Program Record (Offices: Fuel Cell Technologies & Vehicle Technologies)	
Record #: 16009	**Date:** May 25, 2016
Title: Life-Cycle Costs of Mid-Size Light-Duty Vehicles	
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Items

The U.S. Department of Energy (DOE) is pursuing a portfolio of technologies with the potential to significantly reduce greenhouse gas (GHG) emissions and petroleum consumption while being cost-effective. This record documents the assumptions and results of analyses conducted to estimate the life-cycle costs resulting from several fuel/vehicle pathways, for a generic future mid-size car. The results are summarized below.

The costs range from about 19 cents to 25 cents per mile for all advanced technologies, compared to 21 cents per mile for today's gasoline vehicle (non-hybrid, $3.53 per gallon of gasoline), assuming 15-year ownership.[1] For 5-year ownership, costs range from 34 to 43 cents per mile compared to 35 cents per mile for today's gasoline vehicle (non-hybrid). However, if gasoline prices reached $5.64 per gallon, the gasoline vehicle's life-cycle cost would be similar to that of the 90-mile range battery electric vehicle BEV90 (both would be higher than the cost of any of the other advanced technology options) under the 5-year ownership scenario, and higher than those of all the advanced options, including the BEV90, under the 15-year ownership scenario.

Data, Assumptions, References

- Results for all pathways are based on a projected state of the technologies in 2035 (costs shown in 2013 dollars) based on improvements resulting from DOE's R&D portfolio, including light-weight materials, advanced combustion engines, motors, generators, batteries, fuel cells, and on-board storage systems for natural gas and hydrogen fuel.
- Fuel economies were determined using Argonne National Laboratory's (ANL's) Autonomie modeling simulation software (http://www.autonomie.net). Only on-road fuel economy numbers are shown in this document, i.e., using EPA-suggested methodologies for adjusting dynamometer test results to account for realistic driving behavior ("on-road" performance) based on 43% city and 57% highway driving.
- Fuel economy estimates for vehicles are based on the gallon gasoline energy equivalent (gge) of each applicable fuel, approximately 112,200 Btu (lower heating value of E10).

The vehicles analyzed included:

- A gasoline vehicle with an internal combustion engine of the spark-ignition type (ICEV Gasol)
- A diesel vehicle with an internal combustion engine of the compressed-ignition type (ICEV Diesel)
- A natural gas vehicle with an internal combustion engine of the spark-ignition type (ICEV N gas)
- A hybrid-electric vehicle (HEV) with a spark-ignition gasoline engine (HEV Gasol)
- A plug-in hybrid electric vehicle with a charge-depleting (CD) range of 10 miles (PHEV10 Gasol) that is powered by an electric motor and a spark-ignition gasoline engine that can both provide torque to the wheels[2]
- A 35-mile (CD-range) plug-in vehicle of the extended-range electric vehicle (EREV)[3] type (EREV35 Gasol) that is powered by an electric motor and a spark-ignition gasoline engine

[1] High-volume modeled costs assumed for all technology options.
[2] When in charge-depleting mode, the engine may still activate to assist the electric drive.
[3] The powertrain configuration used for the EREV is VOLTEC (name given by GM to the configuration used in the

- A fuel cell hybrid-electric vehicle (FCEV)
- Three battery electric vehicles with respective on-road ranges of 90, 140, and 210 miles—BEV90, BEV140, and BEV210.

Each vehicle's minimum driving range is approximately 320 miles, except where noted for the electric range of the PHEV10, EREV35, and BEVs. The PHEV and EREV have a gasoline-only range of approximately 320 miles (in addition to their stated electric ranges).

Fuel Economy Results in Years of Deployment

Tables 1 and 2 show the fuel economy results generated by Autonomie for three technology achievement levels: low, medium, and high technical progress. Table 1 shows the results for non-electric vehicles and the charge-sustaining mode of the PHEV and EREV in miles per gallon gasoline energy equivalent (Mpgge). Table 2 shows the overall fuel economy results.

Data & Assumptions

The following material provides details on the methodology and assumptions used to estimate the cost of ownership of future light-duty vehicles (excluding insurance, maintenance,[4] and taxes).

Table 1. On-Road Fuel Economy in 2035–Mpgge and Wh/Mile (before accounting for electric vehicle supply system/battery losses for plug-in vehicles)

	On-Road Fuel Economy of Light-Duty Vehicles in 2035									
	ICEV Gasol	ICEV Diesel	ICEV Ngas	HEV Gasol	PHEV10 Gasol	EREV35 Gasol	FCEV	BEV90	BEV140	BEV210
	Medium Technical Progress									
Charge Sustaining, mpgge										
Non-Electric Fuel, mpgge	39.7	45.2	36.2	65.6	65.9	64.4	91.6			
Charge Depleting										
Electricity, Wh/mi					170	230		228	234	251
Non-Electric Fuel, mpgge					201					
	Low Technical Progress									
Charge Sustaining, mpgge										
Non-Electric Fuel, mpgge	34.5	39.4	32.3	55.1	54.5	47.3	75.3			
Charge Depleting										
Electricity, Wh/mi					197	275		266	274	295
Non-Electric Fuel, mpgge					162					
	High Technical Progress									
Charge Sustaining, mpgge										
Non-Electric Fuel, mpgge	46.1	52.5	41.8	78.8	79.4	80.8	110			
Charge Depleting										
Electricity, Wh/mi					146	194		196	201	214
Non-Electric Fuel, mpgge					243					

1. The PHEV10 can operate in a blended mode in the charge-depleting phase if needed. The EREV40 uses only electricity when operating in the charge-depleting mode.
2. The current reference gasoline vehicle's fuel economy is 27 mpg.
3. Major inputs to the calculation of costs of ownership include the price of each vehicle and the annual fuel costs. The retail price of the vehicle is assumed to be 1.5 times the sum of the vehicle component costs to reflect such items as manufacturer overhead and markup costs, transportation costs, and dealer markup.

Chevy Volt). During the charge-depleting mode, only the electric machines are used to propel the vehicle. Four modes of operations are available: one-motor electric vehicle (EV), two-motor EV, series, and power split.

[4] Durability of key components (such as batteries and fuel cells) is assumed to last over the entire ownership period. Regarding maintenance in general, it is likely that each type of car will exhibit different maintenance needs. However, this analysis did not try to calculate maintenance costs because in a few years there will be more data for this purpose.

Table 2. On-Road Fuel Economy in 2035 (Combined Electric & Non-Electric—Plug-in Light-Duty Vehicles [LDVs])—in Mpgge (before accounting for electric vehicle supply system/battery losses for plug-in vehicles)

On-Road Fuel Economy in 2035 (Combined Electric & Non-Electric—Plug-in LDVs)—in Mpgge									
ICEV Gasol	ICEV Diesel	ICEV Ngas	HEV Gasol	PHEV10 Gasol	EREV35 Gasol	FCEV	BEV90	BEV140	BEV210
Medium Technical Progress									
39.7	45.2	36.2	65.6	71.4	94.9	91.6	144	140	131
Low Technical Progress									
34.5	39.4	32.3	55.1	59.0	73.3	75.3	124	120	111
High Technical Progress									
46.1	52.5	41.8	78.8	85.7	116	110	167	163	153

The following formulas were used to obtain combined fuel economy for plug-in LDVs:

Combined #Btus/mi = Uf x #Wh/mi x (3,412 Btus/Wh) + (1-Uf) x #Gge/mi x 112,200 Btus/Gge

Combined mpgge = (1/Combined #Btus/mi) x 112,200 Btus/Gge

Uf is utility factor, i.e., fraction of driving distance in CD mode

- Two cases are presented: (a) ownership period of 5 years (the owner will sell after 5 years) with 17.5% loss in value per year (within range of midsize cars' depreciation estimated for 2013–2016 cars by Kelley Blue Book, http://www.kbb.com/new-cars/best-resale-value-awards), resulting in a resale value at about 38% of the purchase price; and (b) ownership period that is the same as the assumed 15-year car life (with no resale value at the end), assuming the consumer pays up front for the vehicle and a 5% real discount rate for future fuel purchases (this financial scenario was chosen for simplicity's sake, and, as long as all the vehicles are treated the same way, assuming a car loan or not should not matter that much). The cars' numbers of annual miles per year for the 5-year ownership case and 15-year ownership case are from Table 7 featured in the U.S. Department of Transportation's Vehicle Survivability and Travel Mileage Schedule (NHTSA Report No. DOT HS 809 952, January 2006),[5] with that of BEV90 reduced to 70% of the other (longer range) vehicles.
- Major subsystems (i.e., batteries and fuel cells) are assumed to last through the ownership period.
- The efficiency factor associated with combined losses for electric vehicle supply equipment and batteries is assumed to be 98%, 95%, and 92% (i.e., of efficiency loss of 2%, 5%, and 8%) as high, medium and low values (losses assumed unchanging throughout vehicle ownership period).
- Baseline fuel prices (including taxes) other than natural gas and hydrogen are from the Energy Information Administration's (EIA's) Annual Energy Outlook (AEO) 2015 Reference Case (2013 dollars): $3.53 per gallon of gasoline, $3.75 per gge diesel, $17.12 per mmBtu CNG ($1.92 per gge), and 13.9¢/kWh residential electricity ($4.57 per gge). For the baseline (i.e., medium) price of hydrogen, $3.50 per gge was used. This is slightly higher than the average price of hydrogen that would enable FCEVs to be competitive with gasoline HEVs (DOE's Record No. 11007).
- Fuel sensitivity analysis used projected Year 2035 prices for gasoline and diesel from AEO 2015's high and low oil price cases (except as noted below):
  - Gasoline at $2.52 and $5.64 per gallon
  - Diesel at $2.60 and $6.02 per gge
  - Electricity at 13.6¢ and 15.0/kWh (residential rates)
  - CNG at $18.7 and $21.4 per mmBtu (note that EIA projected higher CNG prices in the Low Oil Price scenario compared to the Reference Scenario), or $2.10 and $2.40 per gge[6]

[5] For the 15-year scenario, annual mileage starts at 14,230 miles in 1st year, decreasing to 9,250 miles in 15th year (lifetime 178,000 miles).

[6] CNG prices include motor vehicle fuels taxes and dispensing costs, like those of petroleum fuels.

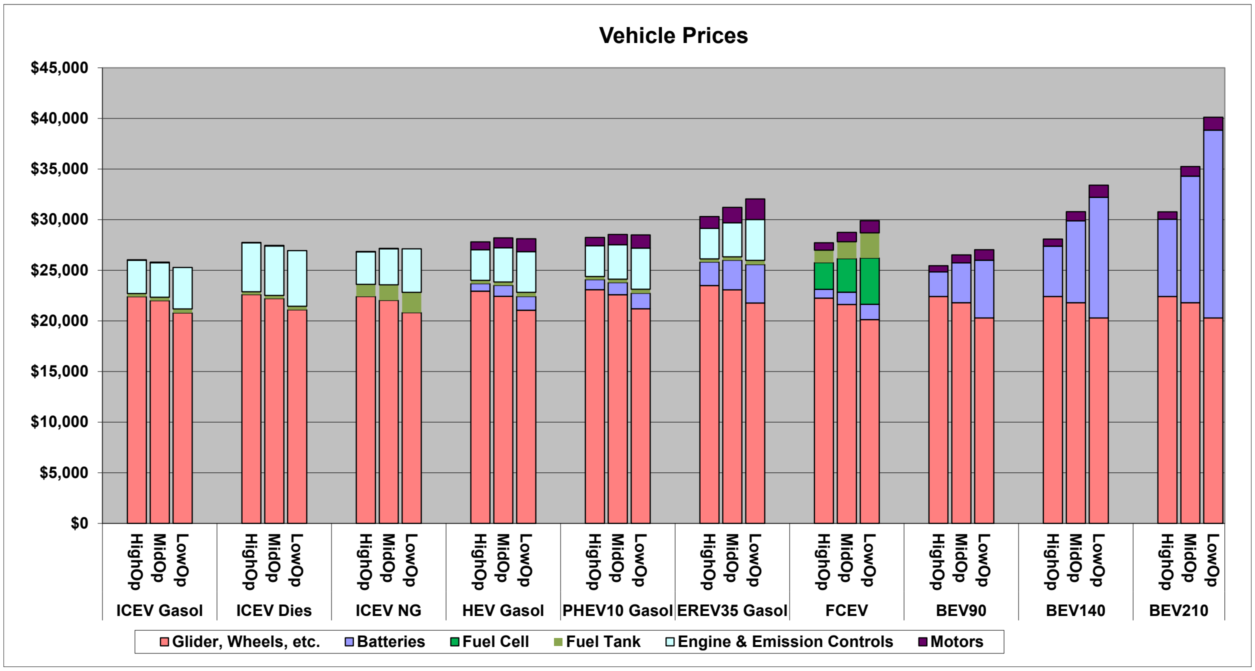


Figure 1. Vehicle Prices in 2035 (three levels of technical progress)[7]

- Hydrogen at $2.50 and $5.00 per gge: the high value is based on an analysis using current (not future) technology and relatively high natural gas prices from AEO 2009 (DOE's Record No. 12024).[8]

Figure 1 shows vehicle retail prices and Table 3 summarizes the major unit cost assumptions.

Table 3. Unit Cost Assumptions for Year 2035 LDVs

	Battery Cost, $/kW for HEVs and FCEVs	Battery Cost, $/Usable kWh for PHEVs, EREV & BEVs	Cost of Natural Gas or H2 Tank, $/kWh	Fuel Cell Cost, $/kW
ICEV Gasol				
ICEV Dies				
ICEV NG			$2.8 ($2.4 - $3.3)	
HEV Gasol	$23 ($19 - $25)			
PHEV10 Gasol		$373 ($370 - $391)		
EREV35 Gasol		$257 ($254 - $269)		
FCEV	$23 ($19 - $25)		$9.5 ($8.2 - $11.7)	$34 ($30 - $40)
BEV (90, 140, 210)		$167 ($120 - $209)		

Usable kWh is a measure of the available fraction of total battery capacity: Vehicle manufacturers use electronics to restrict how fully a battery can be charged and how far the vehicle is able to deplete the charge in its battery. They make different choices for the usable capacity of their batteries because it is known that this factor affects the degradation of the battery over time. The state of charge (SOC) does not go from 0 to 100 percent and

7 Motors' prices include the costs of integrated power electronics.

8 Assuming high-volume markets and >80% utilization rate for fueling stations.

therefore usable capacity is always less than total capacity. Total capacity is what the batteries can store as their SOC goes from fully discharged—SOC of 0 percent—to fully charged, i.e., 100 percent (adapted from http://www.nap.edu/read/21725/chapter/4#22).

Cost Formulas

The following formulas were used to compute the net present value of the fuel and electricity costs per mile:

Fuel Cost Equation

$$\mathrm{NPV_{fuel/mi}} = \frac{\left(\sum_{n=1}^{N} \left(\mathrm{P}_f \,/\, \mathrm{mpg} \,*\, \mathrm{VMT}_n\right) / (1 + \mathrm{i})^n\right.}{\mathrm{TotalVMT}_N}$$

Electricity Cost Equation

$$\mathrm{NPV_{electric/mi}} = \frac{\left(\sum_{n=1}^{N} \left(\mathrm{P}_e \,*\, \mathrm{kWhpM} \,*\, \mathrm{VMT}_n\right) / (1 + \mathrm{i})^n\right.}{\mathrm{TotalVMT}_N}$$

Where:
n = year index
N = ownership period in years
P_f = fuel price ($/gal)
mpg = fuel economy in miles per gallon
P_e = electricity price ($/kWh)
kWhpM = kWh per mile
$\mathrm{TotalVMT_N}$ = total vehicle miles traveled over the N-year ownership period
i = discount rate
$\mathrm{NPV_{fuel/mi}}$ = net present value of fuel cost in $ per mile
$\mathrm{NPV_{electric/mi}}$ = net present value of electricity cost in $ per mile

The Fuel Cost Equation is used for vehicles fueled by gasoline, diesel, natural gas, and hydrogen. The Electricity Cost Equation is used for BEVs. Both equations are used for vehicles that operate on both grid electricity and gasoline (PHEV10 and EREV35) by weighting the electricity and fuel costs by the percent of time the vehicle is driven on grid electricity and fuel, respectively. The term "utility factor" is used to refer to the percent of time the vehicle is driven on grid electricity. For the PHEV10 and EREV35, the Society of Automotive Engineers specified (in SAE J2841) utility factors at 23% and 58.5%, respectively.

Vehicle Cost Equation

The vehicle price (minus discounted resale value) was divided by the number of lifetime miles to get the NPV of the vehicle cost per mile.

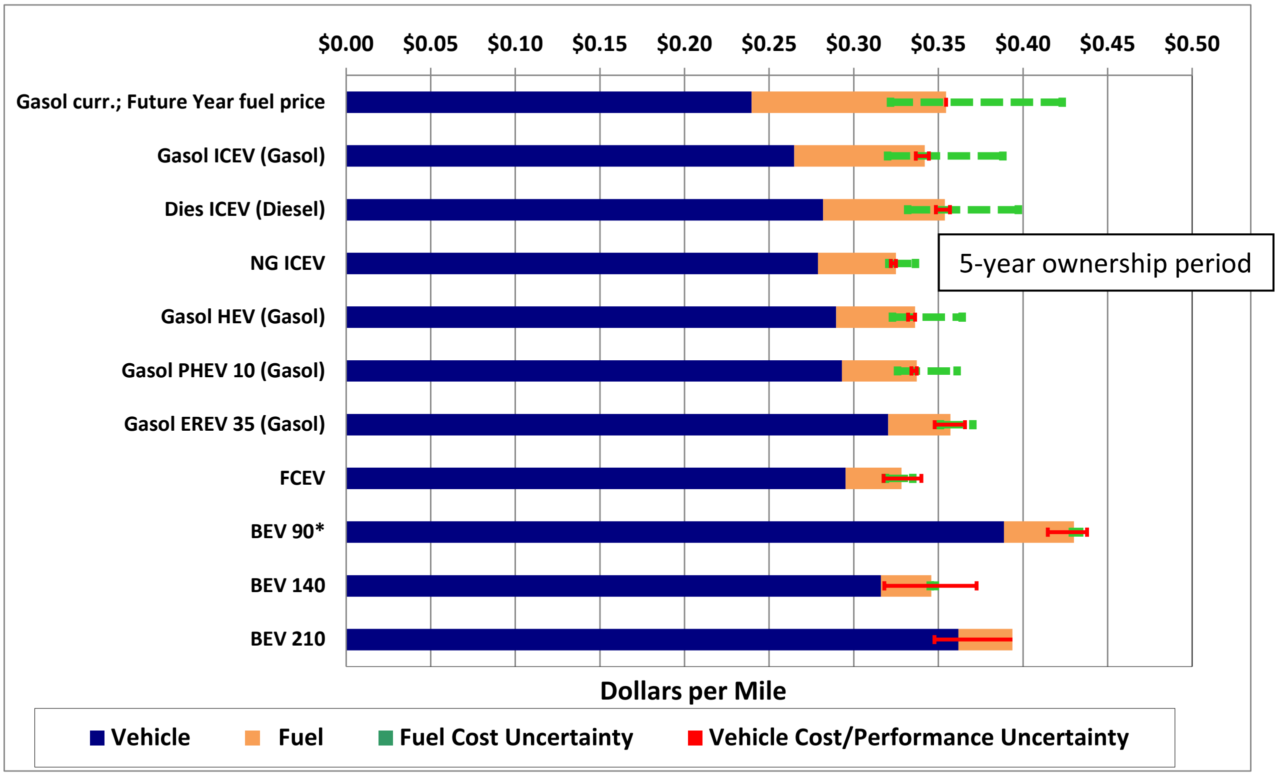
$$\mathrm{NPV_{vehi/mi}} = \left(\mathrm{P_v} - \left(\frac{\mathrm{R_v}}{(1+\mathrm{i})^{\mathrm{n}}}\right)\right)/(\mathrm{n} * \mathrm{VMT})$$

Where:
P_v = price of new vehicle
R_v = vehicle resale value at the end of ownership period

Cost-of-Ownership Results (Excluding Insurance, Maintenance, and Taxes; Based on Prices of Vehicles = 1.5 × Manufacture Costs)

Figures 2 and 3 show life-cycle costs for the 5-year and 15-year ownership periods. Life-cycle costs were calculated for each ownership period, assuming 17.5% annual loss in value for the 5-year case and no resale value for the 15-year case. In each figure, the low/high error bars (sensitivity bands) illustrate uncertainties associated with projecting future vehicle performance and fuel prices. The green sensitivity bands show the effects of variations in the fuel costs and the sensitivity bands show the effects of non-fuel-related uncertainties (three levels of technical progress), including manufactured component costs and ranges of fuel economy of the associated vehicles:

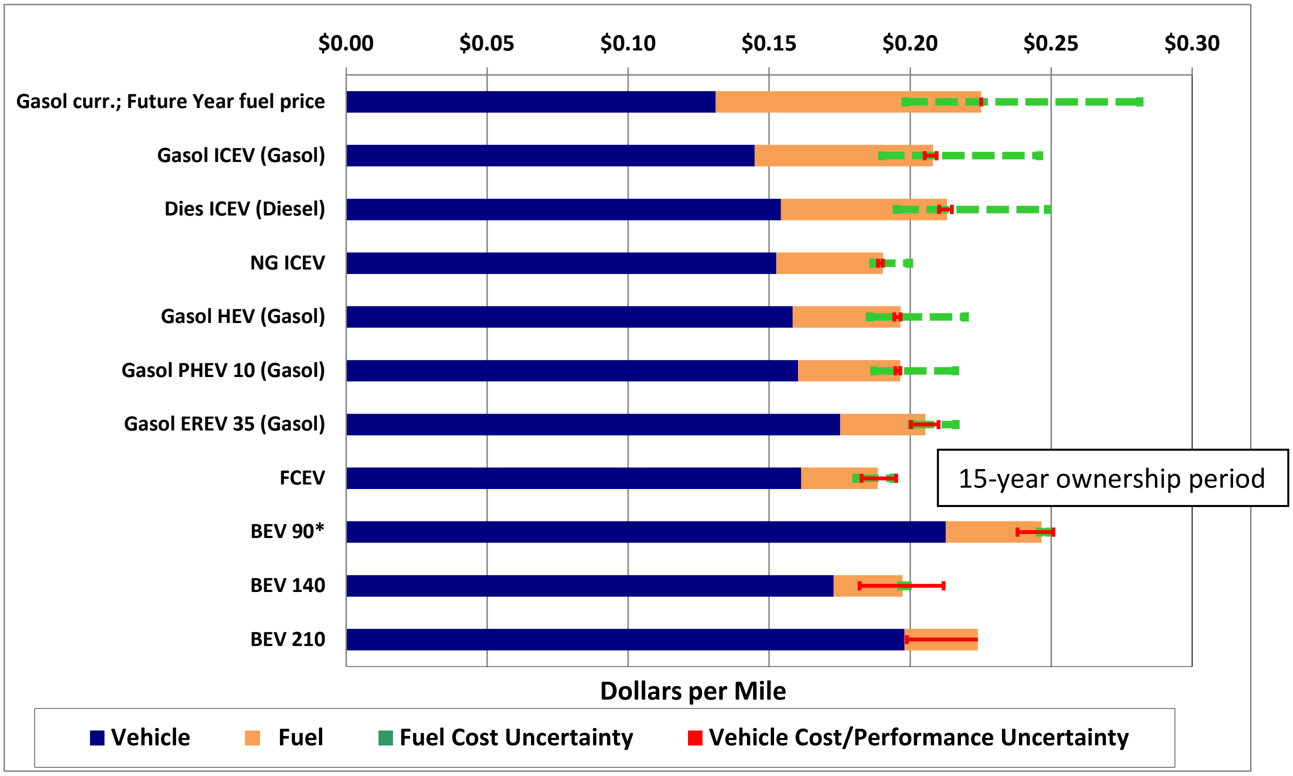
- The reference case, i.e., medium technical progress, is based on medium fuel economy values and medium vehicle prices coupled with medium fuel prices (i.e., EIA reference oil prices and DOE's mid-range estimate of hydrogen price).



*Annual miles for BEV90 assumed to be 30% less than for the other vehicles.

Figure 2. Ownership Costs for Future Mid-Size Car (2035, 5-year ownership, $/mi)

- Vehicle technology sensitivity: The "low" vehicle sensitivity case includes High Technical Progress vehicles with higher fuel economy values and lower prices and the "high" vehicle sensitivity case includes less optimistic vehicles with lower fuel economy values and higher prices (exception: under the High Technical Progress scenario, the costs of advanced ICEVs in 2035 are higher than those of ICEVs under the less optimistic scenario because their engines and transmissions cost more for their superior performance). The fuel prices were kept at their medium values for the vehicle technology sensitivity cases.
- Fuel price sensitivity: The fuel price sensitivity cases show the effect of lower and higher fuel prices on the "mid" case. That is, the fuel economy values and prices of vehicles were kept at their medium values in the fuel price sensitivity cases.
- Vehicle-miles traveled for BEV90 are assumed to be 30% less than those for longer-range vehicles.



*Annual miles for BEV90 assumed to be 30% less than for the other vehicles.

Figure 3. Ownership Costs for Future Mid-Size Car (2035, 15-year ownership, U.S. $/mi)

Notes for Figures 2 and 3

Costs are expressed in constant 2013 dollars, based on a discount rate of 5%.

- Costs are for high-volume sales, 100,000 per year for batteries and 500,000 per year for fuel cells (ANL's battery production cost model, Batpak, is for a 100,000 units-per-year plant whereas the Fuel Cells and Hydrogen Program has been setting targets based on full production, i.e., a plant large enough so that unit costs will not be likely reduced if its production capacity increases beyond 500,000 per year).
- Calculations do not include financing, maintenance, property tax, and insurance (recognizing that these may impact costs differently and that more data is needed before these can be included for new technologies). Durability of key components (such as batteries and fuel cells) is assumed to last over the entire ownership period.
- Vehicle costs and fuel economies were estimated using ANL's Autonomie modeling system for vehicle simulation.

Vehicle prices are derived from factory production costs and include a multiplier of 1.5 to account for such items as manufacturer and dealer markups, distribution costs, and sales tax.

Tables 4 and 5 provide a summary of key results for the base case.

Table 4. Life-Cycle Costs for Medium (Base) Case, 2035 Mid-Size Cars, 5-Year

Midsize	ICEV Gasol	ICEV Dies	ICEV NG	HEV Gasol	PHEV10 Gasol	EREV35 Gasol	FCEV	BEV90	BEV140	BEV210
Cost/Mile (Vehi.)	$0.265	$0.282	$0.279	$0.290	$0.293	$0.320	$0.295	$0.387	$0.317	$0.362
Cost/Mile (Fuel)	$0.077	$0.072	$0.046	$0.047	$0.044	$0.037	$0.033	$0.041`	$0.030	$0.032
Total Cost/Mile	$0.342	$0.354	$0.325	$0.336	$0.337	$0.357	$0.328	$0.428	$0.347	$0.394
Vehicle Price	$25,803	$27,455	$27,168	$28,205	$28,543	$31,208	$28,747	$26,512	$30,790	$35,253

Table 5. Life-Cycle Costs for Medium Technical Progress (Base) Case, 2035 Mid-Size Cars, 15-Year

Midsize	ICEV Gasol	ICEV Dies	ICEV NG	HEV Gasol	PHEV10 Gasol	EREV35 Gasol	FCEV	BEV90	BEV140	BEV210
Cost/Mile (Vehi.)	$0.145	$0.154	$0.152	$0.158	$0.160	$0.175	$0.161	$0.213	$0.173	$0.198
Cost/Mile (Fuel)	$0.063	$0.059	$0.038	$0.038	$0.036	$0.030	$0.027	$0.034	$0.024	$0.026
Total Cost/Mile	$0.208	$0.213	$0.190	$0.197	$0.196	$0.205	$0.189	$0.247	$0.198	$0.224
Vehicle Price	$25,803	$27,455	$27,168	$28,205	$28,543	$31,208	$28,747	$26,512	$30,790	$35,253

The record and analytic approach was independently reviewed by experts at ANL. Major assumptions for this record, including the most recent fuel economy estimates using Autonomie results have benefitted from industry's input throughout the past years. The derivation of on-road fuel economy from Autonomie results was peer reviewed when this method was first published in Report No. ANL/ESD/10-1 by A. Elgowainy et al. The performance and cost targets of major vehicle components were provided by EERE technology teams in the Vehicle Technologies and Fuel Cell Technologies Offices.

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