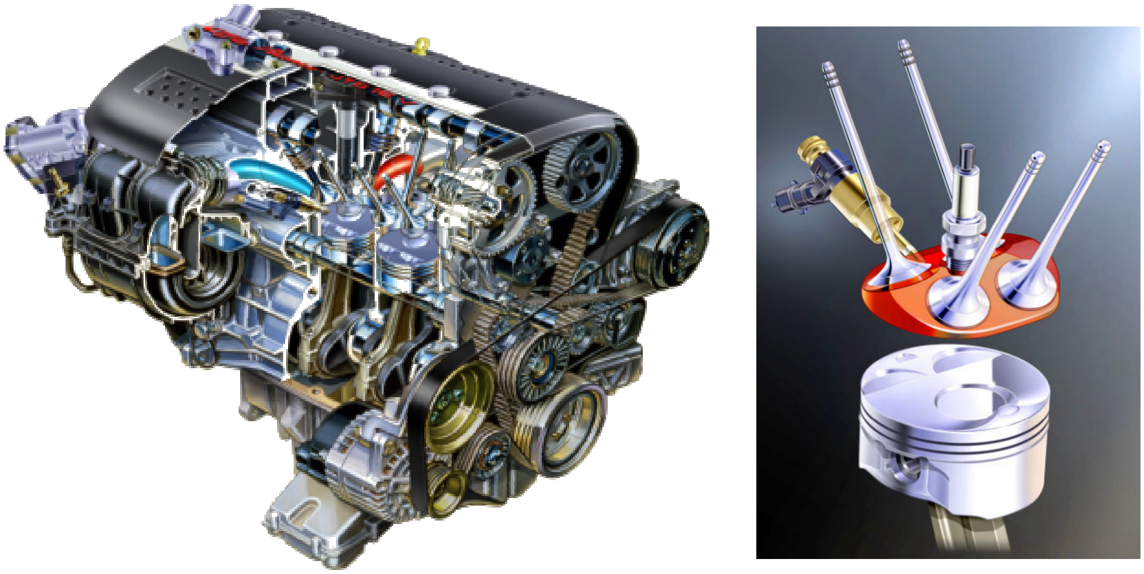


Figure 5-9: Typical homogeneous stoichiometric DI layout [5]

The fuel injection system comprises an electrically-driven low-pressure fuel pump, which feeds a high-pressure mechanical pump, working at up to 200 bar fuel pressure. A common fuel rail supplies the injectors, which produce a highly atomized spray with a Sauter Mean Diameter (SMD) of 15–20 microns, which compares to around 50 microns for a port injector. Two operating strategy options are used in DI gasoline engines, characterized by the mixture preparation strategy.

1. Homogenous, where fuel is injected during the intake stroke with a single injection. The aim is to produce a homogeneous charge by the time of ignition. In this mode, a stoichiometric air/fuel ratio can be used and the exhaust aftertreatment system can be a relatively low-cost conventional three-way catalyst.

2. Stratified, where fuel is injected late in the compression stroke with a single or multiple injections. The aim is to produce an overall lean stratified mixture, with a rich area in the region of the spark plug to enable stable ignition. Multiple injections can be used per cycle to control the degree of stratification. Use of lean mixtures significantly improves efficiency by reducing pumping work, but requires a high-cost lean NOx trap in the exhaust aftertreatment system.

In this study, only homogeneous stoichiometric systems were considered, at the request of the EPA.

5.1.4.1 Advantages of Homogeneous Stoichiometric DI

A compression ratio up to 1.5:1 higher than for a port-injected engine can be used for the same fuel quality due to charge cooling [6]. As a result of the higher compression ratio, part-load efficiency and full-load torque are improved.

Volumetric efficiency is improved by up to 2%, again due to charge cooling [6], which improves full-load torque.

DI increases turbulence in the charge as a result of the energy in the spray itself [7]. This helps to maintain burn rate with high residual levels and thereby improves economy in engines with cam phasers.

In boosted engines, DI allows improved scavenging of the cylinder without any direct charge loss. This reduces residuals and charge temperature, allowing a higher compression ratio to be used for a given fuel quality.

A degree of charge stratification can be used to improve combustion stability under the ignition timing strategy employed for catalyst heating after a cold start.

As a result of a higher compression ratio and improved residual tolerance, drive cycle fuel consumption is improved by 2-3%.

Also, as a result of a higher compression ratio and improved volumetric efficiency, torque is improved by around 5% in naturally aspirated engines.

5.1.4.2 Disadvantages and Technical Risks of Homogeneous Stoichiometric DI

The only disadvantage is the price of the DI fuel system. However, for an engine that already has dual cam phasers, DI represents a reasonably cost-effective next step in technology implementation.

Homogeneous, stoichiometric DI systems are regarded as a mature technology with minimal technical risk. To deliver the full potential benefits, a variable cam phasing system is required.

5.1.4.3 Source of Engine BSFC Maps

The stoichiometric DI BSFC benefit and torque benefit were based on Ricardo data from Port Fuel Injection (PFI) to DI conversion experience. The values agreed with published data [8].

5.1.5 Turbocharged/Downsized Gasoline Engine

Forced induction in the form of turbocharging and supercharging have been used on internal combustion engines for many years. Their traditional role has been one of providing enhance performance for high-end or sports car applications.

With the drive for improved fuel economy, turbocharged engines have been viewed in a different role, one of a fuel economy technology. There are two main reasons for this. Engine friction torque is proportional to engine displacement, but when comparing Friction Mean Effective Pressure (FMEP)—friction torque normalized by displacement—there is very little difference between the full-size engine and the boosted downsized engine, despite the higher cylinder pressure associated with higher Brake Mean Effective Pressure (BMEP). The net result is a natural friction advantage with a boosted down-sized engine. The second benefit is related to reduced pump losses (Pumping Mean Effective Pressure—PMEP). A turbocharged engine runs at significantly higher BMEP levels than a naturally aspirated engine. The upper limit of BMEP levels that can be expected from a naturally aspirated engine is ~ 13.5 bar, whereas a turbocharged engine can produce BMEP levels in excess of 20 bar. Current technology gasoline engines use a throttle to regulate load, but this causes pumping losses. Therefore, by using a small-displacement engine with a turbocharger, the smaller engine works harder (higher in-cylinder load) and this results in lower pumping losses as the throttle has to be further open. The figure below shows the benefit in BSFC achieved by the Bosch-Ricardo GDI V6 engine (DI Boost) compared to a V8 engine, specifically for a Cadillac CTS-V application [9].

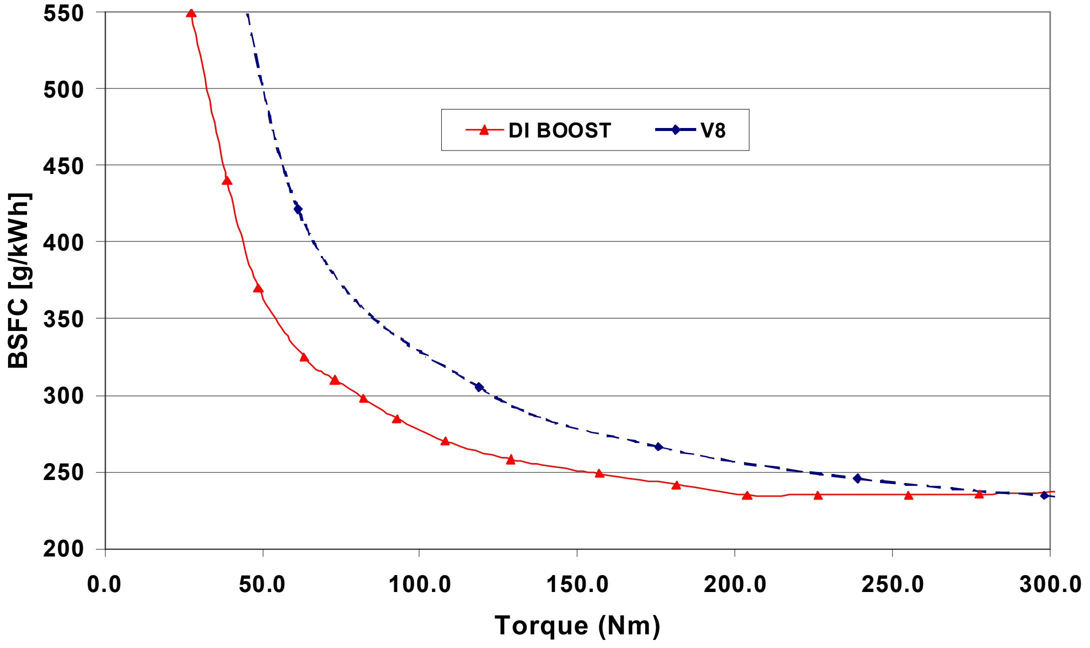


Figure 5-10: BSFC benefit achieved by Bosch-Ricardo GDI V6 Engine Compared to V8 Engine

There is no question that in most cases a boosted downsized engine can replace a conventional naturally aspirated engine and achieve equivalent power and torque.

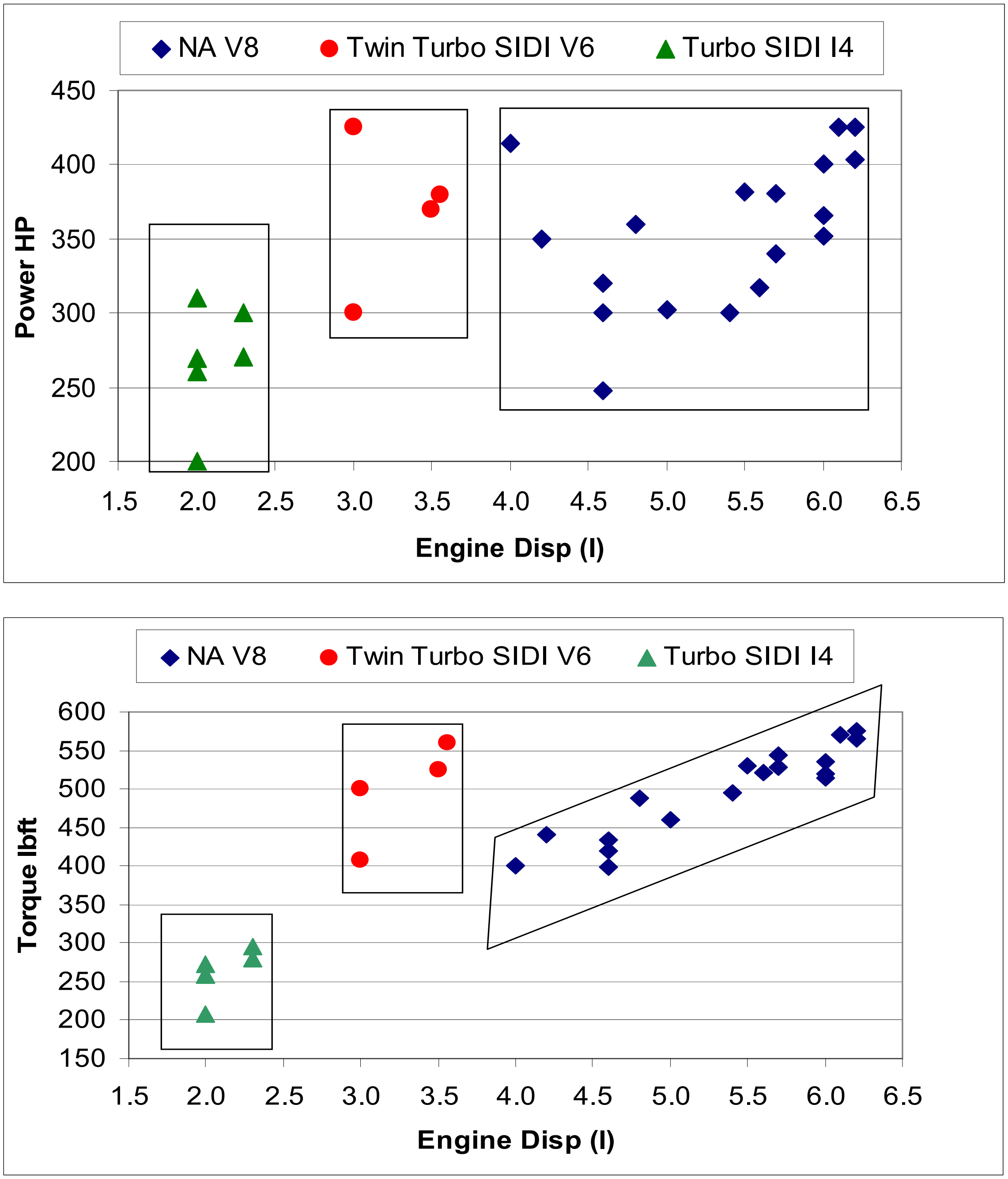


Figure 5-11: Comparison of Naturally Aspirated and Turbocharged Downsized Engines

The challenges associated with acceptance of a downsized boosted engine are:

- Achievement of “seamless” power delivery compared to the naturally aspirated engine (no perceptible turbo lag)
- Emissions performance—the addition of a turbocharger causes additional difficulty with catalyst light-off due to the thermal inertia of the turbo itself
- Additional base engine cost
- Additional vehicle integration costs

The case for using downsized boosted engines has greatly improved with the wider introduction of direct-injection gasoline engines. When combined with cam phasing, a viable technology package is readily available.

Structural changes to the base engine are focused on increasing its structural capability to tolerate higher cylinder pressures. It is reasonable to expect that the maximum cylinder pressure would increase by 25–30% over those typical in a naturally aspirated engine. Higher thermal loads accompany higher pressures, and these must also be considered.

5.1.5.1 Advantages

The downsized, boosted engine can deliver similar torque and power to the larger displacement engine it replaces. This reduces pumping and frictional losses and generates a noticeable improvement in fuel consumption.

5.1.5.2 Disadvantages and Technical Risks

One potential disadvantage is that car buyers have become accustomed to large-displacement engines being high power. Hence, the acceptability of smaller-displacement engines needs to be tested.

With a turbocharged engine there are a number of trade-offs to be considered. If the engine is to be biased to a highly rated variant then it is reasonable to expect that the engine will be a premium recommended product rather than regular fuel. In optimizing the engine, decisions as to the compression ratio and specific rating to be achieved are influenced by the fuel grade. For example, regular fuel can be used if the specific rating chosen is lower and the compression ratio is not raised significantly. While some fuel economy benefit may be lost if regular fuel is used, significant benefits from downsizing can still be realized.

If an engine rating of say 100 bhp/L is targeted, it is reasonable to assume that a regular fuel variant can be developed with a lower compression ratio, for example, 9.5:1 to 10.0:1 and still be a balanced overall product. The engine with the same rating could use 10.5:1 if it were a premium fuel engine. If a higher specific rating were selected, for example greater than 125 bhp/L then it is likely that the compression ratio would be 9.5:1 to 10.0:1 on premium fuel to avoid excessive engine knock. While some compression ratio has been lost, the engine’s performance has increased and the effect of downsizing has been improved, offsetting the loss of compression ratio. Trade offs as to what displacement the engine should be and what rating it should target with which recommended fuel are important to study during the planning stage.

A downsized boosted engine with stoichiometric direct injection presents minimal technical risk. Although, there have been limited demonstrations of this technology achieving SULEV emission levels.

5.1.5.3 Source of Engine BSFC

Ricardo has experience with a number of downsized, boosted engines. Two particular data sets were used for this study, one for a 2.4L I4 engine and the other for a 3.6L V6.

5.1.6 Homogeneous Charge Compression Ignition (HCCI)

HCCI is also known as Controlled Auto Ignition (CAI) and "Active Radical" combustion. In spark ignition, combustion initiates at the plug at a time controlled by the spark and a flame propagates through the charge. HCCI combustion initiates by auto-ignition at multiple sites within the combustion chamber at a time controlled by the charge temperature, pressure, and composition. Excessive rates of heat release are controlled by using high levels of internal EGR or lean mixtures.

The most practical approach to obtaining HCCI combustion in automotive gasoline engines is to use high levels of internal EGR (typically 40–70%) to both raise charge temperature and control heat release rate. A large negative valve overlap is used, often called "recompression strategy." Typical cylinder pressure diagrams for recompression HCCI are provided in Figure 5-12. Due to gas exchange, pressure rise rate and compression temperature constraints, HCCI combustion is only possible in a relatively small speed and load range as depicted in Figure 5-13. The upper load limit can be extended by boosting.

Practical implementation requires short valve-opening periods and control of inlet and exhaust cam phasing. The three main valvetrain options are:

- Cam profile switching and dual cam phasers
- Mechanical variable lift and period system for both intake and exhaust valves and dual cam phasers. The BMW "Valvetronic" valvetrain is a good example [11-13]
- Camless valvetrain

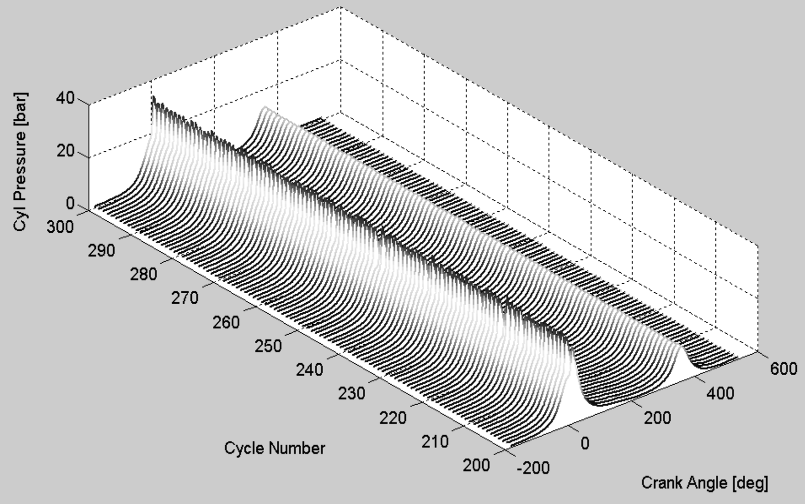


Figure 5-12: Cylinder pressure during HCCI combustion showing low cyclic irregularity and exhaust recompression [10]

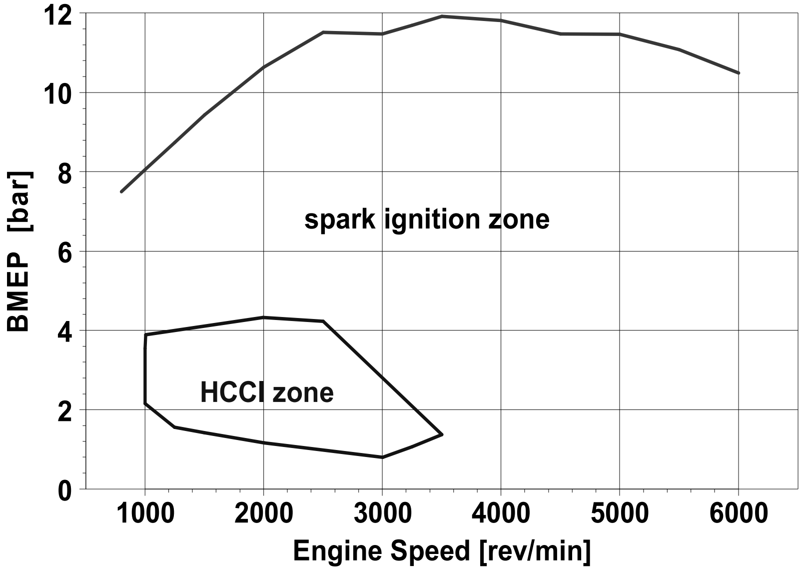


Figure 5-13: Typical speed / load envelope where HCCI combustion can be obtained using mechanical valvetrain

5.1.6.1 Advantages

To determine the benefits of HCCI combustion compared to spark-ignition combustion, it is important to compare it with a baseline spark-ignition engine with the necessary valvetrain technology to enable HCCI. On this basis, the benefits of HCCI combustion are:

- An overall gain in drive cycle fuel consumption
- A 20–30% reduction in drive cycle engine-out NOx emissions
- No engine-out HC emissions penalty
- A low level of cyclic combustion irregularity
- Compatibility with lambda 1 operation, enabling three-way catalyst exhaust aftertreatment to be used
- Compatibility with port or direct fuel injection
- Low system cost for implementation in an engine that already has a suitable valvetrain. (This statement assumes that a cylinder pressure or some other direct combustion sensor is not required to give heat release feedback to the engine management system.)

5.1.6.2 Disadvantages and Technical Risks

One disadvantage of HCCI combustion is that it can only be implemented in engines with variable valvetrains incorporating fast-response variable cam phasing and variable cam profiles. It is unlikely that the benefits of HCCI combustion alone would justify the cost of the necessary valvetrain. However, in engines where the necessary valvetrain has already been justified by the spark-ignition benefits, this disadvantage is not an issue.

Rates of pressure rise with HCCI combustion can be higher than for spark-ignition combustion, which may have implications for engine refinement.

Due to the high compression temperatures required to initiate HCCI combustion, HCCI mode would not be available in a cold engine, which limits the fuel consumption benefit in both legislated drive cycles and short journeys in the real world.

Control disadvantages include issues associated with calibration discontinuities between spark-ignition and HCCI combustion, requiring development of sophisticated strategies for managing the transition. Direct-injection with multiple injections per cycle may be required for control of combustion phasing and to manage the spark-ignition/HCCI transition. Also, HCCI may require cylinder pressure or other direct combustion sensor to give heat release feedback to the engine management system.

Small end bearing design may need to be reviewed for HCCI engines due to the lack of inertia relief in HCCI mode and the effect on lubrication.

HCCI implementation is thought to be 5-10 years away from high-volume production.

5.1.6.3 Source of Engine BSFC Maps

The HCCI BSFC benefit map was based on measured testbed data from a multi-cylinder Ricardo research engine. The engine was fitted with a new cylinder head designed and manufactured by Ricardo, incorporating the BMW ‘Valvetronic‘ mechanical variable lift and period system for both intake and exhaust valves [11-13]. Figures 5-14 through 5-16 below show a section through the valvetrain and a view of the assembled cylinder head along with the range of valve lift profiles available. The work is reported in reference [10] and the engine specification was as follows:

- 4 cylinder
- Bore of 84mm
- Stroke of 90mm
- Compression Ratio of 10.5 :1
- Port fuel injection
- Dual variable cam phasers with 60 degree crank angle range
- Variable lift and period system for both intake and exhaust valves

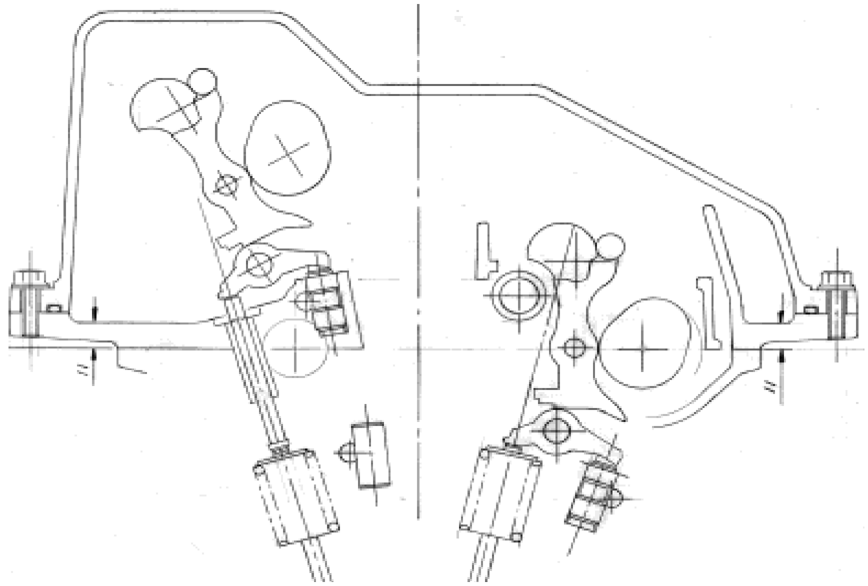


Figure 5-14: Ricardo TMVL (Twin Mechanical Variable Lift) HCCI research cylinder head valvetrain with dual variable valve lift and period and dual variable cam phasing

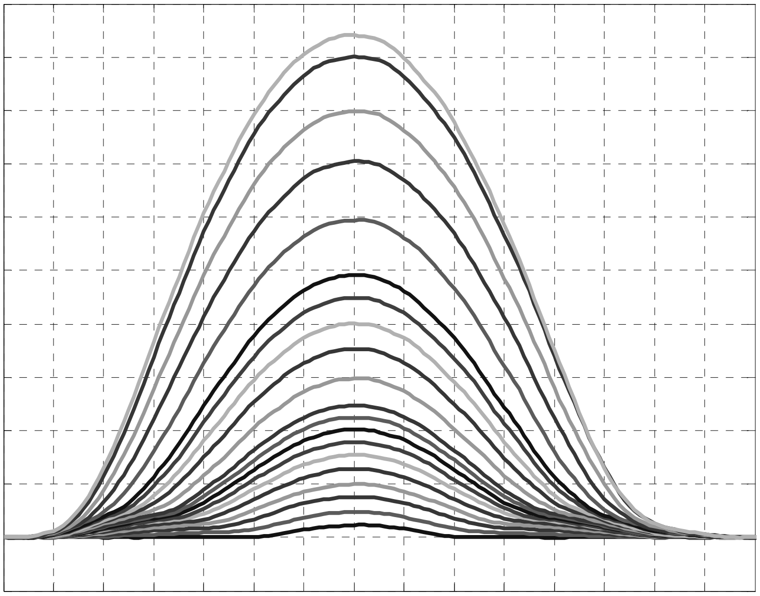


Figure 5-15: Alternative valve lift profiles with the BMW 'Valvetronic' system

Figure 5-16: Ricardo TMVL (Twin Mechanical Variable Lift) HCCI research cylinder head assembly

5.1.7 Camless Valvetrain

The term "camless" is used to describe a valve actuation system where valve motion is controlled by an electrohydraulic [15-16] or an electromagnetic actuator [14], with one actuator per valve or pair of valves. Feedback position control is provided to enable closed-loop control of the lift profile. An example of an electromagnetic actuator produced by Valeo is shown below [13]. The system operates on a 12V power supply. Also below is an example of an electrohydraulic actuator from Lotus [15]. Hydraulic fluid pressure in the electrohydraulic systems is up to 200 bar, provided by an engine-driven pump. Maximum valve velocity is typically 5 m/s, and maximum valve lift up to 15 mm can be achieved.

There are no production engines with camless valvetrains, although a number of research engines have been produced. A number of issues will need to be resolved before production applications can be considered:

- Power consumption
- Providing sufficient opening force for exhaust valves, especially in the case of turbocharged engines
- Control issues, such as cycle-to-cycle repeatability of lift (target 1%) and timing (target 1 degree crankshaft angle) and the ability to control valve-seating velocity ("soft landing")
- Cost
- Negative impact on NVH
- Failure modes and effects (FMEA)

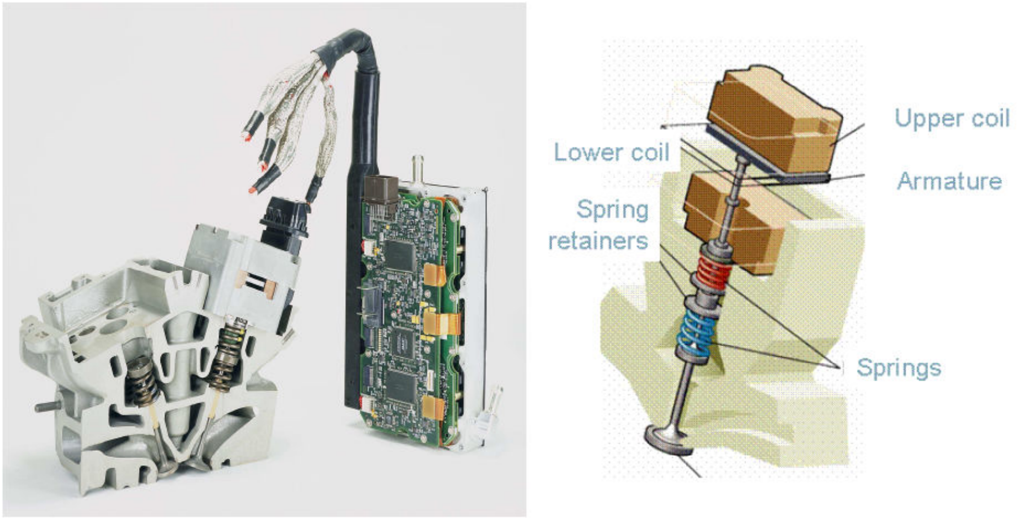


Figure 5-17: Valeo electromagnetic camless actuator [14]

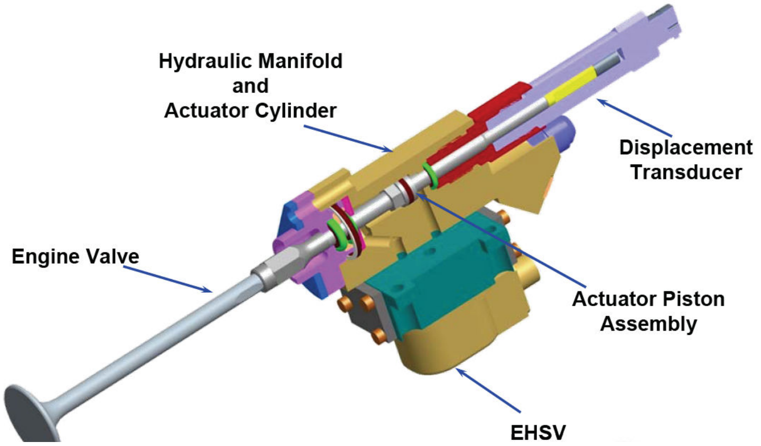


Figure 5-18: Lotus "AVT" Electrohydraulic camless actuator [15]

5.1.7.1 Advantages Compared to CAM Phasers Only

The full flexibility in valve lift profiles and timing provided by a camless valvetrain achieves a reduction in pumping losses at low load above that available from cam phasers and CVVL combined. This results in improved low-load fuel consumption compared to DCP + CVVL.

The camless valvetrain enables the engine to achieve HCCI combustion by exhaust gas recompression. The spark ignition to HCCI transition requires a switch to reduced inlet and exhaust cam periods compared to spark ignition operation with revised phasing.

Simple or complex cylinder deactivation strategies can be achieved by use of the camless system to selectively deactivate valves as required.

A timing drive is not required for camless engines.

5.1.7.2 Disadvantages and Technical Risks

Power consumption of camless systems can be excessive compared to purely mechanical camshafts, which can negate the potential gains in fuel consumption.

In Ricardo's experience, it is more difficult to achieve good cylinder-to-cylinder airflow balance at low load with a valve-throttled engine due to the sensitivity of airflow to small differences in lift caused by production component tolerances.

There is a possibility of mixture quality issues with valve-throttling and port fuel injection, requiring a compromise on pumping work reduction to ensure good mixture quality.

A separate vacuum pump will be necessary to maintain brake servo operation, unless a small amount of engine throttling is maintained.

In a valve-throttled engine, tumble air motion generated by the inlet port is not available in the cylinder at low valve lift, which has an effect on combustion characteristics. The high gas velocities at the valve seat generate high turbulence levels, but most of this has decayed by the time of ignition.

Camless valvetrain technologies are unproven in production and therefore carry a high technical risk, with the issues listed above still to be fully resolved.

5.1.7.3 Source of Engine BSFC Maps

The camless valvetrain BSFC benefit map was based on published data for a 4-cylinder research engine with the Bosch EHVS electrohydraulic valvetrain [16,17]. The report states that this data is from a fully dressed 4-cylinder engine, including all mechanical and hydraulic losses.

5.1.8 Diesel Engine

Advanced diesel technologies offer fuel economy benefits over conventional gasoline technology under all conditions without compromising performance. Benefits include robust fuel economy and low CO_2 under all operating conditions, improved performance and towing, and high torque at low engine speed giving a "fun-to-drive" characteristic.

Diesel engines gain efficiency through high compression ratios and significantly reduced throttling or pumping losses. Diesels are turbocharged to recover exhaust heat and require a high-pressure fuel injection system to enable low-emission combustion to occur. The diesel engine requires robust construction of the cylinder head, block, and piston so that it can withstand the high mechanical loads.

5.1.8.1 Advantages

Diesel engines also have an advantage in that their torque curve shape provides improved vehicle grade capability and torque reserve over gasoline engines. With optimized transmission matching, this enables efficiency gains by allowing the transmission to operate in higher gears for a longer period over the same drive cycle. There are also potential advantages for towing or when a vehicle operates in heavily loaded conditions.

5.1.8.2 Disadvantages and Technical Risks

The US requires significantly lower NOx emissions than Europe. This is a challenge for lean combustion technologies such as diesel engines. The US emissions levels can be achieved, but can require significant complexity in the aftertreatment systems. The emission control also requires novel air and exhaust flow management, multiple turbochargers, and new catalyst types.

5.1.8.3 Source of Engine BSFC Maps

As the diesel engine and emission solution is still under development for the US, it is worth describing in more detail the approach taken for the diesel engine data contained in this report.

5.1.8.4 2L Diesel Engine

This engine was assumed to be an inline 4-cylinder 2-liter with 4 valves per cylinder and dual overhead camshafts. The engine calibration maps were modified from a Euro4 baseline to be compatible with U.S. emissions cycles. The engine layout is shown by the following figure, with the description of components immediately following.

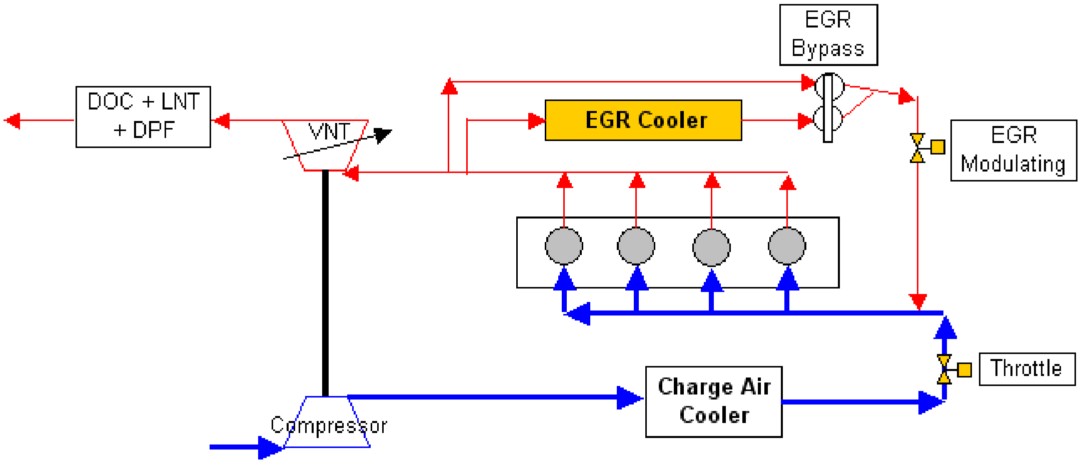


Figure 5-19: Small MPV Engine Layout

5.1.8.4.1 Gas Handling System

Boosting was through a single-stage variable-nozzle turbocharger (VNT) with air-to-air charge-air cooling. High levels of exhaust gas recirculation (EGR) were facilitated through single-stage EGR cooling. The EGR system included a cooler bypass to aid in cold start, light load emissions, and transient operation. This configuration was expected to require an EGR Diesel Oxidation Catalyst (DOC) to mitigate fouling issues in the EGR and intake systems.

5.1.8.4.2 Combustion System

The geometric compression ratio for the map used was 17.5:1. The fuel system was a High-Pressure Common Rail (HPCR) with 1800 bar solenoid injection. Glow plugs were used to aid in cold start, with one or more having cylinder-pressure-sensing capability for adaptation to fuel cetane variations. For 2010-2015, advanced diesel technology will be required in order to achieve Tier 2 Bin 5 emission levels without compromising fuel economy. This includes lower geometric compression ratio, 2000+ bar piezo injection capable of up to 5 close-coupled injections per cycle, and low-temperature combustion concepts like Partially Pre-mixed Compression Ignition (PCCI) and fully pre-mixed or Homogenous Charge Compression Ignition (HCCI).

5.1.8.4.3 Aftertreatment

Aftertreatment included a DOC, Diesel Particulate Filter (DPF), and a Lean NOx Trap (LNT). Simulation using the MSC.EASY5™ results and the specific engine-out NOx map indicate that engine-out NOx will have to be reduced by ~65–70% over the FTP cycle to meet Tier 2 Bin 5 tailpipe emissions. This level of NOx reduction is consistent with expected LNT technology available in 2010-2015 timeframe without the implementation of PCCI/HCCI combustion. As stated above, these low temperature combustion concepts enable the attainment of emissions targets without as much aftertreatment penalty.

5.1.8.5 2.8L Diesel Engine

This engine featured dual or single overhead cam(s). Engine maps were developed from the 2L engine previously described. This application is more likely compatible with a compact V6 architecture. The engine layout is shown in the following figure with, the description of components immediately afterwards.

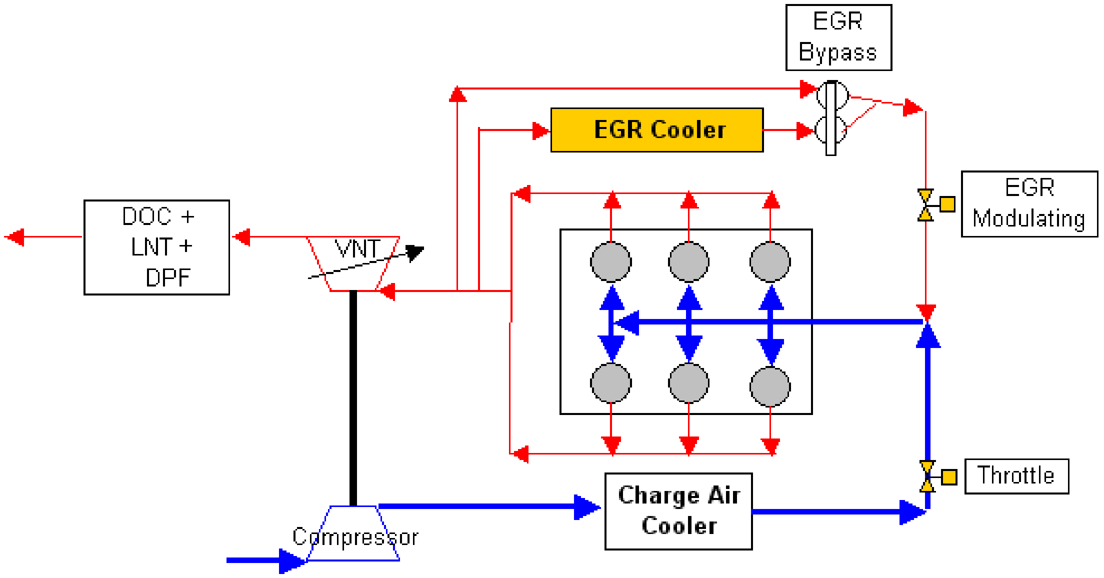


Figure 5-20: Large Car Engine Layout.

5.1.8.5.1 Gas Handling System

Boosting was through a single-stage variable-nozzle turbocharger (VNT) with air-to-air charge-air cooling. Two-stage boosting may be required in practice. High levels of exhaust gas recirculation (EGR) were facilitated through a single-stage EGR cooler. The EGR system included cooler-bypass capability to aid in cold start, light-load emissions, and transient operation. The engine was expected to require EGR DOC to mitigate fouling issues in the EGR and intake systems.

5.1.8.5.2 Combustion System

The geometric compression ratio for the map used was 17.5:1. The fuel system was HPCR with 1800 bar solenoid injection. Glow plugs were used to aid in cold start with one or more having cylinder pressure-sensing capability for adaptation to fuel cetane variations. For 2010-2015, advanced diesel technology will be required in order to maintain T2B5 emission levels without compromising fuel economy. This includes lower geometric compression ratio, 2000+ bar piezo injection capable of up to 5 close-coupled injections per cycle, and low-temperature combustion concepts like PCCI and HCCI.

5.1.8.5.3 Aftertreatment

Aftertreatment included DOC, DPF, and an LNT. Simulation using the MSC.EASY5™ results and the specific engine-out NOx map indicate that engine-out NOx will have to be reduced by ~75–80% over the FTP cycle to meet Tier2 Bin5 tailpipe emissions. Development is ongoing to demonstrate the robustness of such a high conversion efficiency using LNT Technology. Selective Catalytic Reduction (SCR) or LNT are both options depending on technical risk. For this study, LNT was selected.

5.1.8.6 4.8L Diesel Engine

The Truck diesel engine configuration was assumed to be a 4.8L V6 with a cam-in-block, or pushrod, valvetrain. However, an overhead cam or cams may also be used. The engine maps are based on 2010 emissions levels for a 7000-pound ETW vehicle. The engine layout is shown in the following figure, with description of components immediately following.

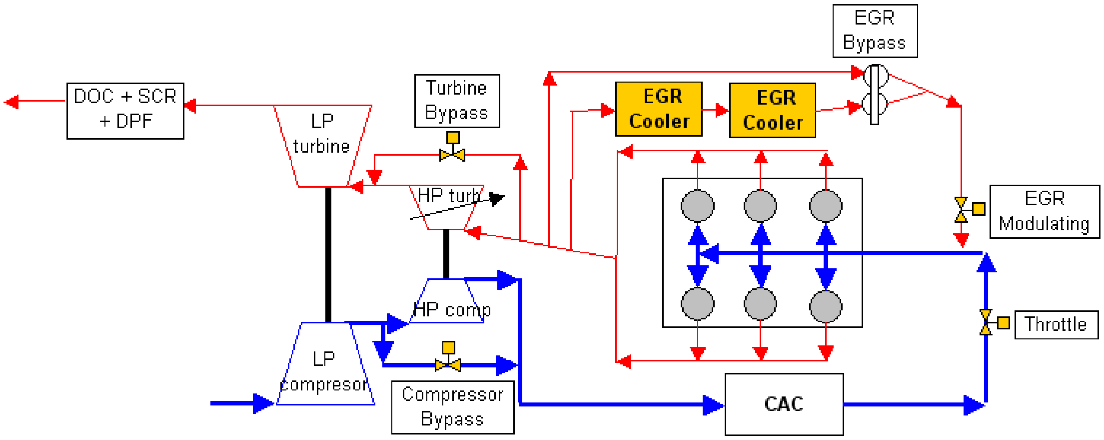


Figure 5-21: Truck Engine Layout

5.1.8.6.1 Gas Handling System

Boosting is through a two-stage series-sequential turbo charging system. The low-pressure turbine is fixed geometry with a wastegate. The high-pressure turbine is a VNT. High levels of exhaust gas recirculation (EGR) were facilitated through a single-stage EGR cooler. For 2010-2015, it is expected that advanced EGR cooling will be required. This will likely include increased cooling capacity, EGR DOC for fouling mitigation, and EGR bypass for reasons previously described.

5.1.8.6.2 Combustion System

The geometric compression ratio was 16:1. The fuel system was HPCR with 1800+ bar solenoid injection. Glow plugs were used to aid in cold start, with one or more having cylinder pressure sensing capability for adaptation to fuel cetane variations. An intake air heater was also required for cold start. For 2010-2015, advanced diesel technology will be required in order to maintain T2B5 emission levels without compromising fuel economy. This includes lower geometric compression ratio, 2000+ bar piezo injection capable of up to 5 close-coupled injections per cycle, and low-temperature combustion concepts like PCCI and HCCI.

5.1.8.6.3 Aftertreatment

Aftertreatment included DOC, DPF, and urea SCR. Simulation using the MSC.EASY5™ results and the specific engine-out NOx map indicate that engine-out NOx will have to be reduced by ~75–80% over the FTP cycle to meet Tier2 Bin5 tailpipe emissions.

5.1.8.7 Diesel Aftertreatment Fuel Economy Impact

For the diesel engines, there are two main contributors to the fuel consumption penalty from the emissions control systems. The first is the diesel particulate filter (DPF). Here, the main penalty of approximately 2% comes from supplying extra fuel to raise the DPF inlet temperature to 550°C or higher. The 550°C regeneration temperature is to facilitate active regeneration, whereby extra hydrocarbons are used to trigger a regeneration event. The fuel may be burned in the engine to raise the engine-out temperature, but is more typically catalytically combusted in the exhaust system to raise the temperature downstream of the turbine. The DPF system consumes the most fuel when the vehicle has been operating at low loads with many transients and generating the most soot to be cleaned out of the DPF per operating hour. If the exhaust gas is hot enough, the DPF needs no additional fuel to stay cleared of soot.

The second part of the fuel consumption penalty comes from the device used to remove nitrogen oxides (NOx) from the exhaust gas. For smaller engines and vehicles, the typical device is the lean NOx trap (LNT), also known as a NOx adsorber catalyst. Here, diesel fuel is used to release NOx from the trapping compound and then to convert the NOx to nitrogen gas. The regeneration penalty averages out to approximately 5% on the city cycle and 3% on the highway cycle.

An alternative, used on larger passenger cars and in use on heavy-duty engines, is the selective catalytic reduction (SCR) system. The SCR system uses urea to generate ammonia; the ammonia then reacts with the NOx to form nitrogen gas and water. There is a fuel economy penalty associated with warming up the urea-SCR system to effective operating temperatures. This is approximately 5% on the city cycle but none on the highway cycle due to the fact that it is performed with a warm start.

For either NOx-control mechanism, the systems consume the most fuel or urea when the engine is at sustained high loads, where the engine-out NOx levels are typically highest. Therefore, an account has been made of the penalty for urban driving to reflect a combination of the DPF and NOx control system fuel consumption penalties. For highway driving, an estimate was made of the fuel consumption penalty, which comes primarily from the NOx control system.

5.1.9 Stop-Start

Stop-Start technology, in combination with efficient electrical accessories, has the potential to improve fuel economy over a wide range of vehicles. Due to the high starting torques for V6 and V8 engines, a 42V starting system is needed for US applications. The advantages and disadvantages of stop-start vary depending on the control strategy implementation and the vehicle drive cycle.

The electrical system architecture is replaced with a Dual Voltage (42V/14V) system. This is driven by a crankshaft-mounted starter/alternator and bi-directional AC drive, which combines the conventional starter and alternator into one electronically controlled unit. The starter/alternator can be belt driven, like the conventional alternator, or a crankshaft-mounted version on the rear face of the engine, which was the case modelled. As the engine starting loads are large at very cold ambient temperatures, it is usual to retain the conventional starter motor. Hence the starter/alternator is only used for starting when the ambient temperature has reached a pre-determined level. The bi-directional AC drive converts battery power from DC to AC to start the engine (inverter). Once the engine is running, the bi-directional AC drive converts AC power from the electric machine to DC power to supply the 42V bus (rectifier). Electric accessories such as water pumps and power steering pumps can also be driven electrically at either 42V or 12V. A DC-DC converter is used to provide power to the 12V circuits from the 42V starter/alternator. It is felt that the market will not support complete migration to 42V power for all loads.

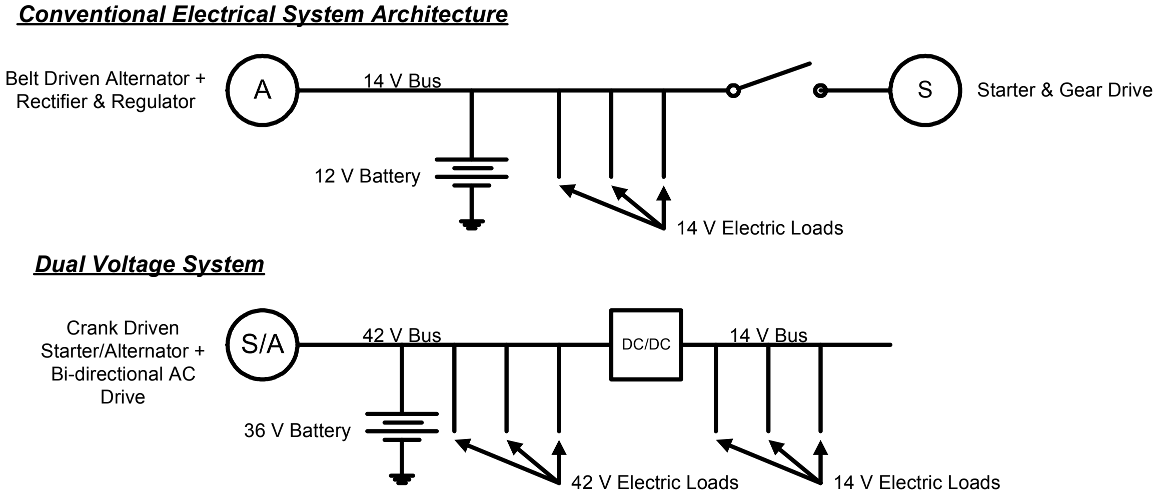


Figure 5-22: Conventional, Dual Voltage System

5.1.9.1 Advantages

Stop-Start, or idle-off operation, is used to reduce fuel consumption due to friction and pumping losses by turning the engine off while stationary. This will take place at traffic signals and under similar conditions when the vehicle is stationary and after the engine has reached the normal operating temperature.

Conventional belt-driven accessories are designed to deliver their maximum required output at relatively low engine speed. As a consequence, the conventional accessories produce unnecessary parasitic losses at high engine speed. By decoupling the accessories from the engine speed, the electric accessory duty cycle can be determined based on demand, thereby reducing parasitic losses compared to the conventional system.

The advantages of the Stop-Start technology are highly dependent on control strategy and drive cycle. The benefits of idle-stop operation favor a drive cycle that has frequent stops. That is, on long highway drives, no savings will be made because the vehicle remains in motion. However, the benefit from electric accessories increases at highway speeds because the duty cycle can be determined from engine operating conditions rather than engine speed. This results in reduced parasitic losses compared to the conventional system. In contrast, city driving may yield significant savings from idle-stop operation and little benefit from electric accessories due to low engine speeds. The electric accessories may also allow faster engine warm-up by reducing coolant flow rate when the engine is below the normal operating temperature.

5.1.9.2 Disadvantages and Technical Risks

The disadvantages associated with the Stop-Start system come from increased control- and electrical-system complexity combined with overall energy conversion efficiency of the electric accessories. Compared to the belt-driven conventional accessories, the electric accessories have decreased conversion efficiency due to the “round trip” efficiency of the electrical system. However, the net result does provide fuel economy benefits due to the decreased duty cycle noted above.

The cost of the system can be considered to be a disadvantage. The conventional starter motor is usually retained to enable cold-ambient start.

5.2 TRANSMISSION TECHNOLOGIES

For detailed simulation of transmission technologies it is important to model the losses that come from several common sources, namely:

- Power transmission elements (usually gears or gear systems, clutches and traction-drive devices)
- Rotating component support elements (bearings)
- Friction losses in sealing elements
- Interaction of the rotating elements with the lubricant (churning losses, drag losses)
- Losses associated with powering ancillary elements such as hydraulic system and lubrication pumps

This section describes how these elements within a transmission system contribute towards the total losses, resulting in a typical level of efficiency for each of the transmission types examined in this study:

- Planetary Automatic Transmissions

- Dual-Clutch Transmissions (wet and dry clutch)
- Continuously Variable Transmissions (CVTs)

5.2.1 Losses in Power Transmission Elements

Gear pairs and gear systems, such as epicyclic gear sets, are the main power transmission elements used in automotive transmissions.

When power is transmitted between a pair of gears some power is lost. As the gear teeth move through mesh, power is absorbed as a result of sliding that occurs at the contact point between the gear teeth and the 'wedging action' as the gear teeth compress the oil between them. The power absorbed or lost is dissipated as heat and noise from the gear mesh. The overall power loss is therefore calculated from the power loss due to oil wedging and the power loss due to sliding. The total gear mesh losses are therefore a function of instantaneous sliding and rolling speed, gear load, oil properties (viscosity, etc.), and gear geometry. Mesh losses generally increase with gear speed and load.

For an overall efficiency analysis, it is more common to assume an average efficiency for all operating conditions. The assumptions made in this study are based on Ricardo's experience with losses for gear meshes as follows:

Single gear mesh	-	0.5–2%
Each mesh in epicyclic	-	0.4–1.8%
Hypoid gear mesh	-	3–6%

Hypoid gears are used in Transaxle final drives and rear axles. The losses are generally much higher than a spur or helical gear pair because of very high sliding velocities in the mesh.

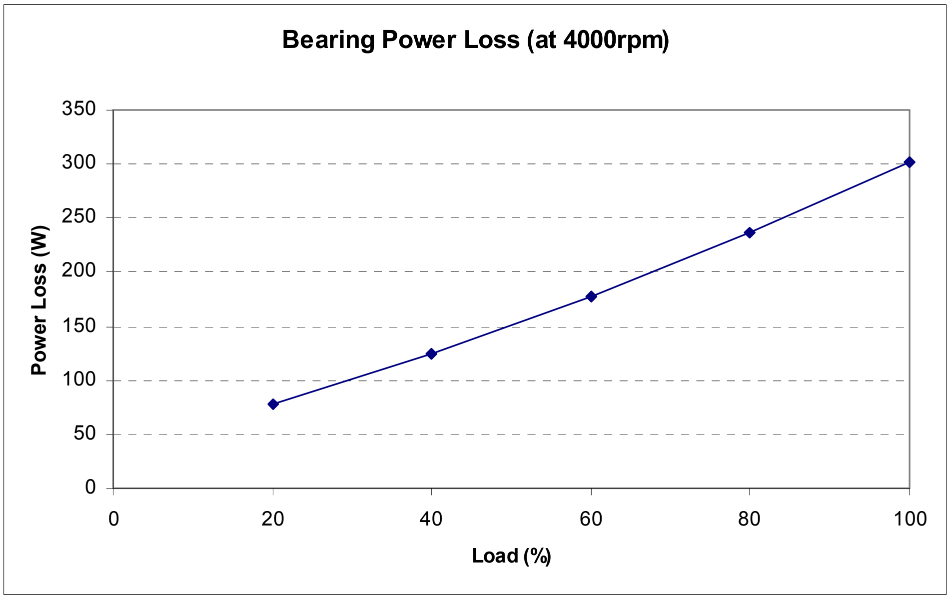
The Continuously Variable Transmission (CVT) is a specific type of automatic transmission that has a different type of power transmission element than a typical gear set. Whereas most transmissions have a series of specific ratio steps to match engine speed to road conditions, the CVT allows any ratio between a minimum and maximum. This is commonly achieved through a belt-drive system where the effective diameters of the belt pulleys are changed to vary the ratio between them.

A number of different types of CVT are produced, namely belt and toroidal. Only the belt-type CVT is considered in this report because it is the most widely used and this trend is expected to continue. However, toroidal types work on similar principles but are not considered realistic for this timeframe.

The efficiency of a CVT belt and variator system is the subject of much research. A figure of 5% was assumed for this study, which is in line with measured data. This is predominantly due to slip between the belt and pulley and also due to deflection of the pulley sheaves.

5.2.2 Losses in Bearings

Bearings are used to support rotating components, such as shafts and gears. In automotive transmissions, rolling element bearings are typically used. The losses in a rolling element bearing are mainly due to rolling and sliding of the elements on the raceways and churning of the lubricating oil. Calculation procedures for estimating bearing losses are readily available from bearing suppliers and were used in this analysis to estimate bearing losses. Losses in bearings will vary according to the exact type of bearing. Taper bearings, which are usually set up with a certain preload, may have higher losses at moderate temperatures and speeds. An example of power loss in a bearing with varying load and varying speed is given below.



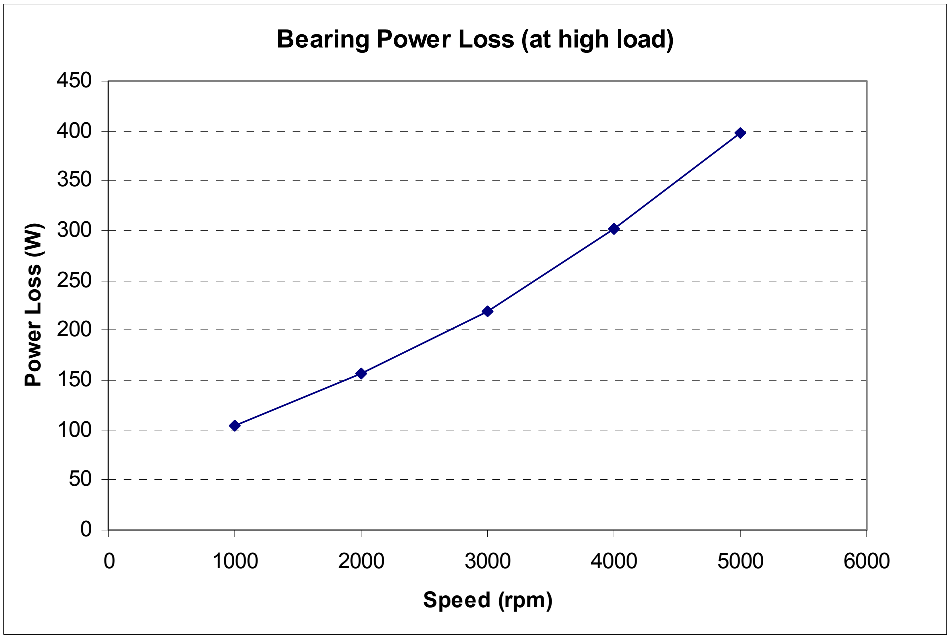


Figure 5-23: Estimated power loss in a deep-groove ball bearing

5.2.3 Losses in Sealing Elements

Seals of various types are commonly used within transmission systems. Radial-lip seals are typically used to seal the input and output shafts. These are available in a number of different materials to suit the application. PTFE/teflon seals will usually offer the lowest power loss due to their low coefficient of friction, but the latest generation of rotating seals is improving the pumping capabilities of the seal, thereby reducing the contact pressure, and thus reducing the heat and frictional losses from the harder materials. Some bearing types can be fitted with integral seals that run on the inner race of the bearing.

Power losses in seals have been calculated from proprietary data available from suppliers. An example of power losses in shaft seals is given below.

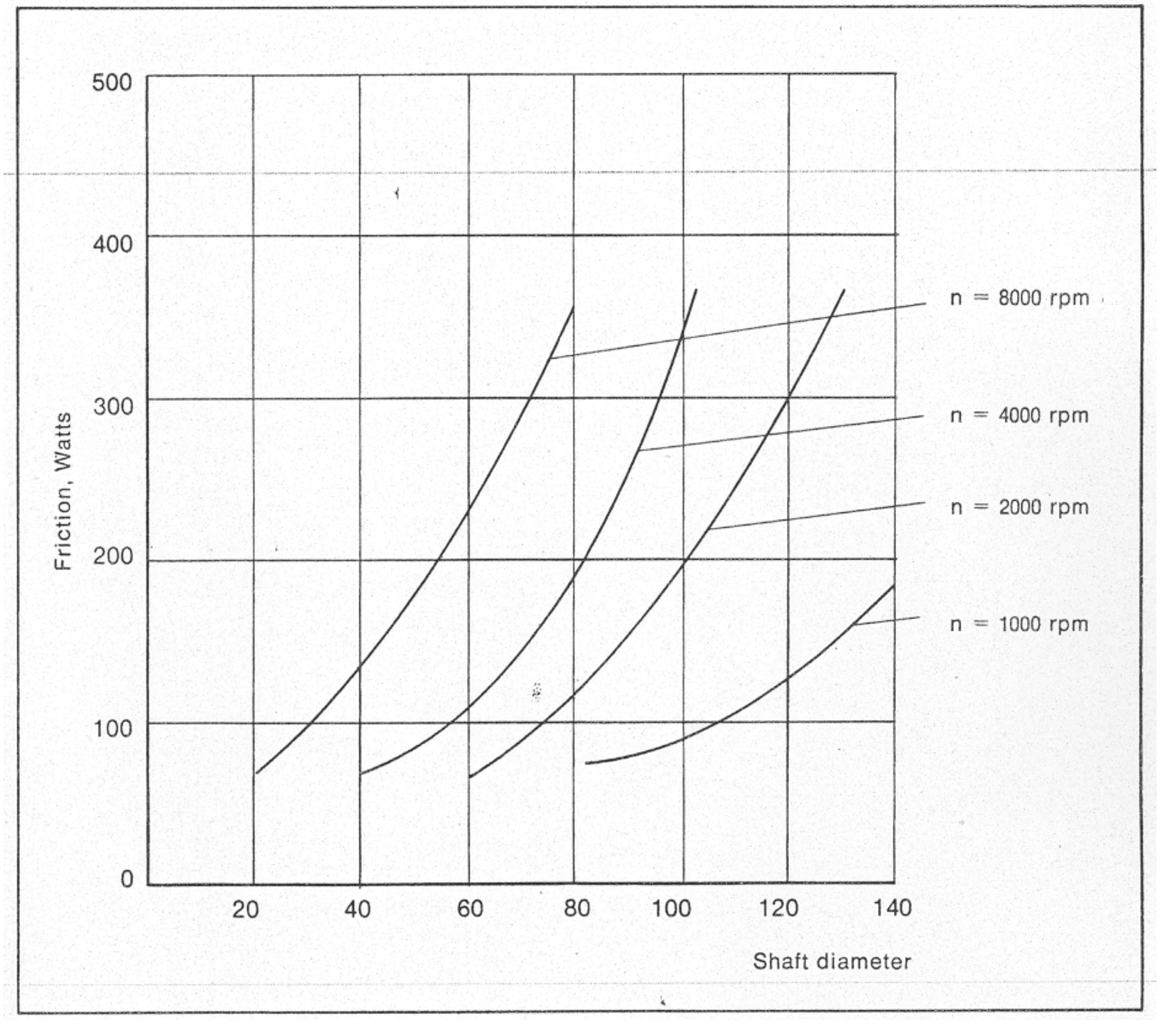


Figure 5-24: Typical Power Loss in Shaft Seals

Automatic transmissions and wet-clutch Dual-Clutch Transmissions (DCTs) also have rotary ‘gland’ seals to allow pressurized hydraulic fluid to be fed to rotating pistons for clutch actuation. These rings are usually manufactured in carbon-based materials or more commonly high-performance thermoplastic materials, such as Vespel.

Power losses in ring seals can be determined from engineering principles. Seal coefficients of friction range from 0.05 to 0.2 for some plastics. A seal coefficient of friction of 0.05 was assumed for this analysis.

5.2.4 Churning and Drag Losses

Churning losses occur when a gear rotates through an oil bath. This mechanism is used in gearboxes to distribute oil (by splash) around gearboxes. Most gearboxes will generate a level of churning loss, dependant on the configuration and oil level. Churning losses can be estimated according to established methodologies.

Churning losses in a transmission can be significant. An example of estimated losses for a final-drive gear in a typical transmission are shown below.

Additional drag losses in automatic transmissions have two main causes:

- Losses associated with open multiplate clutch packs rotating in oil (shearing of oil between plates rotating at different speeds)
- Losses associated with clutch slip (automatics and DCTs)

Multiplate clutches are used primarily in automatic transmissions to change ratio by locking the required element of an epicyclic gear set.

A typical 6-speed automatic may have 5 clutch packs. Two clutch packs are closed for a particular gear selected, but the other 3 are open and may create drag losses dependant on the relative rotational speed of the clutch plates. Clutch drag is heavily dependent on the size of the clutches and on the relative speed, number of plates, plate gap, and amount of oil assumed between the plates. The amount of oil present in the analysis was based on required oil-flow rate and rotational acceleration.

Open clutch drag losses may vary considerably due to differences in transmission architecture, but typical losses at 4000 rpm due to clutch drag could be between 0.5 and 2 kW.

Clutch slip control is used in DCTs to reduce engine torsional vibrations in the transmission and to help clutch control during gear shifting. In some automatics, an additional torque converter ‘lock-up clutch’ can have a controlled amount of slip to help with vibration damping.

Any slip across a driving clutch results in power loss. This is simply a function of the transmitted torque and the slipping speed. Under typical average driving conditions, power loss in a DCT could be around 300-400 Watts.

5.2.5 Pump Losses

Pumps used for hydraulic systems in any form of automatic transmission, and lubrication systems in some manual transmissions, cause a power loss. Pump power is a function of system pressure and flow rate requirement. Typical automatic transmission hydraulic systems operate at a low pressure for cooling and lubrication and higher pressures for shifting and clutch clamping. Automatic transmissions tend to have larger oil volumes (around 5–7 liters) and operate at pressures typically between 10 and 20 bar, with pressures up to 60 bar required for CVTs. Similarly, wet-clutch DCTs require larger oil volumes for clutch cooling. Automatics and wet-clutch DCTs use common oil for transmission lubrication and hydraulics. Dry-clutch DCT transmissions use a small quantity of higher-viscosity oil to separate gears, as the requirements for hydraulic systems are not required.

The pressure ranges in both types of transmissions (clutched transmissions, both automatic and wet-clutch DCTs) and traction-drive transmissions (CVTs) are dictated by the forces required to transmit torque at the clutches in clutched transmission, or at the belt-rolling contact in the CVT-style transmission. The CVT transmissions adjust gear ratio by changing the radius on the primary and secondary pulleys or within the toroidal system. This change in radius vastly varies the amount of force required to transmit torque though the rolling-frictional interface, and in turn, varies the hydraulic pressure required to generate this force.

Power loss due to hydraulic pumps under typical average driving conditions can vary between around 400 W for an optimized variable pressure/volume pump to between 1500 and 2000 W for a single pressure/volume system. Most automatic or wet-clutch DCT transmissions' hydraulic systems have pump maximum displacements in the ranges of 15–26 cc/revolution. System leakage equates to approximately 5–12 liters/min at average pressure ranges. The latest generation of variable-displacement pumps take into account the performance required for fast engagement of system components, but during the majority of the operating conditions at steady-state low-torque conditions swash back to discharge only enough fluid to overcome system leakage and maintain pressure. Lower losses are possible within dry-clutch DCT transmissions due to the sealed actuation hydraulic systems offering the capability to use a hydraulic system with an accumulator or electric actuation. With this type of hydraulic system, the loss reduces to 3–5 W when averaged over a charge cycle under steady-state conditions.

Additionally, the control system required for an automatic—predominantly valves in hydraulic circuit—has a small electrical power draw.

5.2.6 Overall Efficiencies of Transmission Systems

To compare transmission types, efficiencies are described as a result of total losses due to individual components/elements and the arrangement of transmission systems.

5.2.6.1 Automatic Transmission

A typical planetary automatic transmission arrangement is shown. The overall losses are made up from:

- Gear mesh losses – typical losses for each epicyclic ~ 1.5%, with two or three stages for a 6-speed.
- Additional gear mesh losses for some arrangements with final drive gears (~1–3%).
- Bearing and seal losses for input and output shafts plus additional sealing losses for gland seals (estimated between 1 and 2% in total).
- Churning and drag losses for rotating open clutch packs, final-drive gears, and slipping lock-up clutch (if slip- control is employed). These could total up to 5%.
- Losses due to hydraulic system pump between 0.5 and 5%, dependent on operating pressure and control strategy (at system pressures around 20–30 bar).

The total losses present in a planetary automatic transmission would suggest an overall efficiency of between 86% and 90%. However, fuel economy and emissions performance over a drive cycle can lead to better than expected results due to the automatic control of the transmission resulting in shifting strategies to give optimum economy and emissions.

Improvements in efficiency are possible through optimum design of the planetary arrangement, and reduction of hydraulic power requirement through reduced operating pressure and variable-flow pump designs, for example. Efficiencies in the region of 92–93% are possible with an optimized design, reaching as high as 95% in some specific operating conditions.

Losses associated with the torque converter are not considered in this analysis and will be covered in a following section.

5.2.6.2 Dual Clutch Transmission (DCT)

The recent introduction of the DCT sees the first alternative automatic transmission offering significant improvements over traditional planetary automatics at sensible productions volumes (mainly in the Volkswagen-Audi Group products in Europe).

The DCT potentially offers the best of both worlds, with the high mechanical efficiency of a manual and the shift control of an automatic, resulting in strong fuel economy and emissions performance over a drive cycle. Additional performance benefits are reduced shift time with no torque interrupt during the shift.

The DCT is essentially two power transmission paths in parallel, each with its own clutch. A change in gear ratio is achieved by disengaging one clutch while simultaneously engaging the other. Current production units predominantly use wet multiplate clutches, requiring a hydraulic system to clamp and cool the clutches as well as for gear shifting.

5.2.6.2.1 Wet-Clutch DCT

A typical arrangement for a 6-speed wet multiplate clutch DCT is shown in Figure 5-25. The overall losses are made up as follows:

- Gear mesh losses – typically two gear meshes, totaling 1 %
- Bearing and seal losses for input and output shafts plus additional sealing losses for gland seals (estimated between 1 and 2% in total)
- Churning losses between 2 and 6% dependent on transmission layout
- Losses due to hydraulic system pump between 0.5 and 3 % dependent on pressure-control strategy
- Drag losses also occur in the open clutch of around 0.5–1%. Slip control across the driving clutch will also result in 0.5–1% power loss.

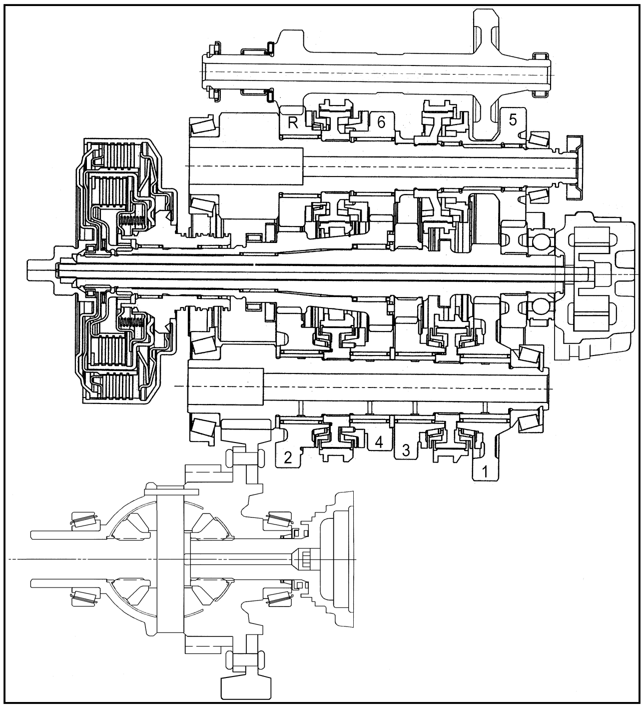


Figure 5-25: Typical transverse wet clutch DCT arrangement

The total efficiency of a wet-clutch DCT could therefore be expected to be between 86% and 94.5%. DCTs use many of the loss-reduction strategies employed in planetary automatics, such as low hydraulic system pressure between shifting, to achieve the higher predicted efficiencies. Although, the wet clutches require a high flow rate for cooling, resulting in high instantaneous pump power requirements.

The efficiency map is similar to a planetary automatic, with the best efficiencies being achieved at high loads and medium speeds, and significant reduction in efficiency at low loads and speeds as the power requirement of the hydraulic system becomes a higher proportion of the overall power transmitted.

5.2.6.2.2 Dry-Clutch DCT

Another iteration, currently being investigated by several manufacturers, is the dry-clutch DCT, using two dry clutches in the place of the wet multiplate clutches. This development significantly reduces the volume of oil required to cool wet clutches and could offer further improvements in efficiency due to reduction of hydraulic pumping losses and churning losses in the transmission due to a lower oil volume. However, dry-clutch DCTs are likely to be limited to smaller vehicle applications, at least initially, due to thermal limitations of the dry clutches.

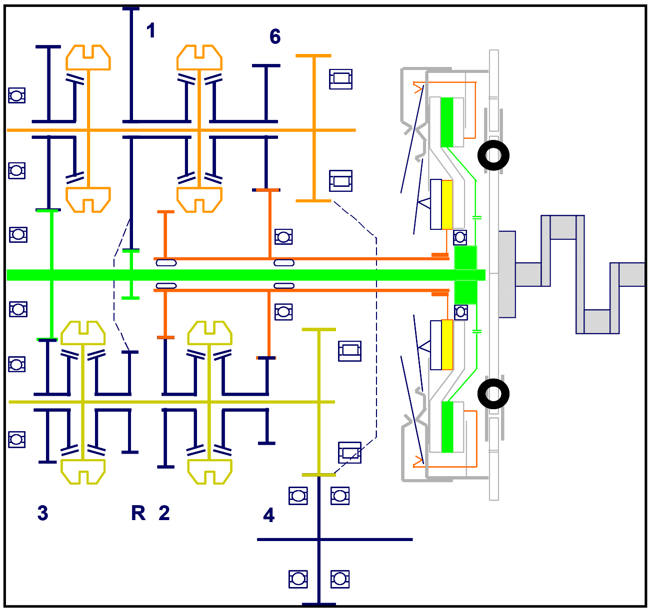


Figure 5-26: Possible dry clutch DCT arrangement

A possible arrangement for a 6-speed dry-clutch DCT is shown in Figure 5-26. The overall losses are made up as follows:

- Gear mesh losses – typically two gear meshes, totaling 1 %
- Bearing and seal losses for ~8 bearings and ~3 seals (input shaft and differential seals) totaling around 500 W or ~1%
- Churning losses between 2 and 6% dependent on transmission layout
- Pumping losses (in pressure lubricated systems) – losses in low-pressure lubrication system are small (<0.5%)
- Drag in the open clutch should be minimal, but if slip control is used, then slip across the driving clutch could result in 0.5–1% power loss.
- The clutch and gear change actuation system will affect overall efficiency. The losses due to the actuation systems will depend on the type of system, electro-hydraulic or electro mechanical, but the average losses in a drive cycle are likely to be around 0.5%.

The total efficiency of a dry-clutch DCT could therefore be expected to be between 90% and 95%. Optimum design should see overall efficiencies between 1–1.5% lower than a similar manual. A more significant reduction would be seen at low loads and speeds due to the relative power requirement of the actuation systems.

The major benefit over the wet-clutch DCT is the reduction in oil volume requirement, resulting in potentially significant reductions in hydraulic power and churning losses in the transmission.

5.2.6.3 Continuously Variable Transmission (CVT)

A typical CVT arrangement is shown in Figure 5-27. The overall losses in a CVT are higher than in a planetary automatic. The 3% loss due to the two epicyclics in a planetary automatic is replaced by a 5% loss due to the belt and variator assembly. Additionally, the torque is transmitted through a single epicyclic (used to select reverse), resulting in an additional 1–1.5% loss.

Bearing and seal losses are similar to a planetary automatic. Churning losses are similar, especially for transverse configurations with final drive gears, but drag losses may be less, since there is usually only one open clutch for either forward or reverse operation.

Hydraulic system losses can be considerably higher than for a planetary automatic. The primary pressure requirement to prevent belt slip can be as high as 40–60 bar. This results in higher hydraulic power, leading to losses in some operating conditions of up to 8%.

Therefore, with an overall efficiency of between 80% and 90%, the CVT may be less efficient than a planetary automatic; higher levels of efficiency will be dependent on configuration and level of design optimization, particularly with regard to reducing operating pressures.

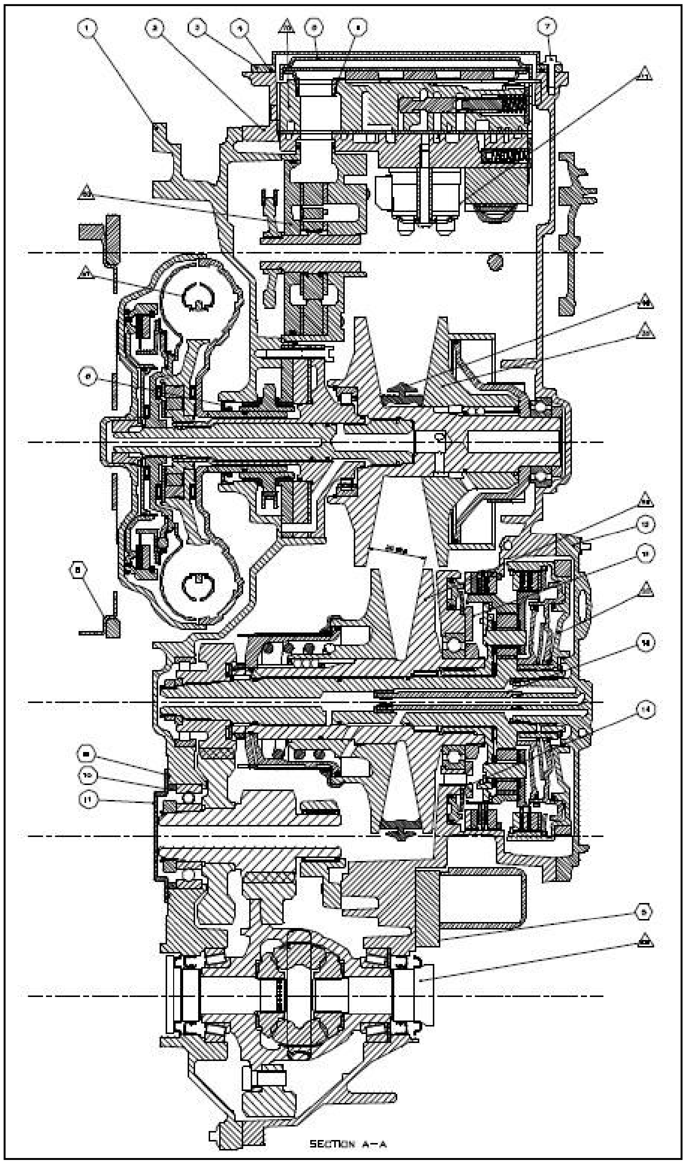


Figure 5-27: Typical transverse CVT arrangement

Although the continuously variable ratio ability of the CVT theoretically allows operation at the optimum point for economy/emissions at any condition, the lower overall efficiency of the system results in similar or poorer performance than a planetary automatic over a typical drive cycle.

5.3 SECTION 5 REFERENCES

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6.0 TECHNOLOGY PACKAGES

For the baseline vehicles, the EPA identified a number of combinations (technology packages) of the individual technologies described in Section 5. The carbon dioxide emission, fuel economy, and vehicle performance were simulated for these technology packages.

The packages were selected to represent potential technology combinations that could be offered in production between 2010 and 2017. These technology packages are described in the tables below and grouped together by each baseline vehicle. All of the packages contain technologies that need a certain level of development, either to mature the technology or to apply the technology to a new application. As a guide, Ricardo has provided a subjective assessment of the readiness of the packages divided into two categories:

- 5 years. Could be in production within 5 years. This means there are some example technologies in production today and/or the technology is likely to be introduced very soon.
- 10 years. Technology is still being developed and might be ready for production release within 5 to 10 years.

Table 6-1: Standard Car Technology Packages

Pk	*Architecture*	*Valvetrain*	*Transmission*	*Accessories*	*Readiness*
Z	I4, PFI	CCP, DVVL	6-spd DCT dry clutch	42V stop-start ePS ePump (42V)	5 years
1	I4, GDI	DCP, DVVL	CVT	ePS ePump (12V) heAlt	5 years
2	I4, GDI	DCP	6-spd AT	ePump (42V) 42V stop-start, ePS	5 years

Table 6-2: Small MPV Technology Packages

Pkg	Architecture	Valvetrain	Transmission	Accessories	Readiness
Z	I4, PFI	CCP, DVVL	6-spd DCT wet clutch	42V stop-start ePS ePump (42V)	5 years
1	I4, GDI	DCP, DVVL	CVT	ePS ePump (12V) heAlt	5 years
2	I4, GDI	DCP	6-spd AT	42V stop-start ePS ePump (42V)	5 years
5	I4, Diesel		6-spd DCT wet clutch	ePS ePump (12V) heAlt	5 years
15	I4, GDI downsized turbo	DCP	6-spd DCT wet clutch	ePS ePump (12V) heAlt	5 years
15a	I4, GDI	Camless	6-spd DCT wet clutch	ePS ePump (12V) heAlt	10 years
15b	I4, dual-mode HCCI / GDI		6-spd DCT wet clutch	ePS ePump (12V) heAlt	10 years

Table 6-3: Full-size Car Technology Packages

Pkg	*Architecture*	*Valvetrain*	*Transmission*	*Accessories*	*Readiness*
4	I4, GDI downsized turbo	DCP	6-spd AT	ePS ePump (12V) heAlt	5 years
5	I4, Diesel		6-spd DCT wet clutch	ePS ePump (12V) heAlt	5 years
6a	Small V6, GDI	DCP, CVVL	6-spd DCT wet clutch	ePS ePump (12V) heAlt	5 years
16	Large V6, GDI	CCP, Deac	6-speed AT	42V stop-start ePS ePump (42V)	5 years
Y1	Large V6, GDI	Camless	6-speed DCT wet clutch	ePS ePump (12V) heAlt	10 years
Y2	Large V6, dual-mode HCCI / GDI		6-speed DCT wet clutch	ePS ePump (12V) heAlt	10 years

Table 6-4: Large MPV Technology Packages

Pkg	*Architecture*	*Valvetrain*	*Transmission*	*Accessories*	*Readiness*
4	I4, GDI downsized turbo	DCP	6-speed AT	ePS ePump (12V) heAlt	5 years
6b	Small V6, GDI	CCP, Deac	6-spd DCT wet clutch	ePS ePump (12V) heAlt	5 years
16	Large V6, GDI	CCP, Deac	6-speed AT	42V stop-start ePS ePump (42V)	5 years

Table 6-5: Truck Technology Packages

Pkg	*Architecture*	*Valvetrain*	*Transmission*	*Accessories*	*Readiness*
9	V8, GDI	Deac	6-spd DCT wet clutch	42V stop-start ePS ePump (42V)	5 years
10	Large V6, GDI, downsized turbo	DCP	6-spd DCT wet clutch	ePS ePump (12V) heAlt	5 years
11	Large V6 Diesel		6-spd DCT wet clutch	ePS ePump (12V) heAlt	5 years
12	V8, GDI	CCP, Deac	6-spd AT	42V stop-start ePS ePump (42V)	5 years
17	V8, GDI	DCP, DVVL	6-spd AT	ePS ePump (12V) heAlt	5 years
X1	V8, GDI	Camless	6-spd DCT wet clutch	ePS ePump (12V) heAlt	10 years
X2	V8, dual-mode HCCI / GDI		6-spd DCT wet clutch	ePS ePump (12V) heAlt	10 years

6.1 ADDITIONAL TECHNOLOGIES

6.1.1 Aerodynamic Drag and Rolling Resistance

The EPA considers that OEMs could be able to achieve a 20% reduction in aerodynamic drag forces in the future along with a 10% reduction in vehicle rolling resistance. Ricardo did not investigate the validity of this viewpoint. However, these levels of reductions relative to the baseline vehicle were included in the simulations.

6.1.2 Friction Multiplier

The EPA believes that powertrain friction can also be reduced by use of low-viscosity oils and/or low-friction components. Although the friction reduction could have been included in the simulations, this would have taken more time and effort. Therefore, a simplification was made only for the reduced-friction technology and that was to assume the fuel consumption, and hence carbon dioxide emissions, could be reduced by 2.5%. This “friction multiplier” was kept constant and applied to all the final simulation cases.

7.0 RESULTS

This section presents the results for the study and discusses selected powertrain-technology package results, incremental results on selected vehicle / technology package combinations, and the final results.

7.1 SELECTED POWERTRAIN (ENGINE & TRANSMISSION) TECHNOLOGY PACKAGE RESULTS

The main focus of the study was on combinations of powertrain and vehicle technology packages. However, it can be useful to review results for technology packages just featuring powertrain technology. To this end, results were collated for powertrain technologies grouped into four categories:

- Direct Injection engines with cylinder deactivation
- Turbocharged, downsized, direct injection engines
- Gasoline engines with Camless valvetrains
- Gasoline engines operating on HCCI

7.1.1Direct Injection Gasoline Engines with Cylinder Deactivation

Three vehicle/technology package combinations incorporated direct injection with cylinder deactivation. These were the full size car, the large MPV, and the truck. All had similar peak torque-to-weight ratios. Table 7.1 shows the combined fuel economy benefit was similar for the three packages, ranging from 14 to 19%, depending on the vehicle application.

Table 7-1: Powertrain (engine & transmission) only results for cylinder deactivation cases

Powertrain (Engine & Transmission) Only Results - Cylinder Deactivation cases

Vehicle	Technology Package Description									Fuel Economy						Performance					
	EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec
										mpg	mpg	mpg	%	%	%	sec	sec	sec	sec	mph	meters
Full Size Car	16	3.5L V6 CCP + Deac GDI	AT 6spd FDR 3.08	N	base	Bag1	base	base	N	24.9	38.3	29.6	15.0%	17.5%	15.9%	2.6	6.5	2.2	3.6	34.0	23.5
Large MPV	16	3.8L V6 CCP + Deac GDI	AT 6spd FDR 3.17	N	base	Bag1	base	base	N	23.6	34.7	27.5	19.0%	19.5%	19.2%	3.2	8.8	3.3	5.2	28.4	17.6
Truck	12	5.4L-3V V8 CCP + Deac GDI	AT 6spd FDR 3.6	N	base	Bag1	base	base	N	17.1	25.3	20.0	15.2%	11.8%	13.9%	2.4	7.3	2.8	4.4	35.0	24.4

7.1.2 Turbo/Downsize, Gasoline Direct Injection Engines

There were four vehicle/technology package combinations with a turbo/downsized, gasoline direct-injected engine; Table 7-2 shows that the benefit of the powertrain is application-specific. Comparing the two vehicle packages with DCT transmissions, the small MPV had a much lower displacement-to-weight ratio than the truck (0.6 vs 0.9cc/lb) and so benefited less from the advanced technology powertrain combination. This is because even the baseline powertrain in the small MPV was spending more of its time near the engine's peak efficiency islands (or minimum BSFC) than the truck which operated typically on test cycles well below its peak efficiency area. The two vehicle packages with 6-speed automatic transmissions both had similar displacement-to-weight ratios (0.88 and 0.84 cc/lb for the full size car and large MPV, respectively) and had similar benefit levels for the advanced powertrain combinations (7.2% and 13.4%, respectively.)

Table 7-2: Powertrain (engine & transmission) only results for turbo/downsized cases

Powertrain (Engine & Transmission) Only Results - Turbo/Downsized cases

Vehicle	Technology Package Description									Fuel Economy						Performance					
	EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec
										mpg	mpg	mpg	%	%	%	sec	sec	sec	sec	mph	meters
Small MPV	15	1.5L I4 Turbo DCP GDI	DCT 6spd FDR 3.5	N	base	Bag1	base	base	N	29.7	37.5	32.7	19.9%	4.3%	13.7%	4.3	9.8	3.3	5.5	18.7	10.0
Full Size Car	4	2.2L I4 Turbo DCP GDI	AT 6spd FDR 3.08	N	base	Bag1	base	base	N	23.2	33.8	27.1	9.5%	3.0%	7.2%	2.6	6.6	2.3	3.4	33.7	22.0
Large MPV	4	2.1L I4 Turbo DCP GDI	AT 6spd FDR 3.17	N	base	Bag1	base	base	N	22.9	32.0	26.2	15.3%	10.2%	13.4%	3.3	8.2	2.9	4.9	27.5	16.2
Truck	10	3.6L V6 Turbo DCP GDI	DCT 6spd FDR 3.6	N	base	Bag1	base	base	N	19.3	25.3	21.6	34.5%	13.0%	26.1%	2.6	6.4	2.2	3.7	35.8	21.7

7.1.3 Camless Gasoline Engines

The small MPV, the full size car, and the truck each had a technology package with camless valvetrain engine and DCT transmission. These are compared in Table 7-3 and show a fuel economy benefit ranging from 20 to 26%, depending on the vehicle application. Since the camless engine technology package is primarily reducing the engine pumping losses, its benefit should scale with torque-to-weight ratio for the vehicle. The torque-to-weight ratio relates to the load levels that the engine runs at on a drive cycle. Hence, vehicles with a low torque-to-weight ratio will run at higher engine loads, and so benefit less from camless technology. Figure 7-1 shows this to be valid. Since camless valvetrains still need to be proven in terms of robustness and cost, Ricardo considers camless engine technology to be high risk for application to high-volume production within the timeframe of this study.

Table 7-3: Powertrain (engine & transmission) only results for camless valvetrain cases

Powertrain (Engine & Transmission) Only Results - Camless valvetrain cases

Vehicle	Technology Package Description									Fuel Economy						Performance					
	EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec
										mpg	mpg	mpg	%	%	%	sec	sec	sec	sec	mph	meters
Small MPV	15a	2.4L I4 Camless GDI	DCT 6spd FDR 3.5	N	base	Bag1	base	base	N	30.6	40.7	34.4	23.4%	13.4%	19.6%	3.6	9.8	3.5	5.6	25.7	17.5
Full Size Car	Y1	3.5L V6 Camless GDI	DCT 6spd FDR 3.08	N	base	Bag1	base	base	N	28.0	39.3	32.2	29.5%	20.6%	26.2%	2.6	6.5	2.2	3.6	34.0	23.5
Truck	X1	5.4L V8 Camless GDI	DCT 6spd FDR 3.6	N	base	Bag1	base	base	N	19.4	26.3	22.0	30.3%	16.0%	24.9%	2.4	7.3	2.8	4.4	35.0	24.4

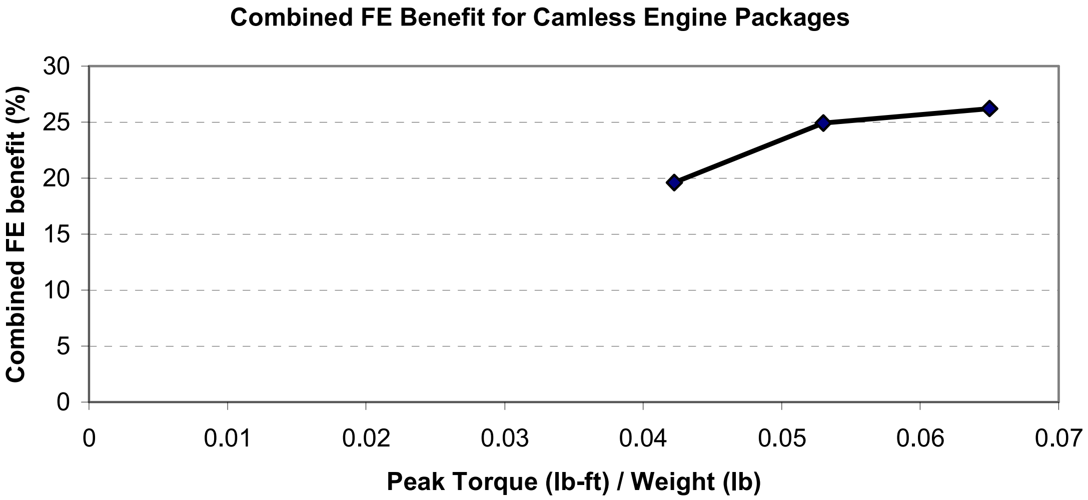

Figure 7-1: Combined FE benefit vs. peak torque-to-weight ratio for Camless engine packages

7.1.4 Gasoline Engines Operating on HCCI

The small MPV, the full size car, and the truck each had a technology package with an engine using HCCI combustion and a DCT transmission. These are compared in Table 7.4 and show fuel economy benefit ranging from 16 to 26%, depending on the vehicle application. The HCCI engine technology package reduces pumping losses with a flexible valvetrain and improves combustion efficiency over a small light-load range as described in Section 5.1.6. HCCI combustion solutions are still in their infancy. Hence, Ricardo considers HCCI engine technology to be high risk for application to high-volume production within the timeframe of this study.

Table 7-4: Powertrain (engine & transmission) only results for HCCI cases

Powertrain (Engine & Transmission) Only Results - HCCI cases

Vehicle	Technology Package Description									Fuel Economy						Performance					
	EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec
										mpg	mpg	mpg	%	%	%	sec	sec	sec	sec	mph	meters
Small MPV	15b	2.4L I4 HCCI GDI	DCT 6spd FDR 3.5	N	base	Bag1	base	base	N	29.5	39.7	33.3	19.0%	10.4%	15.7%	3.6	9.8	3.5	5.6	25.7	17.5
Full Size Car	Y2	3.5L V6 HCCI GDI	DCT 6spd FDR 3.08	N	base	Bag1	base	base	N	27.6	39.5	31.9	29.8%	20.2%	26.3%	2.6	6.5	2.2	3.6	34.0	23.5
Truck	X2	5.4L V8 HCCI GDI	DCT 6spd FDR 3.6	N	base	Bag1	base	base	N	19.2	26.5	21.9	29.3%	17.0%	24.7%	2.4	7.3	2.8	4.4	35.0	24.4

7.2 INCREMENTAL RESULTS ON SELECTED VEHICLE / TECHNOLOGY PACKAGE COMBINATIONS

As a means of indicating the relative benefit of certain technology solutions, a series of simulations were undertaken by adding technologies in order to build up to the total technology package. The effects on fuel economy and CO_2 output of individual technologies applied sequentially to a specific vehicle class were thus examined. Technologies were added in a given sequence and the effects at each stage were determined. Each of the tables below starts with the baseline configuration for a vehicle class and ends with the complete technology package results.

It is important to note that no optimization was performed for any of the incremental technology simulations listed. Therefore, adding a technology could actually produce reduced fuel economy. This illustrates the key point that technologies need to be considered in certain packages and optimized for the specific applications. It is also consistent with the understanding in the industry that fuel economy improvements from different technologies cannot merely be added together to determine their total benefit. In the cases analyzed here, the optimization was only performed for the complete technology packages.

Table 7-5: Incremental fuel economy and CO$_2$ benefits for Standard Car / Technology Package Z

Incremental Action*	Fuel Economy						CO$_2$					
	City (mpg)	Hwy (mpg)	Combined (mpg)	Incremental benefit			City (g/mi)	Hwy (g/mi)	Combined (g/mi)	Incremental benefit		
				City	Hwy	Combined				City	Hwy	Combined
Standard Car baseline 2.4L-4V VVT / 5spd AT (3.39 FDR)	26.9	41.8	32.0	----	----	----	338	217	284	----	----	----
CCP & DVVL	27.5	42.5	32.7	2%	2%	2%	330	214	278	2%	2%	2%
6spd DCT (3.23 FDR)	30.0	45.8	35.5	9%	8%	9%	303	198	256	8%	7%	8%
42V Stop-Start	31.7	45.8	36.8	6%	0%	4%	287	198	247	5%	0%	3%
42V Electric accessories & Fast engine warm-up	32.9	46.7	37.9	4%	2%	3%	277	194	240	3%	2%	3%
Aero drag reduction of 20% & Tire rolling resistance reduction of 10%	33.9	50.8	39.9	3%	9%	5%	268	179	228	3%	8%	5%
Aggressive shift/lock scheduling (2.96 FDR)	35.5	52.2	41.5	5%	3%	4%	256	174	219	4%	3%	4%
Oil and friction modifier, 2.5% FE improvement	36.4	53.5	42.5	3%	3%	3%	250	170	214	2%	2%	2%

**Note: Optimization was performed on the final package only, no attempt was made to optimize after each incremental action.*

Table 7-6: Incremental fuel economy and CO$_2$ benefits for Small MPV / Technology Package 2

Incremental Action*	Fuel Economy						CO$_2$					
	City (mpg)	Hwy (mpg)	Combined (mpg)	Incremental benefit			City (g/mi)	Hwy (g/mi)	Combined (g/mi)	Incremental benefit		
				City	Hwy	Combined				City	Hwy	Combined
Small MPV baseline 2.4L-4V VVT / 4spd AT (3.91 FDR)	24.8	35.9	28.8	----	----	----	367	253	316	----	----	----
GDI	25.4	36.8	29.5	2%	3%	3%	358	247	308	2%	2%	2%
DCP & 6spd AT (3.50 FDR)	26.2	37.3	30.2	3%	1%	2%	347	244	301	3%	1%	2%
42V Stop-Start	27.6	37.3	31.3	6%	0%	4%	329	243	290	5%	0%	3%
42V Electric accessories & Fast engine warm-up	28.5	37.4	31.9	3%	0%	2%	319	243	285	3%	0%	2%
Aero drag reduction of 20% & Tire rolling resistance reduction of 10%	29.7	41.1	34.0	4%	10%	6%	306	221	268	4%	9%	6%
Aggressive shift/lock scheduling (2.80 FDR)	30.5	42.1	34.8	3%	2%	3%	298	216	261	3%	2%	2%
Oil and friction modifier, 2.5% FE improvement	31.3	43.1	35.7	3%	3%	3%	290	211	255	2%	2%	2%

**Note: Optimization was performed on the final package only, no attempt was made to optimize after each incremental action.*

Table 7-7: Incremental fuel economy and CO$_2$ benefits for Full Size Car / Technology Package 6a

Incremental Action*	Fuel Economy						CO$_2$					
	City (mpg)	Hwy (mpg)	Combined (mpg)	Incremental benefit			City (g/mi)	Hwy (g/mi)	Combined (g/mi)	Incremental benefit		
				City	Hwy	Combined				City	Hwy	Combined
Full size car baseline 3.5L-4V / 5spd AT (2.87 FDR)	21.7	32.6	25.5	----	----	----	420	279	356	----	----	----
3.0L-4V engine	19.9	29.6	23.4	-8%	-9%	-8%	456	307	389	-9%	-10%	-9%
DCP	20.9	31.2	24.5	5%	5%	5%	435	292	371	5%	5%	5%
CVVL	21.7	31.9	25.3	4%	2%	3%	419	285	359	4%	2%	3%
GDI	22.2	32.7	26.0	3%	3%	3%	409	278	350	2%	2%	2%
6spd DCT (3.08 FDR)	24.3	34.3	27.9	9%	5%	8%	375	265	325	8%	4%	7%
Electric accessories & Fast engine warm-up	25.7	34.9	29.2	6%	2%	4%	354	261	312	6%	2%	4%
Aero drag reduction of 20% & Tire rolling resistance reduction of 10%	26.5	37.9	30.6	3%	9%	5%	343	240	297	3%	8%	5%
3.20 FDR for performance improvement	26.2	37.4	30.3	-1%	-1%	-1%	347	243	300	-1%	-1%	-1%
Oil and friction modifier, 2.5% FE improvement	26.9	38.3	31.1	3%	3%	3%	338	237	293	2%	2%	2%
**Note: Optimization was performed on the final package only, no attempt was made to optimize after each incremental action.*												

Table 7-8: Incremental fuel economy and CO$_2$ benefits for Large MPV / Technology Package 4

Incremental Action*	Fuel Economy						CO$_2$					
	City (mpg)	Hwy (mpg)	Combined (mpg)	Incremental benefit			City (g/mi)	Hwy (g/mi)	Combined (g/mi)	Incremental benefit		
				City	Hwy	Combined				City	Hwy	Combined
Large MPV baseline 3.8L-2V / 4spd AT (3.43 FDR)	19.8	29.0	23.1	----	----	----	458	313	393	----	----	----
DCP	20.8	30.7	24.3	5%	6%	5%	437	296	373	5%	5%	5%
GDI	21.4	31.5	25.0	3%	3%	3%	425	289	364	3%	3%	3%
2.1L Turbo	22.4	31.3	25.7	5%	-1%	3%	406	290	354	4%	-1%	3%
6spd AT (3.17 FDR)	22.9	32.0	26.2	2%	2%	2%	397	284	346	2%	2%	2%
Electric accessories & Fast engine warm-up	23.9	32.6	27.2	5%	2%	4%	380	279	335	4%	2%	3%
Aero drag reduction of 20% & Tire rolling resistance reduction of 10%	24.8	34.6	28.4	4%	6%	5%	366	263	319	4%	6%	5%
Oil and friction modifier, 2.5% FE improvement	25.5	35.4	29.2	3%	3%	3%	357	256	312	2%	2%	2%
**Note: Optimization was performed on the final package only, no attempt was made to optimize after each incremental action.*												

Table 7-9: Incremental fuel economy and CO$_2$ benefits for Truck with Technology Package 11

	Fuel Economy						CO$_2$					
	City (mpg)	Hwy (mpg)	Combined (mpg)	Incremental benefit			City (g/mi)	Hwy (g/mi)	Combined (g/mi)	Incremental benefit		
Incremental Action*				City	Hwy	Combined				City	Hwy	Combined
Truck baseline 5.4L-3V VVT / 4spd AT (3.73 FDR)	14.9	22.6	17.6	----	----	----	612	402	517	----	----	----
4.8L Diesel with baseline transmission	17.8	26.7	21.0	20%	18%	19%	567	378	482	7%	6%	7%
Aggressive shift/lockup scheduling	19.2	27.0	22.1	8%	1%	5%	525	375	458	7%	1%	5%
6spd DCT (3.73 FDR)	21.9	27.7	24.2	14%	3%	10%	461	365	418	12%	3%	9%
FDR 3.73 --> 3.15	22.2	29.2	24.9	1%	6%	3%	454	345	405	1%	5%	3%
ePS & High-efficiency Alternator	22.9	29.8	25.6	3%	2%	3%	440	339	395	3%	2%	3%
Aero drag reduction of 10%	23.2	30.8	26.1	1%	4%	2%	435	327	387	1%	3%	2%
Electric accessories (ePumps) & Fast engine warm-up	23.7	30.8	26.5	2%	0%	1%	425	327	381	2%	0%	1%
Aftertreatment penalty	22.2	30.2	25.2	-7%	-2%	-5%	455	334	401	-7%	-2%	-5%
Oil and friction modifier, 2.5% FE improvement	22.7	31.0	25.8	3%	3%	3%	444	326	391	2%	2%	2%

**Note: Optimization was performed on the final package only, no attempt was made to optimize after each incremental action.*

7.3 FINAL RESULTS

The complete advanced technology packages, which are a combination of several powertrain and vehicle technologies, include:

- advanced engine & transmission
- selected packages include a 42V stop-start system
- electric accessories (except for the mechanically driven cooling fan for the Truck) and high-efficiency alternator (which is inherent in the 42V stop-start systems)
- fast engine warm-up
- aerodynamic drag reduction
- rolling resistance reduction (except for the Truck)
- a post-simulation multiplier intended to be indicative of the potential FE and CO$_2$ benefits from friction reduction throughout the drivetrain.

For the Small MPV, Full Size Car, and Truck vehicle classes technology packages considered as low readiness (or high risk) are shown separately at the bottom of each table, specifically, packages containing Camless and HCCI technologies. This is because these are considered to require long-term development prior to application for high-volume production.

The final results with the originally identified performance metrics are shown below in tables for each vehicle class. There are two tables for each vehicle class, one presents the CO$_2$ results alongside the performance results and the other states FE results alongside the performance results. Although, the focus of this study was on CO$_2$

reduction, the FE results are also shown. The same vehicle and technology package information with complete performance results (initial and additional) are shown in the Appendix.

It is important to note the following regarding the final results:

- Every performance metric for a given advanced technology package cannot be matched to the baselines, since the shape of the engine torque curve and the transmission characteristics may be different. Therefore a spectrum of performance parameters was evaluated without attempting to meet or exceed each of the baseline's metrics.
- The benefits for each complete technology package are relative to the baseline vehicle and do not imply that every vehicle model sold in that class would be able to achieve all of the assumed inputs or benefits. Some vehicle models already implement some of the advanced technologies, and so would not derive the full benefit level stated here.

Table 7-10: Standard Car Vehicle Class CO$_2$ Emissions

Standard Car Vehicle Class

Technology Package Description									CO$_2$						Performance							
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW	
									g/mi	g/mi	g/mi	%	%	%	sec	sec	sec	sec	mph	meters	%	gear
Base-line	2.4L-4V I4 DCP	AT 5spd FDR 3.39	N	Mech	Bag1	base	base	N	338	217	284	-	-	-	3.2	8.7	3.4	5.4	28.3	19.2	13.8	3rd
Z	2.4L-4V I4 DVVL + CCP	DCT 6spd FDR 2.96	Y	ePS ePump	Y	-20%	-10%	Y	250	170	214	26%	22%	25%	3.8	8.8	3.1	4.7	22.4	12.7	15.3	3rd
		DCT 6spd FDR 3.07							250	170	214	26%	22%	25%	3.5	7.9	2.9	4.3	25.1	15.3	16.0	3rd
		DCT 6spd FDR 3.23							250	172	215	26%	21%	24%	3.4	7.6	2.8	4.3	26.2	16.0	16.7	3rd
		DCT 6spd FDR 3.40							249	174	215	26%	20%	24%	3.3	7.6	2.8	4.3	27.2	16.7	17.5	3rd
1	2.4L-4V I4 DVVL + DCP GDI	CVT FDR 6.23	N	ePS ePump heAlt	Y	-20%	-10%	Y	297	200	253	12%	8%	11%	3.7	9.1	3.2	5.0	24.9	16.3	17.9	-
		CVT w/ revised ratio FDR 5.00							295	198	251	13%	9%	11%	3.7	9.2	3.3	5.1	24.8	16.2	17.9	-
		CVT w/ revised ratio FDR 5.25							295	201	253	13%	8%	11%	3.6	9.0	3.3	4.9	25.5	16.7	17.9	-
		CVT w/ revised ratio FDR 5.50							296	204	255	12%	6%	10%	3.5	8.9	3.3	4.9	26.3	17.4	17.9	-
		CVT w/ revised ratio FDR 6.00							298	211	259	12%	3%	9%	3.3	8.6	3.2	4.9	27.9	18.6	17.9	-
2	2.4L-4V I4 DCP GDI	AT 6spd FDR 2.96	Y	ePS ePump	Y	-20%	-10%	Y	277	180	233	18%	17%	18%	3.4	8.8	3.3	5.3	26.7	16.8	14.8	3rd

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 7-11: Standard Car Vehicle Class Fuel Economy

Standard Car Vehicle Class

Technology Package Description									Fuel Economy						Performance							
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW	
									mpg	mpg	mpg	%	%	%	sec	sec	sec	sec	mph	meters	%	gear
Base-line	2.4L-4V I4 DCP	AT 5spd FDR 3.39	N	Mech	Bag1	base	base	N	26.9	41.8	32.0	-	-	-	3.2	8.7	3.4	5.4	28.3	19.2	13.8	3rd
Z	2.4L-4V I4 DVVL + CCP	DCT 6spd FDR 2.96	Y	ePS ePump	Y	-20%	-10%	Y	36.4	53.5	42.5	35%	28%	33%	3.8	8.8	3.1	4.7	22.4	12.7	15.3	3rd
		DCT 6spd FDR 3.07							36.4	53.6	42.6	35%	28%	33%	3.5	7.9	2.9	4.3	25.1	15.3	16.0	3rd
		DCT 6spd FDR 3.23							36.4	52.8	42.3	35%	26%	32%	3.4	7.6	2.8	4.3	26.2	16.0	16.7	3rd
		DCT 6spd FDR 3.40							36.4	52.3	42.2	35%	25%	32%	3.3	7.6	2.8	4.3	27.2	16.7	17.5	3rd
1	2.4L-4V I4 DVVL + DCP GDI	CVT FDR 6.23	N	ePS ePump heAlt	Y	-20%	-10%	Y	30.6	45.5	35.9	14%	9%	12%	3.7	9.1	3.2	5.0	24.9	16.3	17.9	-
		CVT w/ revised ratio FDR 5.00							30.8	45.9	36.2	15%	10%	13%	3.7	9.2	3.3	5.1	24.8	16.2	17.9	-
		CVT w/ revised ratio FDR 5.25							30.8	45.2	35.9	14%	8%	12%	3.6	9.0	3.3	4.9	25.5	16.7	17.9	-
		CVT w/ revised ratio FDR 5.50							30.7	44.5	35.7	14%	7%	11%	3.5	8.9	3.3	4.9	26.3	17.4	17.9	-
		CVT w/ revised ratio FDR 6.00							30.5	43.1	35.1	13%	3%	9%	3.3	8.6	3.2	4.9	27.9	18.6	17.9	-
2	2.4L-4V I4 DCP GDI	AT 6spd FDR 2.96	Y	ePS ePump	Y	-20%	-10%	Y	32.8	50.6	39.0	22%	21%	22%	3.4	8.8	3.3	5.3	26.7	16.8	14.8	3rd

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 7-12: Small MPV Vehicle Class CO_2 Emissions

Small MPV Vehicle Class

Technology Package Description									CO_2						Performance							
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW	
									g/mi	g/mi	g/mi	%	%	%	sec	sec	sec	sec	mph	meters	%	gear
Base-line	2.4L-4V I4 DCP	AT 4spd FDR 3.91	N	Mech except ePS	Bag1	base	base	N	367	253	316	-	-	-	3.8	10.4	3.7	6.0	24.6	16.7	14.8	2nd
Z	2.4L I4 DVVL + CCP	DCT 6spd FDR 3.10	Y	ePS ePump	Y	-20%	-10%	Y	272	208	243	26%	18%	23%	4.4	10.4	3.7	6.1	18.8	10.8	16.7	2nd
1	2.4L I4 DVVL + DCP GDI	CVT FDR 5.8	N	ePS ePump heAlt	Y	-20%	-10%	Y	313	231	276	15%	9%	13%	4.7	10.3	3.4	5.2	18.7	12.0	16.7	-
		CVT w/ revised ratio FDR 4.64							310	227	273	16%	10%	14%	4.7	10.3	3.4	5.2	18.7	12.0	16.7	-
		CVT w/ revised ratio FDR 4.90							309	229	273	16%	10%	13%	4.5	10.3	3.4	5.2	19.3	12.3	16.7	-
		CVT w/ revised ratio FDR 5.15							309	231	274	16%	9%	13%	4.3	10.0	3.4	5.2	20.3	13.0	16.7	-
		CVT w/ revised ratio FDR 5.50							310	234	276	16%	7%	13%	4.1	9.7	3.4	5.2	21.6	13.8	16.7	-
2	2.4L I4 DCP GDI	AT 6spd FDR 2.8	Y	ePS ePump	Y	-20%	-10%	Y	290	211	255	21%	17%	19%	3.8	10.7	4.5	6.9	24.5	16.1	16.9	2nd
5	1.9L I4 Diesel with aftertreatment	DCT 6spd FDR 3.00	N	ePS ePump heAlt	Y	-20%	-10%	Y	282	205	247	23%	19%	22%	3.9	10.4	3.9	6.3	24.1	12.9	13.1	3rd
15	1.5L I4 Turbo DCP GDI	DCT 6spd FDR 3.2	N	ePS ePump heAlt	Y	-20%	-10%	Y	272	211	244	26%	17%	23%	4.6	10.1	3.6	4.9	16.6	8.9	12.9	3rd
		DCT 6spd FDR 3.36							272	211	245	26%	17%	22%	4.4	9.8	3.3	5.2	17.8	9.5	13.6	3rd
		DCT 6spd FDR 3.52							272	212	245	26%	16%	22%	4.3	9.6	3.2	5.2	18.9	10.1	14.1	3rd
		DCT 6spd FDR 3.68							273	213	246	26%	16%	22%	4.1	9.5	3.2	5.2	20.0	10.7	14.6	3rd
Low Technology Readiness - 10 Years																						
15a	2.4L I4 Camless GDI	DCT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-20%	-10%	Y	262	193	231	29%	24%	27%	4.3	10.3	3.7	6.1	19.6	11.7	16.6	2nd
15b	2.4L I4 HCCI GDI	DCT 6 spd FDR 3.1	N	ePS ePump heAlt	Y	-20%	-10%	Y	270	197	237	26%	22%	25%	4.3	10.3	3.7	6.1	19.6	11.7	16.6	2nd

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 7-13: Small MPV Vehicle Class Fuel Economy

Small MPV Vehicle Class

Technology Package Description									Fuel Economy						Performance							
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW	
									mpg	mpg	mpg	%	%	%	sec	sec	sec	sec	mph	meters	%	gear
Base-line	2.4L-4V I4 DCP	AT 4spd FDR 3.91	N	Mech except ePS	Bag1	base	base	N	24.8	35.9	28.8	-	-	-	3.8	10.4	3.7	6.0	24.6	16.7	14.8	2nd
Z	2.4L I4 DVVL + CCP	DCT 6spd FDR 3.10	Y	ePS ePump	Y	-20%	-10%	Y	33.4	43.8	37.4	35%	22%	30%	4.4	10.4	3.7	6.1	18.8	10.8	16.7	2nd
1	2.4L I4 DVVL + DCP GDI	CVT FDR 5.8	N	ePS ePump heAlt	Y	-20%	-10%	Y	29.0	39.4	32.9	17%	10%	14%	4.7	10.3	3.4	5.2	18.7	12.0	16.7	-
		CVT w/ revised ratio FDR 4.64							29.3	40.0	33.3	18%	11%	16%	4.7	10.3	3.4	5.2	18.7	12.0	16.7	-
		CVT w/ revised ratio FDR 4.90							29.4	39.7	33.3	19%	11%	16%	4.5	10.3	3.4	5.2	19.3	12.3	16.7	-
		CVT w/ revised ratio FDR 5.15							29.4	39.4	33.2	19%	10%	15%	4.3	10.0	3.4	5.2	20.3	13.0	16.7	-
		CVT w/ revised ratio FDR 5.50							29.4	38.8	33.0	19%	8%	14%	4.1	9.7	3.4	5.2	21.6	13.8	16.7	-
2	2.4L I4 DCP GDI	AT 6spd FDR 2.8	Y	ePS ePump	Y	-20%	-10%	Y	31.3	43.1	35.7	26%	20%	24%	3.8	10.7	4.5	6.9	24.5	16.1	16.9	2nd
5	1.9L I4 Diesel with aftertreatment	DCT 6spd FDR 3.00	N	ePS ePump heAlt	Y	-20%	-10%	Y	35.9	49.3	40.9	45%	37%	42%	3.9	10.4	3.9	6.3	24.1	12.9	13.1	3rd
15	1.5L I4 Turbo DCP GDI	DCT 6spd FDR 3.2	N	ePS ePump heAlt	Y	-20%	-10%	Y	33.4	43.1	37.2	35%	20%	29%	4.6	10.1	3.6	4.9	16.6	8.9	12.9	3rd
		DCT 6spd FDR 3.36							33.4	43.1	37.2	35%	20%	29%	4.4	9.8	3.3	5.2	17.8	9.5	13.6	3rd
		DCT 6spd FDR 3.52							33.4	42.9	37.1	35%	19%	29%	4.3	9.6	3.2	5.2	18.9	10.1	14.1	3rd
		DCT 6spd FDR 3.68							33.3	42.7	36.9	34%	19%	28%	4.1	9.5	3.2	5.2	20.0	10.7	14.6	3rd
Low Technology Readiness - 10 Years																						
15a	2.4L I4 Camless GDI	DCT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-20%	-10%	Y	34.7	47.1	39.3	40%	31%	37%	4.3	10.3	3.7	6.1	19.6	11.7	16.6	2nd
15b	2.4L I4 HCCI GDI	DCT 6 spd FDR 3.1	N	ePS ePump heAlt	Y	-20%	-10%	Y	33.6	46.1	38.3	36%	28%	33%	4.3	10.3	3.7	6.1	19.6	11.7	16.6	2nd

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 7-14: Full Size Car Vehicle Class CO_2 Emissions

Full Size Car Vehicle Class

Technology Package Description									CO_2						Performance							
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW	
									g/mi	g/mi	g/mi	%	%	%	sec	sec	sec	sec	mph	meters	%	gear
Base-line	3.5L-4V V6	AT 5spd FDR 2.87	N	Mech	Bag1	base	base	N	420	279	356	-	-	-	2.6	6.7	2.3	3.8	33.7	24.6	24.6	2nd
4	2.2L I4 Turbo DCP GDI	AT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y	346	236	296	18%	15%	17%	2.6	6.6	2.3	3.4	33.7	22.0	25.6	2nd
5	2.8L I4/5 Diesel with aftertreatment	DCT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y	316	221	273	25%	21%	23%	2.6	7.1	2.7	4.3	33.8	21.7	18.5	4th
		DCT 6spd 6.55 span FDR 3.08							315	221	273	25%	21%	24%	2.5	7.1	2.7	4.3	34.3	22.4	18.5	4th
	2.8L I4/5 US Diesel with aftertreatment	DCT 6spd 6.55 span FDR 3.08							340	220	286	19%	21%	20%	2.5	7.1	2.7	4.3	34.3	22.4	18.5	4th
6a	3.0L V6 DCP + CVVL GDI	DCT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y	334	234	289	20%	16%	19%	3.3	7.3	2.3	3.3	26.8	16.8	26.1	2nd
		DCT 6spd FDR 3.20							338	237	293	19%	15%	18%	3.1	7.1	2.3	3.4	28.6	17.8	26.1	2nd
		DCT 6spd 6.55 span FDR 3.08							334	234	289	20%	16%	19%	3.1	7.0	2.3	3.5	28.7	17.9	25.6	2nd
16	3.5L V6 CCP + Deac GDI	AT 6spd FDR 2.7	Y	ePS ePump	Y	-20%	-10%	Y	301	205	257	28%	27%	28%	2.7	6.8	2.5	3.6	33.3	21.8	27.2	2nd
Low Technology Readiness - 10 Years																						
Y1	3.5L V6 Camless GDI	DCT 6spd FDR 2.80	N	ePS ePump heAlt	Y	-20%	-10%	Y	278	199	242	34%	29%	32%	3.1	6.8	2.2	3.2	29.3	17.9	28.7	2nd
Y2	3.5L V6 HCCI GDI	DCT 6spd FDR 2.80	N	ePS ePump heAlt	Y	-20%	-10%	Y	290	197	248	31%	29%	30%	3.1	6.8	2.2	3.2	29.3	17.9	28.7	2nd

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 7-15: Full Size Car Vehicle Class Fuel Economy

Full Size Car Vehicle Class

Technology Package Description									Fuel Economy						Performance							
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW	
									mpg	mpg	mpg	%	%	%	sec	sec	sec	sec	mph	meters	%	gear
Base-line	3.5L-4V V6	AT 5spd FDR 2.87	N	Mech	Bag1	base	base	N	21.7	32.6	25.5	-	-	-	2.6	6.7	2.3	3.8	33.7	24.6	24.6	2nd
4	2.2L I4 Turbo DCP GDI	AT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y	26.3	38.5	30.7	21%	18%	20%	2.6	6.6	2.3	3.4	33.7	22.0	25.6	2nd
5	2.8L I4/5 Diesel with aftertreatment	DCT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y	31.9	45.8	37.0	47%	40%	45%	2.6	7.1	2.7	4.3	33.8	21.7	18.5	4th
		DCT 6spd 6.55 span FDR 3.08							32.1	45.7	37.0	48%	40%	45%	2.5	7.1	2.7	4.3	34.3	22.4	18.5	4th
	2.8L I4/5 US Diesel with aftertreatment	DCT 6spd 6.55 span FDR 3.08							29.7	45.9	35.3	37%	41%	38%	2.5	7.1	2.7	4.3	34.3	22.4	18.5	4th
6a	3.0L V6 DCP + CVVL GDI	DCT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y	27.2	38.8	31.4	25%	19%	23%	3.3	7.3	2.3	3.3	26.8	16.8	26.1	2nd
		DCT 6spd FDR 3.20							26.9	38.3	31.0	24%	18%	22%	3.1	7.1	2.3	3.4	28.6	17.8	26.1	2nd
		DCT 6spd 6.55 span FDR 3.08							27.2	38.8	31.4	26%	19%	23%	3.1	7.0	2.3	3.5	28.7	17.9	25.6	2nd
16	3.5L V6 CCP + Deac GDI	AT 6spd FDR 2.7	Y	ePS ePump	Y	-20%	-10%	Y	30.2	44.4	35.3	40%	36%	38%	2.7	6.8	2.5	3.6	33.3	21.8	27.2	2nd
Low Technology Readiness - 10 Years																						
Y1	3.5L V6 Camless GDI	DCT 6spd FDR 2.80	N	ePS ePump heAlt	Y	-20%	-10%	Y	32.7	45.7	37.5	51%	40%	47%	3.1	6.8	2.2	3.2	29.3	17.9	28.7	2nd
Y2	3.5L V6 HCCI GDI	DCT 6spd FDR 2.80	N	ePS ePump heAlt	Y	-20%	-10%	Y	31.4	46.1	36.6	45%	42%	44%	3.1	6.8	2.2	3.2	29.3	17.9	28.7	2nd

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 7-16: Large MPV Vehicle Class CO_2 Emissions

Large MPV Vehicle Class

Technology Package Description									CO_2						Performance							
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW	
									g/mi	g/mi	g/mi	%	%	%	sec	sec	sec	sec	mph	meters	%	gear
Base-line	3.8L-2V V6	AT 4spd FDR 3.43	N	Mech	Bag1	base	base	N	458	313	393	-	-	-	3.3	9.3	3.5	5.6	27.5	16.9	17.7	2nd
4	2.1L I4 Turbo DCP GDI	AT 6spd FDR 3.17	N	ePS ePump heAlt	Y	-20%	-10%	Y	357	256	312	22%	18%	21%	3.2	8.0	2.8	4.3	27.8	16.5	17.1	3rd
6b	3.0L V6 CCP + Deac GDI	DCT 6spd FDR 3.17	N	ePS ePump heAlt	Y	-20%	-10%	Y	335	245	295	27%	22%	25%	3.9	8.5	2.8	4.2	21.3	11.9	16.8	3rd
		DCT 6spd FDR 3.72							333	248	295	27%	21%	25%	3.5	8.1	2.7	4.2	24.5	13.6	19.7	3rd
		DCT 6spd FDR 3.00							338	243	295	26%	22%	25%	4.1	8.7	2.8	4.1	20.1	11.3	15.5	3rd
	2.7L V6 CCP + Deac GDI	DCT 6spd FDR 3.72							323	244	287	30%	22%	27%	3.8	8.9	3.0	4.8	21.7	12.1	17.4	3rd
16	3.8L V6 CCP + Deac GDI	AT 6spd FDR 2.7	Y	ePS ePump	Y	-20%	-10%	Y	325	225	280	29%	28%	29%	3.3	9.3	3.4	5.6	27.1	15.6	17.0	2nd

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 7-17: Large MPV Vehicle Class Fuel Economy

Large MPV Vehicle Class

Technology Package Description									Fuel Economy						Performance							
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW	
									mpg	mpg	mpg	%	%	%	sec	sec	sec	sec	mph	meters	%	gear
Base-line	3.8L-2V V6	AT 4spd FDR 3.43	N	Mech	Bag1	base	base	N	19.8	29.0	23.1	-	-	-	3.3	9.3	3.5	5.6	27.5	16.9	17.7	2nd
4	2.1L I4 Turbo DCP GDI	AT 6spd FDR 3.17	N	ePS ePump heAlt	Y	-20%	-10%	Y	25.5	35.4	29.2	28%	22%	26%	3.2	8.0	2.8	4.3	27.8	16.5	17.1	3rd
6b	3.0L V6 CCP + Deac GDI	DCT 6spd FDR 3.17	N	ePS ePump heAlt	Y	-20%	-10%	Y	27.1	37.1	30.9	37%	28%	33%	3.9	8.5	2.8	4.2	21.3	11.9	16.8	3rd
		DCT 6spd FDR 3.72							27.3	36.6	30.8	38%	26%	33%	3.5	8.1	2.7	4.2	24.5	13.6	19.7	3rd
		DCT 6spd FDR 3.00							26.9	37.4	30.8	36%	29%	33%	4.1	8.7	2.8	4.1	20.1	11.3	15.5	3rd
	2.7L V6 CCP + Deac GDI	DCT 6spd FDR 3.72							28.2	37.3	31.6	42%	28%	37%	3.8	8.9	3.0	4.8	21.7	12.1	17.4	3rd
16	3.8L V6 CCP + Deac GDI	AT 6spd FDR 2.7	Y	ePS ePump	Y	-20%	-10%	Y	28.0	40.3	32.4	41%	39%	40%	3.3	9.3	3.4	5.6	27.1	15.6	17.0	2nd

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 7-18: Truck Vehicle Class CO_2 Emissions

Truck Vehicle Class

Technology Package Description									CO_2						Performance							
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	60 MPH Grade Capability at GCW	
									g/mi	g/mi	g/mi	%	%	%	sec	sec	sec	sec	mph	meters	%	gear
Base-line	5.4L-3V V8 CCP	AT 4spd FDR 3.73	N	Mech	Bag1	base	base	N	612	402	517	-	-	-	2.6	7.7	3.0	4.6	33.6	23.3	8.8	2nd
6-Spd AT	5.4L-3V V8 CCP	AT 6spd FDR 3.60	N	Mech	Bag1	base	base	N	586	396	500	x	x	x	2.3	7.5	2.9	5.0	35.9	26.2	8.5	3rd
9	5.4L-3V V8 CCP + Deac GDI	DCT 6spd FDR 3.3	Y	ePS ePump	Y	-10%	base	Y	432	315	379	29%	22%	27%	2.7	7.8	2.8	4.6	32.7	21.1	8.4	3rd
10	3.6L V6 Turbo DCP GDI	DCT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-10%	base	Y	404	319	366	34%	21%	29%	2.9	6.7	2.2	3.5	31.5	19.3	12.3	2nd
		DCT 6spd FDR 3.26							416	321	373	32%	20%	28%	2.8	6.4	2.2	3.6	32.6	19.8	12.5	2nd
		DCT 6spd FDR 3.41							418	323	376	32%	19%	27%	2.7	6.4	2.2	3.6	33.5	20.5	13.0	2nd
		DCT 6spd FDR 3.57							421	325	378	31%	19%	27%	2.6	6.3	2.2	3.6	35.5	21.4	12.9	2nd
11	4.8L V6 Diesel with aftertreatment	DCT 6spd FDR 3.15	N	ePS ePump heAlt	Y	-10%	base	Y	444	326	391	27%	19%	24%	2.7	7.7	2.7	4.7	32.5	20.4	10.2	3rd
12	5.4L-3V V8 CCP + Deac GDI	AT 6spd FDR 3.1	Y	ePS ePump	Y	-10%	base	Y	459	328	400	25%	18%	23%	2.4	7.5	2.9	4.9	35.6	25.2	10.7	2nd
17	5.4L V8 DVVL + DCP GDI	AT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-10%	base	Y	492	333	420	20%	17%	19%	2.2	7.1	2.7	4.5	37.1	27.3	10.7	2nd
Low Technology Readiness - 10 Years																						
X1	5.4L V8 Camless GDI	DCT 6spd FDR 3.35	N	ePS ePump heAlt	Y	-10%	base	Y	422	314	374	31%	22%	28%	2.7	7.7	2.8	4.6	32.8	21.2	8.6	3rd
X2	5.4L V8 HCCI GDI	DCT 6spd FDR 3.35	N	ePS ePump heAlt	Y	-10%	base	Y	425	311	374	31%	23%	28%	2.7	7.7	2.8	4.6	32.8	21.2	8.6	3rd

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table 7-19: Truck Vehicle Class Fuel Economy

Truck Vehicle Class

Technology Package Description									Fuel Economy						Performance							
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	60 MPH Grade Capability at GCW	
									mpg	mpg	mpg	%	%	%	sec	sec	sec	sec	mph	meters	%	gear
Base-line	5.4L-3V V8 CCP	AT 4spd FDR 3.73	N	Mech	Bag1	base	base	N	14.9	22.6	17.6	-	-	-	2.6	7.7	3.0	4.6	33.6	23.3	8.8	2nd
6-Spd AT	5.4L-3V V8 CCP	AT 6spd FDR 3.60	N	Mech	Bag1	base	base	N	15.5	23.0	18.2	x	x	x	2.3	7.5	2.9	5.0	35.9	26.2	8.5	3rd
9	5.4L-3V V8 CCP + Deac GDI	DCT 6spd FDR 3.3	Y	ePS ePump	Y	-10%	base	Y	21.0	28.9	23.9	41%	28%	36%	2.7	7.8	2.8	4.6	32.7	21.1	8.4	3rd
10	3.6L V6 Turbo DCP GDI	DCT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-10%	base	Y	22.5	28.5	24.9	52%	26%	42%	2.9	6.7	2.2	3.5	31.5	19.3	12.3	2nd
		DCT 6spd FDR 3.26							21.8	28.3	24.3	47%	25%	39%	2.8	6.4	2.2	3.6	32.6	19.8	12.5	2nd
		DCT 6spd FDR 3.41							21.7	28.1	24.2	46%	24%	38%	2.7	6.4	2.2	3.6	33.5	20.5	13.0	2nd
		DCT 6spd FDR 3.57							21.6	27.9	24.1	46%	23%	37%	2.6	6.3	2.2	3.6	35.5	21.4	12.9	2nd
11	4.8L V6 Diesel with aftertreatment	DCT 6spd FDR 3.15	N	ePS ePump heAlt	Y	-10%	base	Y	22.7	31.0	25.8	53%	37%	47%	2.7	7.7	2.7	4.7	32.5	20.4	10.2	3rd
12	5.4L-3V V8 CCP + Deac GDI	AT 6spd FDR 3.1	Y	ePS ePump	Y	-10%	base	Y	19.8	27.7	22.7	33%	23%	29%	2.4	7.5	2.9	4.9	35.6	25.2	10.7	2nd
17	5.4L V8 DVVL + DCP GDI	AT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-10%	base	Y	18.5	27.3	21.6	24%	21%	23%	2.2	7.1	2.7	4.5	37.1	27.3	10.7	2nd
Low Technology Readiness - 10 Years																						
X1	5.4L V8 Camless GDI	DCT 6spd FDR 3.35	N	ePS ePump heAlt	Y	-10%	base	Y	21.5	28.9	24.3	45%	28%	38%	2.7	7.7	2.8	4.6	32.8	21.2	8.6	3rd
X2	5.4L V8 HCCI GDI	DCT 6spd FDR 3.35	N	ePS ePump heAlt	Y	-10%	base	Y	21.4	29.2	24.3	44%	29%	38%	2.7	7.7	2.8	4.6	32.8	21.2	8.6	3rd

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

7.4 CLOSING COMMENTS

The intent of the study was to carry out a scientific, objective study of the effectiveness of packages of advanced powertrain and vehicle technologies to reduce CO_2 emissions from light-duty passenger vehicles. The technology packages included advanced engines, transmissions, 42V engine stop-start systems, electrically-driven engine accessories combined with fast warm-up strategies, aerodynamic drag and rolling resistance reductions, and a friction reduction multiplier.

The technology packages assessed as high readiness level (or low risk) were predicted to offer CO_2 reduction potentials ranging from 9 – 29% on the combined metro-highway drive cycle, and those with low technology readiness (or high risk) up to 32%. The effects on vehicle performance were also reported along with the CO_2 emission benefits as they can have a strong impact on vehicle purchase decisions.

The potential benefits in reducing CO_2 are seen to be significant, but it is important to note that these are realized through the combination of a number of technologies. Most of these technologies would add cost to the vehicles. The assessment of the economic impact of these technology packages was outside of the scope of this study.

Finally, the CO_2 and performance results for combinations of technologies represent what could potentially be achieved when applied to a specific baseline vehicle. The results are seen to vary significantly between different vehicle applications. Hence, determination of the benefit of specific technology combinations to other vehicle platforms would require a similar level of scientific analysis.

TERMINOLOGY

AT	Automatic Transmission, used here to refer to a planetary gearbox with torque converter
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
CAI	Controlled Auto-Ignition
CCP	Coordinated Cam Phaser (intake and exhaust cams have same phasing change)
CPS	Crankshaft Position Sensor
CO_2	Carbon Dioxide, a known greenhouse gas
CVVL	Continuously Variable Valve Lift by means of a mechanical linkage
CVT	Continuously Variable Transmission
DCP	Dual Cam Phasers, one each on intake and exhaust cam giving independent control of inlet and exhaust valve timing
DCT	Dual Clutch Transmission (either wet-clutch or dry-clutch)
DEAC	Cylinder Deactivation
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DVVL	Discrete Variable Valve Lift, two or three stage variable valve lift by means of cam profile switching
ECU	Engine Control Unit
EGR	Exhaust Gas Residual
EPA	Environmental Protection Agency
ePS	Electric Power Steering (either full electric or electro-hydraulic)
ePump	Both electric water pump and electric engine oil pump
ETW	EPA Equivalent Test Weight
FDR	Final Drive Ratio
FMEP	Friction Mean Effective Pressure

FTP75	Federal Test Procedure, commonly referred to as the EPA City test cycle
GCW	Gross Combined Weight
GDI	Gasoline Direct Injection, with combustion occurring at stoichiometric conditions
GHG	Green House Gas
HC	Hydrocarbon Emissions
HCCI	Homogenous Charge Compression Ignition
HeAlt	High efficiency Alternator
HPCR	High Pressure Common Rail, diesel fuel injection system
HWFET	HighWay Fuel Economy Test, EPA test cycle commonly referred to as the Highway cycle
I4	In-line 4 cylinder engine
I5	In-line 5 cylinder engine
ICP	Intake Cam Phaser
LNT	Lean NO_x Trap
MPV	Multi-Purpose Vehicle
NO_x	Nitrogen Oxides
OEM	Original Equipment Manufacturer, used to mean the automotive vehicle manufacturers
PCCI	Pre-mixed Charge Compression Ignition, synonymous w/ HCCI
PFI	Port Fuel Injection
PMEP	Pumping Mean Effective Pressure
SCR	Selective Catalytic Reduction
T2B5	Tier 2 Bin 5 emissions standard
Turbo	Turbocharger
V6	Vee-6 cylinder engine
V8	Vee-8 cylinder engine

VNT	Variable Nozzle Turbocharger
VVT	Variable Valve Timing
WOT	Wide-Open Throttle, or full engine load

APPENDIX

This appendix shows the complete final results tables, which include the data shown in Sections 1 and 7 and the additional performance metrics as discussed in Section 2.10.3.

Table A-1: Standard Car Vehicle Class CO$_2$ Emissions

Standard Car Vehicle Class																												
Technology Package Description									CO$_2$						Performance													
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW		0-10 MPH	0-50 MPH	0-70 MPH	60 MPH Top Gear ETW Grade Capability^{A}	70 MPH Top-Gear ETW Grade Capability^{A}
									g/mi	g/mi	g/mi	%	%	%	sec	sec	sec	sec	mph	meters	%	gear	sec	sec	sec	%	%
Base-line	2.4L-4V I4 DCP	AT 5spd FDR 3.39	N	Mech	Bag1	base	base	N	338	217	284	-	-	-	3.2	8.7	3.4	5.4	28.3	19.2	13.8	3rd	1.3	6.6	12.0	5.2	4.6
Z	2.4L-4V I4 DVVL + CCP	DCT 6spd FDR 2.96	Y	ePS ePump	Y	-20%	-10%	Y	250	170	214	26%	22%	25%	3.8	8.8	3.1	4.7	22.4	12.7	15.3	3rd	1.6	6.9	11.6	4.7	4.2
		DCT 6spd FDR 3.07							250	170	214	26%	22%	25%	3.5	7.9	2.9	4.3	25.1	15.3	16.0	3rd	1.4	6.4	10.7	5.0	4.5
		DCT 6spd FDR 3.23							250	172	215	26%	21%	24%	3.4	7.6	2.8	4.3	26.2	16.0	16.7	3rd	1.3	6.2	10.5	5.5	5.0
		DCT 6spd FDR 3.40							249	174	215	26%	20%	24%	3.3	7.6	2.8	4.3	27.2	16.7	17.5	3rd	1.3	6.1	10.4	5.9	5.4
1	2.4L-4V I4 DVVL + DCP GDI	CVT FDR 6.23	N	ePS ePump heAlt	Y	-20%	-10%	Y	297	200	253	12%	8%	11%	3.7	9.1	3.2	5.0	24.9	16.3	17.9	-	1.2	6.9	11.9	6.6	6.1
		CVT w/ revised ratio FDR 5.00							295	198	251	13%	9%	11%	3.7	9.2	3.3	5.1	24.8	16.2	17.9	-	1.3	6.9	12.0	6.6	6.1
		CVT w/ revised ratio FDR 5.25							295	201	253	13%	8%	11%	3.6	9.0	3.3	4.9	25.5	16.7	17.9	-	1.2	6.8	11.7	7.1	6.6
		CVT w/ revised ratio FDR 5.50							296	204	255	12%	6%	10%	3.5	8.9	3.3	4.9	26.3	17.4	17.9	-	1.2	6.7	11.6	7.6	7.2
		CVT w/ revised ratio FDR 6.00							298	211	259	12%	3%	9%	3.3	8.6	3.2	4.9	27.9	18.6	17.9	-	1.1	6.5	11.3	8.7	8.2
2	2.4L-4V I4 DCP GDI	AT 6spd FDR 2.96	Y	ePS ePump	Y	-20%	-10%	Y	277	180	233	18%	17%	18%	3.4	8.8	3.3	5.3	26.7	16.8	14.8	3rd	1.2	6.7	12.0	4.7	4.2

Footnote A: Top-gear grade capability is constrainted to the top gear and is used as an indication of torque reserve. See section 2 for discussion on performance metrics.

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table A-2: Standard Car Vehicle Class Fuel Economy

Standard Car Vehicle Class																											
Technology Package Description									Fuel Economy						Performance												
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW		0-10 MPH	0-50 MPH	0-70 MPH	60 MPH Top Gear ETW Grade Capability A	70 MPH Top-Gear ETW Grade Capability A
									mpg	mpg	mpg	%	%	%	sec	sec	sec	sec	mph	meters	%	gear	sec	sec	sec	%	%
Base-line	2.4L-4V I4 DCP	AT 5spd FDR 3.39	N	Mech	Bag1	base	base	N	26.9	41.8	32.0	-	-	-	3.2	8.7	3.4	5.4	28.3	19.2	13.8	3rd	1.3	6.6	12.0	5.2	4.6
Z	2.4L-4V I4 DVVL + CCP	DCT 6spd FDR 2.96	Y	ePS ePump	Y	-20%	-10%	Y	36.4	53.5	42.5	35%	28%	33%	3.8	8.8	3.1	4.7	22.4	12.7	15.3	3rd	1.6	6.9	11.6	4.7	4.2
		DCT 6spd FDR 3.07							36.4	53.6	42.6	35%	28%	33%	3.5	7.9	2.9	4.3	25.1	15.3	16.0	3rd	1.4	6.4	10.7	5.0	4.5
		DCT 6spd FDR 3.23							36.4	52.8	42.3	35%	26%	32%	3.4	7.6	2.8	4.3	26.2	16.0	16.7	3rd	1.3	6.2	10.5	5.5	5.0
		DCT 6spd FDR 3.40							36.4	52.3	42.2	35%	25%	32%	3.3	7.6	2.8	4.3	27.2	16.7	17.5	3rd	1.3	6.1	10.4	5.9	5.4
1	2.4L-4V I4 DVVL + DCP GDI	CVT FDR 6.23	N	ePS ePump heAlt	Y	-20%	-10%	Y	30.6	45.5	35.9	14%	9%	12%	3.7	9.1	3.2	5.0	24.9	16.3	17.9	-	1.2	6.9	11.9	6.6	6.1
		CVT w/ revised ratio FDR 5.00							30.8	45.9	36.2	15%	10%	13%	3.7	9.2	3.3	5.1	24.8	16.2	17.9	-	1.3	6.9	12.0	6.6	6.1
		CVT w/ revised ratio FDR 5.25							30.8	45.2	35.9	14%	8%	12%	3.6	9.0	3.3	4.9	25.5	16.7	17.9	-	1.2	6.8	11.7	7.1	6.6
		CVT w/ revised ratio FDR 5.50							30.7	44.5	35.7	14%	7%	11%	3.5	8.9	3.3	4.9	26.3	17.4	17.9	-	1.2	6.7	11.6	7.6	7.2
		CVT w/ revised ratio FDR 6.00							30.5	43.1	35.1	13%	3%	9%	3.3	8.6	3.2	4.9	27.9	18.6	17.9	-	1.1	6.5	11.3	8.7	8.2
2	2.4L-4V I4 DCP GDI	AT 6spd FDR 2.96	Y	ePS ePump	Y	-20%	-10%	Y	32.8	50.6	39.0	22%	21%	22%	3.4	8.8	3.3	5.3	26.7	16.8	14.8	3rd	1.2	6.7	12.0	4.7	4.2

Footnote A: Top-gear grade capability is constrainted to the top gear and is used as an indication of torque reserve. See section 2 for discussion on performance metrics.

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table A-3: Small MPV Vehicle Class CO_2 Emissions

Small MPV Vehicle Class

Technology Package Description									CO_2						Performance												
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW		0-10 MPH	0-50 MPH	0-70 MPH	60 MPH Top Gear ETW Grade Capability ^{A}	70 MPH Top-Gear ETW Grade Capability ^{A}
									g/mi	g/mi	g/mi	%	%	%	sec	sec	sec	sec	mph	meters	%	gear	sec	sec	sec	%	%
Base-line	2.4L-4V I4 DCP	AT 4spd FDR 3.91	N	Mech except ePS	Bag1	base	base	N	367	253	316	-	-	-	3.8	10.4	3.7	6.0	24.6	16.7	14.8	2nd	1.2	7.5	13.5	3.6	3.1
Z	2.4L I4 DVVL + CCP	DCT 6spd FDR 3.10	Y	ePS ePump	Y	-20%	-10%	Y	272	208	243	26%	18%	23%	4.4	10.4	3.7	6.1	18.8	10.8	16.7	2nd	1.8	8.1	14.2	2.6	2.1
1	2.4L I4 DVVL + DCP GDI	CVT FDR 5.8	N	ePS ePump heAlt	Y	-20%	-10%	Y	313	231	276	15%	9%	13%	4.7	10.3	3.4	5.2	18.7	12.0	16.7	-	1.7	8.0	13.2	3.3	2.8
		CVT w/ revised ratio FDR 4.64							310	227	273	16%	10%	14%	4.7	10.3	3.4	5.2	18.7	12.0	16.7	-	1.7	8.0	13.2	3.3	2.8
		CVT w/ revised ratio FDR 4.90							309	229	273	16%	10%	13%	4.5	10.3	3.4	5.2	19.3	12.3	16.7	-	1.6	8.0	13.2	3.7	3.2
		CVT w/ revised ratio FDR 5.15							309	231	274	16%	9%	13%	4.3	10.0	3.4	5.2	20.3	13.0	16.7	-	1.6	7.7	12.9	4.2	3.8
		CVT w/ revised ratio FDR 5.50							310	234	276	16%	7%	13%	4.1	9.7	3.4	5.2	21.6	13.8	16.7	-	1.5	7.4	12.6	4.8	4.5
2	2.4L I4 DCP GDI	AT 6spd FDR 2.8	Y	ePS ePump	Y	-20%	-10%	Y	290	211	255	21%	17%	19%	3.8	10.7	4.5	6.9	24.5	16.1	16.9	2nd	1.2	8.3	15.2	1.9	1.4
5	1.9L I4 Diesel with aftertreatment	DCT 6spd FDR 3.00	N	ePS ePump heAlt	Y	-20%	-10%	Y	282	205	247	23%	19%	22%	3.9	10.4	3.9	6.3	24.1	12.9	13.1	3rd	1.7	7.8	14.1	4.8	5.2
15	1.5L I4 Turbo DCP GDI	DCT 6spd FDR 3.2	N	ePS ePump heAlt	Y	-20%	-10%	Y	272	211	244	26%	17%	23%	4.6	10.1	3.6	4.9	16.6	8.9	12.9	3rd	2.2	8.2	13.0	2.6	2.4
		DCT 6spd FDR 3.36							272	211	245	26%	17%	22%	4.4	9.8	3.3	5.2	17.8	9.5	13.6	3rd	2.1	7.7	12.9	3.1	2.9
		DCT 6spd FDR 3.52							272	212	245	26%	16%	22%	4.3	9.6	3.2	5.2	18.9	10.1	14.1	3rd	2.0	7.5	12.7	3.6	3.4
		DCT 6spd FDR 3.68							273	213	246	26%	16%	22%	4.1	9.5	3.2	5.2	20.0	10.7	14.6	3rd	1.9	7.3	12.5	4.1	3.9
Low Technology Readiness - 10 Years																											
15a	2.4L I4 Camless GDI	DCT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-20%	-10%	Y	262	193	231	29%	24%	27%	4.3	10.3	3.7	6.1	19.6	11.7	16.6	2nd	1.7	8.0	14.1	2.6	2.1
15b	2.4L I4 HCCI GDI	DCT 6 spd FDR 3.1	N	ePS ePump heAlt	Y	-20%	-10%	Y	270	197	237	26%	22%	25%	4.3	10.3	3.7	6.1	19.6	11.7	16.6	2nd	1.7	8.0	14.1	2.6	2.1

Footnote A: Top-gear grade capability is constrainted to the top gear and is used as an indication of torque reserve. See section 2 for discussion on performance metrics.

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table A-4: Small MPV Vehicle Class Fuel Economy

Small MPV Vehicle Class

Technology Package Description									Fuel Economy						Performance												
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW		0-10 MPH	0-50 MPH	0-70 MPH	60 MPH Top Gear ETW Grade Capability [A]	70 MPH Top-Gear ETW Grade Capability [A]
									mpg	mpg	mpg	%	%	%	sec	sec	sec	sec	mph	meters	%	gear	sec	sec	sec	%	%
Base-line	2.4L-4V I4 DCP	AT 4spd FDR 3.91	N	Mech except ePS	Bag1	base	base	N	24.8	35.9	28.8	-	-	-	3.8	10.4	3.7	6.0	24.6	16.7	14.8	2nd	1.2	7.5	13.5	3.6	3.1
Z	2.4L I4 DVVL + CCP	DCT 6spd FDR 3.10	Y	ePS ePump	Y	-20%	-10%	Y	33.4	43.8	37.4	35%	22%	30%	4.4	10.4	3.7	6.1	18.8	10.8	16.7	2nd	1.8	8.1	14.2	2.6	2.1
1	2.4L I4 DVVL + DCP GDI	CVT FDR 5.8	N	ePS ePump heAlt	Y	-20%	-10%	Y	29.0	39.4	32.9	17%	10%	14%	4.7	10.3	3.4	5.2	18.7	12.0	16.7	-	1.7	8.0	13.2	3.3	2.8
		CVT w/ revised ratio FDR 4.64							29.3	40.0	33.3	18%	11%	16%	4.7	10.3	3.4	5.2	18.7	12.0	16.7	-	1.7	8.0	13.2	3.3	2.8
		CVT w/ revised ratio FDR 4.90							29.4	39.7	33.3	19%	11%	16%	4.5	10.3	3.4	5.2	19.3	12.3	16.7	-	1.6	8.0	13.2	3.7	3.2
		CVT w/ revised ratio FDR 5.15							29.4	39.4	33.2	19%	10%	15%	4.3	10.0	3.4	5.2	20.3	13.0	16.7	-	1.6	7.7	12.9	4.2	3.8
		CVT w/ revised ratio FDR 5.50							29.4	38.8	33.0	19%	8%	14%	4.1	9.7	3.4	5.2	21.6	13.8	16.7	-	1.5	7.4	12.6	4.8	4.5
2	2.4L I4 DCP GDI	AT 6spd FDR 2.8	Y	ePS ePump	Y	-20%	-10%	Y	31.3	43.1	35.7	26%	20%	24%	3.8	10.7	4.5	6.9	24.5	16.1	16.9	2nd	1.2	8.3	15.2	1.9	1.4
5	1.9L I4 Diesel with aftertreatment	DCT 6spd FDR 3.00	N	ePS ePump heAlt	Y	-20%	-10%	Y	35.9	49.3	40.9	45%	37%	42%	3.9	10.4	3.9	6.3	24.1	12.9	13.1	3rd	1.7	7.8	14.1	4.8	5.2
15	1.5L I4 Turbo DCP GDI	DCT 6spd FDR 3.2	N	ePS ePump heAlt	Y	-20%	-10%	Y	33.4	43.1	37.2	35%	20%	29%	4.6	10.1	3.6	4.9	16.6	8.9	12.9	3rd	2.2	8.2	13.0	2.6	2.4
		DCT 6spd FDR 3.36							33.4	43.1	37.2	35%	20%	29%	4.4	9.8	3.3	5.2	17.8	9.5	13.6	3rd	2.1	7.7	12.9	3.1	2.9
		DCT 6spd FDR 3.52							33.4	42.9	37.1	35%	19%	29%	4.3	9.6	3.2	5.2	18.9	10.1	14.1	3rd	2.0	7.5	12.7	3.6	3.4
		DCT 6spd FDR 3.68							33.3	42.7	36.9	34%	19%	28%	4.1	9.5	3.2	5.2	20.0	10.7	14.6	3rd	1.9	7.3	12.5	4.1	3.9
Low Technology Readiness - 10 Years																											
15a	2.4L I4 Camless GDI	DCT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-20%	-10%	Y	34.7	47.1	39.3	40%	31%	37%	4.3	10.3	3.7	6.1	19.6	11.7	16.6	2nd	1.7	8.0	14.1	2.6	2.1
15b	2.4L I4 HCCI GDI	DCT 6 spd FDR 3.1	N	ePS ePump heAlt	Y	-20%	-10%	Y	33.6	46.1	38.3	36%	28%	33%	4.3	10.3	3.7	6.1	19.6	11.7	16.6	2nd	1.7	8.0	14.1	2.6	2.1

Footnote A: Top-gear grade capability is constrainted to the top gear and is used as an indication of torque reserve. See section 2 for discussion on performance metrics.

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table A-5: Full Size Car Vehicle Class CO_2 Emissions

Full Size Car Vehicle Class																											
Technology Package Description									**CO_2**						**Performance**												
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW		0-10 MPH	0-50 MPH	0-70 MPH	60 MPH Top Gear ETW Grade Capability ^{A}	70 MPH Top-Gear ETW Grade Capability ^{A}
									g/mi	g/mi	g/mi	%	%	%	sec	sec	sec	sec	mph	meters	%	gear	sec	sec	sec	%	%
Base-line	3.5L-4V V6	AT 5spd FDR 2.87	N	Mech	Bag1	base	base	N	420	279	356	-	-	-	2.6	6.7	2.3	3.8	33.7	24.6	24.6	2nd	0.8	4.9	8.7	6.4	5.9
4	2.2L I4 Turbo DCP GDI	AT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y	346	236	296	18%	15%	17%	2.6	6.6	2.3	3.4	33.7	22.0	25.6	2nd	1.0	5.0	8.4	4.8	5.0
5	2.8L I4/5 Diesel with aftertreatment	DCT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y	316	221	273	25%	21%	23%	2.6	7.1	2.7	4.3	33.8	21.7	18.5	4th	1.1	5.3	9.6	10.6	10.5
		DCT 6spd 6.55 span FDR 3.08							315	221	273	25%	21%	24%	2.5	7.1	2.7	4.3	34.3	22.4	18.5	4th	1.1	5.2	9.5	10.6	10.5
	2.8L I4/5 US Diesel with aftertreatment	DCT 6spd 6.55 span FDR 3.08							340	220	286	19%	21%	20%	2.5	7.1	2.7	4.3	34.3	22.4	18.5	4th	1.1	5.2	9.5	10.6	10.5
6a	3.0L V6 DCP + CVVL GDI	DCT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y	334	234	289	20%	16%	19%	3.3	7.3	2.3	3.3	26.8	16.8	26.1	2nd	1.2	5.7	8.9	4.7	4.3
		DCT 6spd FDR 3.20							338	237	293	19%	15%	18%	3.1	7.1	2.3	3.4	28.6	17.8	26.1	2nd	1.2	5.5	8.8	5.4	4.9
		DCT 6spd 6.55 span FDR 3.08							334	234	289	20%	16%	19%	3.1	7.0	2.3	3.5	28.7	17.9	25.6	2nd	1.2	5.5	8.9	4.7	4.3
16	3.5L V6 CCP + Deac GDI	AT 6spd FDR 2.7	Y	ePS ePump	Y	-20%	-10%	Y	301	205	257	28%	27%	28%	2.7	6.8	2.5	3.6	33.3	21.8	27.2	2nd	1.0	5.1	8.8	4.6	4.2
Low Technology Readiness - 10 Years																											
Y1	3.5L V6 Camless GDI	DCT 6spd FDR 2.80	N	ePS ePump heAlt	Y	-20%	-10%	Y	278	199	242	34%	29%	32%	3.1	6.8	2.2	3.2	29.3	17.9	28.7	2nd	1.2	5.3	8.5	4.9	4.6
Y2	3.5L V6 HCCI GDI	DCT 6spd FDR 2.80	N	ePS ePump heAlt	Y	-20%	-10%	Y	290	197	248	31%	29%	30%	3.1	6.8	2.2	3.2	29.3	17.9	28.7	2nd	1.2	5.3	8.5	4.9	4.6

Footnote A: Top-gear grade capability is constrainted to the top gear and is used as an indication of torque reserve. See section 2 for discussion on performance metrics.

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table A-6: Full Size Car Vehicle Class Fuel Economy

Full Size Car Vehicle Class																												
Technology Package Description									Fuel Economy						Performance													
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW		0-10 MPH	0-50 MPH	0-70 MPH	60 MPH Top Gear ETW Grade Capability ^{A}	70 MPH Top-Gear ETW Grade Capability ^{A}
									mpg	mpg	mpg	%	%	%	sec	sec	sec	sec	mph	meters	%	gear	sec	sec	sec	%	%
Base-line	3.5L-4V V6	AT 5spd FDR 2.87	N	Mech	Bag1	base	base	N	21.7	32.6	25.5	-	-	-	2.6	6.7	2.3	3.8	33.7	24.6	24.6	2nd	0.8	4.9	8.7	6.4	5.9
4	2.2L I4 Turbo DCP GDI	AT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y	26.3	38.5	30.7	21%	18%	20%	2.6	6.6	2.3	3.4	33.7	22.0	25.6	2nd	1.0	5.0	8.4	4.8	5.0
5	2.8L I4/5 Diesel with aftertreatment	DCT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y	31.9	45.8	37.0	47%	40%	45%	2.6	7.1	2.7	4.3	33.8	21.7	18.5	4th	1.1	5.3	9.6	10.6	10.5
		DCT 6spd 6.55 span FDR 3.08							32.1	45.7	37.0	48%	40%	45%	2.5	7.1	2.7	4.3	34.3	22.4	18.5	4th	1.1	5.2	9.5	10.6	10.5
	2.8L I4/5 US Diesel with aftertreatment	DCT 6spd 6.55 span FDR 3.08							29.7	45.9	35.3	37%	41%	38%	2.5	7.1	2.7	4.3	34.3	22.4	18.5	4th	1.1	5.2	9.5	10.6	10.5
6a	3.0L V6 DCP + CVVL GDI	DCT 6spd FDR 3.08	N	ePS ePump heAlt	Y	-20%	-10%	Y	27.2	38.8	31.4	25%	19%	23%	3.3	7.3	2.3	3.3	26.8	16.8	26.1	2nd	1.2	5.7	8.9	4.7	4.3
		DCT 6spd FDR 3.20							26.9	38.3	31.0	24%	18%	22%	3.1	7.1	2.3	3.4	28.6	17.8	26.1	2nd	1.2	5.5	8.8	5.4	4.9
		DCT 6spd 6.55 span FDR 3.08							27.2	38.8	31.4	26%	19%	23%	3.1	7.0	2.3	3.5	28.7	17.9	25.6	2nd	1.2	5.5	8.9	4.7	4.3
16	3.5L V6 CCP + Deac GDI	AT 6spd FDR 2.7	Y	ePS ePump	Y	-20%	-10%	Y	30.2	44.4	35.3	40%	36%	38%	2.7	6.8	2.5	3.6	33.3	21.8	27.2	2nd	1.0	5.1	8.8	4.6	4.2
Low Technology Readiness - 10 Years																												
Y1	3.5L V6 Camless GDI	DCT 6spd FDR 2.80	N	ePS ePump heAlt	Y	-20%	-10%	Y	32.7	45.7	37.5	51%	40%	47%	3.1	6.8	2.2	3.2	29.3	17.9	28.7	2nd	1.2	5.3	8.5	4.9	4.6
Y2	3.5L V6 HCCI GDI	DCT 6spd FDR 2.80	N	ePS ePump heAlt	Y	-20%	-10%	Y	31.4	46.1	36.6	45%	42%	44%	3.1	6.8	2.2	3.2	29.3	17.9	28.7	2nd	1.2	5.3	8.5	4.9	4.6

Footnote A: Top-gear grade capability is constrainted to the top gear and is used as an indication of torque reserve. See section 2 for discussion on performance metrics.

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table A-7: Large MPV Vehicle Class CO_2 Emissions

Large MPV Vehicle Class																											
Technology Package Description									CO_2						Performance												
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW		0-10 MPH	0-50 MPH	0-70 MPH	60 MPH Top Gear ETW Grade Capability ^{A}	70 MPH Top-Gear ETW Grade Capability ^{A}
									g/mi	g/mi	g/mi	%	%	%	sec	sec	sec	sec	mph	meters	%	gear	sec	sec	sec	%	%
Base-line	3.8L-2V V6	AT 4spd FDR 3.43	N	Mech	Bag1	base	base	N	458	313	393	-	-	-	3.3	9.3	3.5	5.6	27.5	16.9	17.7	2nd	1.3	6.8	12.4	5.7	5.2
4	2.1L I4 Turbo DCP GDI	AT 6spd FDR 3.17	N	ePS ePump heAlt	Y	-20%	-10%	Y	357	256	312	22%	18%	21%	3.2	8.0	2.8	4.3	27.8	16.5	17.1	3rd	1.3	6.0	10.3	4.3	4.5
6b	3.0L V6 CCP + Deac GDI	DCT 6spd FDR 3.17	N	ePS ePump heAlt	Y	-20%	-10%	Y	335	245	295	27%	22%	25%	3.9	8.5	2.8	4.2	21.3	11.9	16.8	3rd	1.7	6.7	10.9	4.5	3.8
		DCT 6spd FDR 3.72							333	248	295	27%	21%	25%	3.5	8.1	2.7	4.2	24.5	13.6	19.7	3rd	1.6	6.2	10.4	5.9	5.2
		DCT 6spd FDR 3.00							338	243	295	26%	22%	25%	4.1	8.7	2.8	4.1	20.1	11.3	15.5	3rd	1.8	6.9	11.0	4.0	3.5
	2.7L V6 CCP + Deac GDI	DCT 6spd FDR 3.72							323	244	287	30%	22%	27%	3.8	8.9	3.0	4.8	21.7	12.1	17.4	3rd	1.7	6.8	11.6	5.0	4.3
16	3.8L V6 CCP + Deac GDI	AT 6spd FDR 2.7	Y	ePS ePump	Y	-20%	-10%	Y	325	225	280	29%	28%	29%	3.3	9.3	3.4	5.6	27.1	15.6	17.0	2nd	1.4	6.7	12.3	4.0	3.6

Footnote A: Top-gear grade capability is constrainted to the top gear and is used as an indication of torque reserve. See section 2 for discussion on performance metrics.

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table A-8: Large MPV Vehicle Class Fuel Economy

Large MPV Vehicle Class

Technology Package Description									Fuel Economy						Performance												
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	70 MPH Grade Capability at ETW		0-10 MPH	0-50 MPH	0-70 MPH	60 MPH Top Gear ETW Grade Capability ^{A}	70 MPH Top-Gear ETW Grade Capability ^{A}
									mpg	mpg	mpg	%	%	%	sec	sec	sec	sec	mph	meters	%	gear	sec	sec	sec	%	%
Base-line	3.8L-2V V6	AT 4spd FDR 3.43	N	Mech	Bag1	base	base	N	19.8	29.0	23.1	-	-	-	3.3	9.3	3.5	5.6	27.5	16.9	17.7	2nd	1.3	6.8	12.4	5.7	5.2
4	2.1L I4 Turbo DCP GDI	AT 6spd FDR 3.17	N	ePS ePump heAlt	Y	-20%	-10%	Y	25.5	35.4	29.2	28%	22%	26%	3.2	8.0	2.8	4.3	27.8	16.5	17.1	3rd	1.3	6.0	10.3	4.3	4.5
6b	3.0L V6 CCP + Deac GDI	DCT 6spd FDR 3.17	N	ePS ePump heAlt	Y	-20%	-10%	Y	27.1	37.1	30.9	37%	28%	33%	3.9	8.5	2.8	4.2	21.3	11.9	16.8	3rd	1.7	6.7	10.9	4.5	3.8
		DCT 6spd FDR 3.72							27.3	36.6	30.8	38%	26%	33%	3.5	8.1	2.7	4.2	24.5	13.6	19.7	3rd	1.6	6.2	10.4	5.9	5.2
		DCT 6spd FDR 3.00							26.9	37.4	30.8	36%	29%	33%	4.1	8.7	2.8	4.1	20.1	11.3	15.5	3rd	1.8	6.9	11.0	4.0	3.5
	2.7L V6 CCP + Deac GDI	DCT 6spd FDR 3.72							28.2	37.3	31.6	42%	28%	37%	3.8	8.9	3.0	4.8	21.7	12.1	17.4	3rd	1.7	6.8	11.6	5.0	4.3
16	3.8L V6 CCP + Deac GDI	AT 6spd FDR 2.7	Y	ePS ePump	Y	-20%	-10%	Y	28.0	40.3	32.4	41%	39%	40%	3.3	9.3	3.4	5.6	27.1	15.6	17.0	2nd	1.4	6.7	12.3	4.0	3.6

Footnote A: Top-gear grade capability is constrainted to the top gear and is used as an indication of torque reserve. See section 2 for discussion on performance metrics.

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table A-9: Truck Vehicle Class CO_2 Emissions

Truck Vehicle Class																												
Technology Package Description									CO_2						Performance													
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	60 MPH Grade Capability at GCW		0-10 MPH	0-50 MPH	0-70 MPH	60 MPH Top Gear ETW Grade Capability ^{A}	70 MPH Top-Gear ETW Grade Capability ^{A}	60 MPH Top Gear GCW Grade Capability ^{A}
									g/mi	g/mi	g/mi	%	%	%	sec	sec	sec	sec	mph	meters	%	gear	sec	sec	sec	%	%	%
Base-line	5.4L-3V V8 CCP	AT 4spd FDR 3.73	N	Mech	Bag1	base	base	N	612	402	517	-	-	-	2.6	7.7	3.0	4.6	33.6	23.3	8.8	2nd	0.9	5.6	10.2	6.2	5.7	2.6
6-Spd AT	5.4L-3V V8 CCP	AT 6spd FDR 3.60	N	Mech	Bag1	base	base	N	586	396	500	x	x	x	2.3	7.5	2.9	5.0	35.9	26.2	8.5	3rd	0.7	5.2	10.2	5.5	5.0	2.3
9	5.4L-3V V8 CCP + Deac GDI	DCT 6spd FDR 3.3	Y	ePS ePump	Y	-10%	base	Y	432	315	379	29%	22%	27%	2.7	7.8	2.8	4.6	32.7	21.1	8.4	3rd	1.0	5.5	10.1	5.3	4.8	2.2
10	3.6L V6 Turbo DCP GDI	DCT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-10%	base	Y	404	319	366	34%	21%	29%	2.9	6.7	2.2	3.5	31.5	19.3	12.3	2nd	1.2	5.1	8.6	6.1	5.6	2.5
		DCT 6spd FDR 3.26							416	321	373	32%	20%	28%	2.8	6.4	2.2	3.6	32.6	19.8	12.5	2nd	1.1	5.0	8.6	6.9	6.2	2.8
		DCT 6spd FDR 3.41							418	323	376	32%	19%	27%	2.7	6.4	2.2	3.6	33.5	20.5	13.0	2nd	1.1	4.9	8.5	7.4	6.7	3.1
		DCT 6spd FDR 3.57							421	325	378	31%	19%	27%	2.6	6.3	2.2	3.6	35.5	21.4	12.9	2nd	1.1	4.8	8.4	8.0	7.3	3.3
11	4.8L V6 Diesel with aftertreatment	DCT 6spd FDR 3.15	N	ePS ePump heAlt	Y	-10%	base	Y	444	326	391	27%	19%	24%	2.7	7.7	2.7	4.7	32.5	20.4	10.2	3rd	1.2	5.5	10.2	8.0	9.0	3.3
12	5.4L-3V V8 CCP + Deac GDI	AT 6spd FDR 3.1	Y	ePS ePump	Y	-10%	base	Y	459	328	400	25%	18%	23%	2.4	7.5	2.9	4.9	35.6	25.2	10.7	2nd	0.8	5.2	10.1	4.7	4.1	1.9
17	5.4L V8 DVVL + DCP GDI	AT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-10%	base	Y	492	333	420	20%	17%	19%	2.2	7.1	2.7	4.5	37.1	27.3	10.7	2nd	0.7	4.9	9.4	4.7	4.1	2.0
Low Technology Readiness - 10 Years																												
X1	5.4L V8 Camless GDI	DCT 6spd FDR 3.35	N	ePS ePump heAlt	Y	-10%	base	Y	422	314	374	31%	22%	28%	2.7	7.7	2.8	4.6	32.8	21.2	8.6	3rd	1.0	5.5	10.0	5.5	5.0	2.4
X2	5.4L V8 HCCI GDI	DCT 6spd FDR 3.35	N	ePS ePump heAlt	Y	-10%	base	Y	425	311	374	31%	23%	28%	2.7	7.7	2.8	4.6	32.8	21.2	8.6	3rd	1.0	5.5	10.0	5.5	5.0	2.4

Footnote A: Top-gear grade capability is constrainted to the top gear and is used as an indication of torque reserve. See section 2 for discussion on performance metrics.

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied

Table A-10: Truck Vehicle Class Fuel Economy

Truck Vehicle Class																												
Technology Package Description									Fuel Economy						Performance													
EPA Package Identifier	Engine	Transmission	42V Stop-Start	Accessories	Warm-up Model	Aero Drag	Rolling Resistance	Frictional Multiplier	FTP75 (City)	HWFET (Highway)	Combined (Metro-Highway)	FTP75 (City) Benefit	HWFET (Highway) Benefit	Combined (Metro-Highway) Benefit	0-30 MPH	0-60 MPH	30-50 MPH	50-70 MPH	Vel at 3 sec	Dist at 3 sec	60 MPH Grade Capability at GCW		0-10 MPH	0-50 MPH	0-70 MPH	60 MPH Top Gear ETW Grade Capability [A]	70 MPH Top-Gear ETW Grade Capability [A]	60 MPH Top Gear GCW Grade Capability [A]
									mpg	mpg	mpg	%	%	%	sec	sec	sec	sec	mph	meters	%	gear	sec	sec	sec	%	%	%
Base-line	5.4L-3V V8 CCP	AT 4spd FDR 3.73	N	Mech	Bag1	base	base	N	14.9	22.6	17.6	-	-	-	2.6	7.7	3.0	4.6	33.6	23.3	8.8	2nd	0.9	5.6	10.2	6.2	5.7	2.6
6-Spd AT	5.4L-3V V8 CCP	AT 6spd FDR 3.60	N	Mech	Bag1	base	base	N	15.5	23.0	18.2	x	x	x	2.3	7.5	2.9	5.0	35.9	26.2	8.5	3rd	0.7	5.2	10.2	5.5	5.0	2.3
9	5.4L-3V V8 CCP + Deac GDI	DCT 6spd FDR 3.3	Y	ePS ePump	Y	-10%	base	Y	21.0	28.9	23.9	41%	28%	36%	2.7	7.8	2.8	4.6	32.7	21.1	8.4	3rd	1.0	5.5	10.1	5.3	4.8	2.2
10	3.6L V6 Turbo DCP GDI	DCT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-10%	base	Y	22.5	28.5	24.9	52%	26%	42%	2.9	6.7	2.2	3.5	31.5	19.3	12.3	2nd	1.2	5.1	8.6	6.1	5.6	2.5
		DCT 6spd FDR 3.26							21.8	28.3	24.3	47%	25%	39%	2.8	6.4	2.2	3.6	32.6	19.8	12.5	2nd	1.1	5.0	8.6	6.9	6.2	2.8
		DCT 6spd FDR 3.41							21.7	28.1	24.2	46%	24%	38%	2.7	6.4	2.2	3.6	33.5	20.5	13.0	2nd	1.1	4.9	8.5	7.4	6.7	3.1
		DCT 6spd FDR 3.57							21.6	27.9	24.1	46%	23%	37%	2.6	6.3	2.2	3.6	35.5	21.4	12.9	2nd	1.1	4.8	8.4	8.0	7.3	3.3
11	4.8L V6 Diesel with aftertreatment	DCT 6spd FDR 3.15	N	ePS ePump heAlt	Y	-10%	base	Y	22.7	31.0	25.8	53%	37%	47%	2.7	7.7	2.7	4.7	32.5	20.4	10.2	3rd	1.2	5.5	10.2	8.0	9.0	3.3
12	5.4L-3V V8 CCP + Deac GDI	AT 6spd FDR 3.1	Y	ePS ePump	Y	-10%	base	Y	19.8	27.7	22.7	33%	23%	29%	2.4	7.5	2.9	4.9	35.6	25.2	10.7	2nd	0.8	5.2	10.1	4.7	4.1	1.9
17	5.4L V8 DVVL + DCP GDI	AT 6spd FDR 3.1	N	ePS ePump heAlt	Y	-10%	base	Y	18.5	27.3	21.6	24%	21%	23%	2.2	7.1	2.7	4.5	37.1	27.3	10.7	2nd	0.7	4.9	9.4	4.7	4.1	2.0
Low Technology Readiness - 10 Years																												
X1	5.4L V8 Camless GDI	DCT 6spd FDR 3.35	N	ePS ePump heAlt	Y	-10%	base	Y	21.5	28.9	24.3	45%	28%	38%	2.7	7.7	2.8	4.6	32.8	21.2	8.6	3rd	1.0	5.5	10.0	5.5	5.0	2.4
X2	5.4L V8 HCCI GDI	DCT 6spd FDR 3.35	N	ePS ePump heAlt	Y	-10%	base	Y	21.4	29.2	24.3	44%	29%	38%	2.7	7.7	2.8	4.6	32.8	21.2	8.6	3rd	1.0	5.5	10.0	5.5	5.0	2.4

Footnote A: Top-gear grade capability is constrainted to the top gear and is used as an indication of torque reserve. See section 2 for discussion on performance metrics.

Engine Terminology: I4 = Inline 4 cylinder, V8 = Vee-engine 8 cylinders, 2/3/4v = 2/3/4 valves/cylinder, GDI = Gasoline Direct Injection (Stoichiometric), DCP = Dual Cam Phasers, CCP = Coordinated Cam Phasers, ICP = Intake Cam Phaser, DVVL = Discrete Variable Valve Lift, CVVL = Continuously Variable Valve Lift, Deac = Cylinder Deactivation, HCCI = Homogenous Charge Compression Ignition

Transmission Terminology: AT = Automatic Trans, DCT = Dual-Clutch Trans (Dry clutch for Std Car, Wet clutch for all others), CVT = Continuously Variable Trans, FDR = Final Drive Ratio

Accessories Terminology: Mech = Mechanically-driven accessories, ePS = electric Power Steering, ePump = electric engine oil and coolant pumps, heAlt = High-efficiency Alternator

Warm-up Model Terminology: Bag1 = Correction factor for Bag1 is 0.8*Bag3, Y = Physics-based engine warm-up model applied