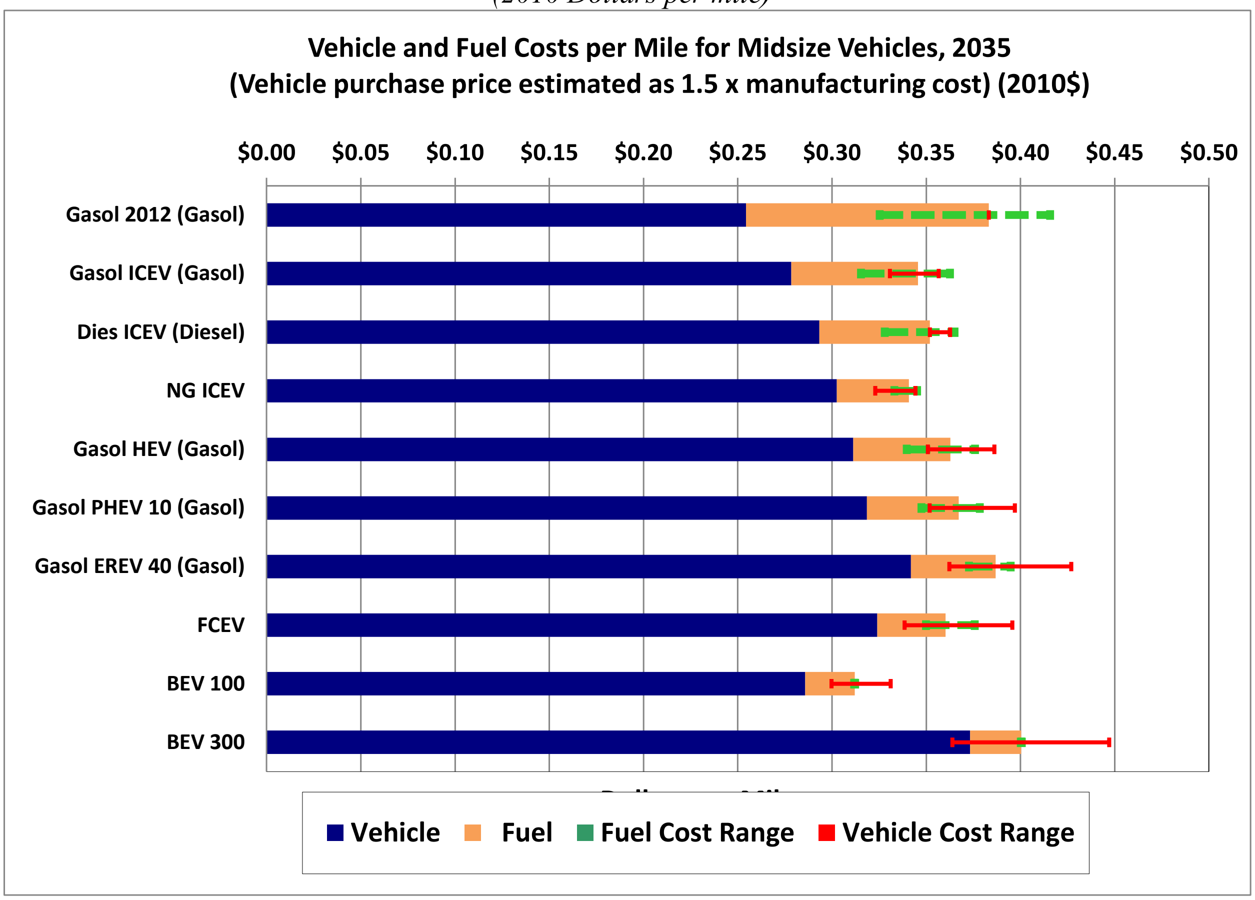
Program Record (Offices of Vehicle Technologies & Fuel Cell Technologies)	
Record #: 13006	**Date:** April 24, 2013
Title: Life-cycle Costs of Mid-Size Light-Duty Vehicles	
Originator: Tien Nguyen & Jake Ward	
Approved by: Sunita Satyapal Pat Davis	**Date:** April 25, 2013

Items:

DOE is pursuing a portfolio of technologies with the potential to significantly reduce greenhouse gases (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 future mid-size car. The results are summarized graphically in the following figure.

Costs of Operation for Future Mid-Size Car

(2010 Dollars per mile)



Low/high: sensitivity to uncertainties associated with fuel economy and fuels prices

Notes:

- For a projected state of technologies in 2035: internal combustion engine vehicles (ICEV), hybrid-electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), extended-range electric vehicle (EREV), fuel cell hybrid-electric vehicles (FCEV), and battery electric vehicles (BEV).
- Costs are for high-volume sales (100,000 per year for batteries and 500,000 per year for fuel cells)
- 5-year ownership, 14,000 miles per year, 7% net discount rate
- Resale value at 25% of new vehicle price

Data, Assumptions, References:

- Results for all pathways are based on a projected state of the technologies in 2035 (costs shown in 2010 dollars)
- The U.S. Environmental Protection Agency's latest method was used in deriving on-road fuel economies from results of simulations of laboratory driving tests. For information on EPA's method, see: http://www.gpo.gov/fdsys/pkg/FR-2009-11-25/pdf/E9-27945.pdf and http://www.smidgeindustriesltd.com/leaf/EPA/EPA_test_procedure_for_EVs-PHEVs-1-13-2011.pdf
- Fuel economies (as measured in the laboratory on standard test cycles) for all fuel/vehicle systems were determined using ANL's Autonomie modeling system, a vehicle simulation system used to assess the fuel consumption and performance of advanced vehicles. For information on Autonomie, see: http://www.transportation.anl.gov/modeling_simulation/PSAT/autonomie.html

  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, including the use of air conditioning, frequency of acceleration, etc.
- Fuel economy estimates for vehicles are based on the gallon gasoline equivalent (gge) of each applicable fuel, approximately 115,000 Btu or 121.33 MJ or 33.7 kWh (lower heating value)
- These cost results will be periodically updated to reflect changes in the assumptions and refinements to the previously mentioned models.

The vehicles analyzed are based on scenarios of 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:

- A gasoline vehicle with an internal combustion engine of the spark-ignition type (abbreviated as Gasol ICEV); assumed without hybridization
- A diesel vehicle with an internal combustion engine of the compressed-ignition type (Diesel ICEV); assumed without hybridization
- A natural gas vehicle with an internal combustion engine of the spark-ignition type (abbreviated as NG ICEV), the natural gas counterpart of the Gasol ICEV
- A hybrid-electric vehicle (HEV) with a spark-ignition gasoline engine (Gasol HEV)
- A plug-in hybrid electric vehicle (PHEV)[1] with a nominal charge-depleting (CD) range of 10 miles, powered by an electric motor and a spark-ignition gasoline engine - abbreviated as PHEV10
- A plug-in vehicle of the extended-range electric vehicle (EREV)[2] type, with a nominal CD range of 40 miles, powered by an electric motor and a spark-ignition gasoline engine - abbreviated as EREV40
- A fuel cell hybrid-electric vehicle (FCEV)

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[1] The PHEV is of the power-split type, with both the internal combustion engine and the electric motor providing torque to the wheels. When in charge-depleting mode, the engine may still activate to assist the electric drive as needed.

[2] The powertrain configuration used for the EREV is VOLTEC (name given by GM to the configuration used in the 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.

- A battery electric vehicle (BEV) with a nominal range of 100 miles[3] - abbreviated as BEV100
- A BEV with a nominal range of 300 miles - abbreviated as BEV300.

Each vehicle's minimum driving range is approximately 320 miles, except where noted for the electric range of the PHEV10, EREV40 and the two 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 through 6 show the fuel economy results generated by the Autonomie Model for advanced technology vehicles, for the three technology achievement levels: (1) Medium Optimistic, (2) Less Optimistic, and (3) More Optimistic. Table 1 shows the results for non-electric vehicles and the charge-sustaining mode of the PHEV and EREV in miles per gallon gasoline-equivalent (Mpgge). Table 2 shows the overall fuel economy results.

Table 1. On-Road Fuel Economy of Light-Duty Vehicles in 2035– in Miles/Gallon gasoline- equivalent (Mpgge) and Watt-hours per Mile (Wh/mi)

	ICEV Gasol	ICEV Diesel	ICEV Ngas	HEV Gasol	PHEV10 Gasol	EREV40 Gasol	FCEV	BEV100	BEV300
Medium Optimism									
Charge Sustaining, mpgge									
Non-Electric Fuel, mpgge	49.1	55.0	49.4	64.1	62.7	53.0	79.3		
Charge Depleting									
Electricity, Wh/mi					181	271		257	266
Non-Electric Fuel, mpgge					183				
Less Optimistic									
Charge Sustaining, mpgge									
Non-Electric Fuel, mpgge	36.9	41.3	40.4	49.1	48.1	41.9	63.5		
Charge Depleting									
Electricity, Wh/mi					202	311		306	321
Non-Electric Fuel, mpgge					135				
More Optimistic									
Charge Sustaining, mpgge									
Non-Electric Fuel, mpgge	64.0	72.3	58.5	83.4	81.8	64.6	97.9		
Charge Depleting									
Electricity, Wh/mi					152	232		216	221
Non-Electric Fuel, mpgge					240				

<u>Notes for Table 1</u>:

1. The PHEV10 can operate in a blended mode in the charge-depleting phase if needed.
2. The EREV40 uses only electricity when operating in the charge-depleting mode.
3. The 2012 reference gasoline vehicle's fuel economy is 26 mpg (on-road)
4. On-road fuel economy is based on combining city (43% of distance driven) & highway (57% of distance driven), using EPA's adjustment method in http://edocket.access.gpo.gov/2006/pdf/06-9749.pdf

[3] The BEV100 and BEV300 are sized to travel 100 and 300 miles, respectively, on EPA's "UDDS" drive cycle.
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Table 2. On-Road Fuel Economy in 2035 (Combined Electric & Non-Electric - Plug-in LDVs) – in Miles/Gallon gasoline- equivalent (Mpgge)

ICEV Gasol	ICEV Diesel	ICEV Ngas	HEV Gasol	PHEV10 Gasol	EREV40 Gasol	FCEV	BEV100	BEV300
Medium Optimism								
49.1	55.0	49.4	64.1	68.1	74.3	79.3	131	127
Less Optimistic								
36.9	41.3	40.4	49.1	52.8	60.4	63.5	110	105
More Optimistic								
64.0	72.3	58.5	83.4	88.2	89.4	97.9	156	153

Data & Assumptions

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

- 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. The sums of manufactured costs (normalized relative to the cost of the reference vehicle, 2012 gasoline ICEV) are summarized in Figure 1
- Two cases are presented: one based on an ownership period of five years with a resale value at 25% of the purchase price (this assumption is more conservative than actual values listed on the website Kelly Blue Book 2012 so that the results are not biased in favor of advanced vehicles that may cost more than gasoline ICEVs) and one based on an ownership period that is the same as the assumed 15-yr car life (with no resale value at the end). The calculations are based on a 7% real discount rate that applies to future fuel purchases, but not the capital investment in the vehicle because it was assumed that the consumer pays cash for the vehicle. The cars were assumed to log 14,000 mi per year for the five-year ownership case, and 10,000 miles per year for the 15-year ownership case, on the basis of 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)

[4] Durability of key components (such as batteries and fuel cells) is assumed to last over the entire ownership period. Therefore the effect of excluding maintenance is relatively minor for advanced LDVs.

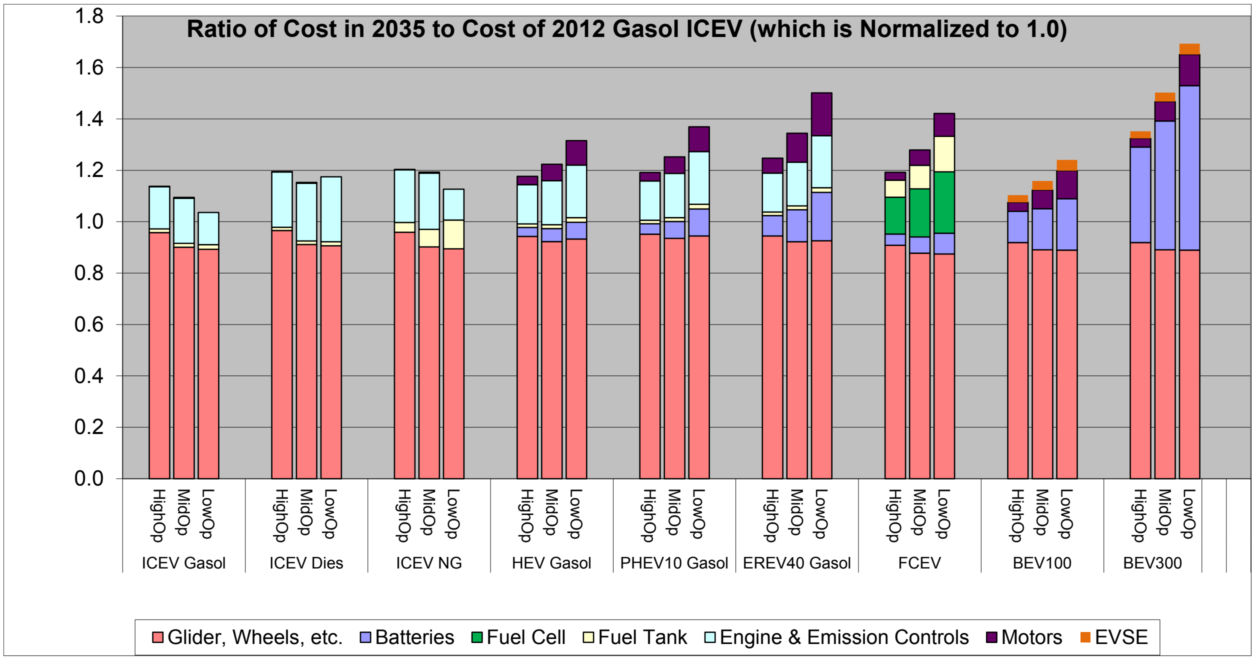

Figure 1. Vehicle Manufacturing Costs Relative to 2012 ICEV in 2035 (three levels of R&D success)

- Year 2035 cost (2010 dollars) for major vehicle subsystems for three scenarios considered (i.e., More Optimistic, Medium Optimism, and Less Optimistic):
    - Batteries for BEVs: $75, $81 and $84 per total kWh
    - Batteries for EREV40s: $110, $130 and $145 per total kWh
    - Batteries for PHEV10s: $240, $280 and $320 per total kWh
    - Batteries for HEVs and FCEVs: $20, $25, $28 per kW
    - On-board natural gas storage: $3.00, $4.30 and $5.70 per kWh of fuel. $3.00 per kWh corresponds to ARPA-E's success for sorbent tanks whereas $5.70 corresponds to the estimated cost of Type 4 tanks for 2025 in the National Petroleum Council (NPC) 2012 report (Table NG-11) and $4.30 per kWh (rounded to the nearest dime) is the midpoint between these two costs
    - Fuel cell: $32, $35 and $38 per kW
    - On-board hydrogen storage: $8.40, $9.40 and $11.50 per kWh of fuel
- Major subsystems (i.e., batteries and fuel cells) are assumed to last through the assumed ownership period
- The fraction of miles driven in the CD mode is somewhat variable because, for the PHEV10, the internal combustion engine may activate even before the 10-mile nominal CD phase is over. Autonomie simulation resulted in a range of 22% to 27%. For this analysis, an average value of 25% is a reasonable approximation for the PHEV10. Simulation of the EREV40 resulted in a range of 48% to 51%, and so 50%, a round number, can be a reasonable approximation for the fraction of miles in the CD mode[5]. These values are consistent with the Society of Automotive Engineers document SAE J2841, after the nominal all-electric range of the EREV40 has been adjusted with a 70% factor to take into account of more realistic driving conditions (Elgowainy et al. 2010)

[5] For the EREV40, the difference in fuel cost per mile is only a tenth of a penny between CD at 48% versus at 51%.

- The efficiency loss associated with charging and battery performance is assumed to be 2%, 5% and 8% (i.e., efficiency factor of 98%, 95% and 92%) as high, medium and low values
- The natural gas vehicle scenario involves the assumptions of two different fuel tank technologies as a function of R&D success: Type 4 carbon fiber tanks for the medium-optimism and less optimistic cases, and sorbent tanks[6] for the more optimistic case. Natural gas for the tanks would be compressed natural gas (CNG at 3600 psi or 250 bars) for Type 4 tanks and natural gas compressed at significantly lower pressures (values to be defined in another analysis) for sorbent tanks. For CNG, the assumption was EIA's projected $18.06 per MBtu in 2010 dollars - approximately $2.30 per gge, including fuel excise taxes, natural gas feedstock costs, and the O&M and amortized capital costs of the compression/dispensing facility (Department of Energy 2012a, "Natural Gas Heavy-duty Vehicle Reference" Case[7]). For sorbent tanks, it was assumed that the processed natural gas's price is 80% the price of CNG ($1.84 per gge), pending further analysis of the cost impact of reduced compression for sorbent tanks
- Baseline prices (including taxes) of most fuels (other than natural gas and hydrogen) are from the Energy Information Administration's Annual Energy Outlook (AEO) 2012 Reference Case (2010 dollars): $4.03 per gallon of gasoline, $3.94 per gge diesel, and 11.8¢/kWh electricity (approximately $3.98 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 (Department of Energy's Record No. 11007). Cellulosic biofuels such as renewable gasoline and diesel were not analyzed explicitly. However, one can assume that their prices per gge should be equal to those of their petroleum counterparts for them to penetrate the market. If so, the life-cycle costs of advanced LDVs fueled by such biofuels would be similar to the estimates in this document for petroleum fuels because the vehicles are not that different from conventionally fueled vehicles, even in the case of E85
- Fuel sensitivity analysis used projected Year 2035 prices for gasoline and diesel from AEO 2012's high and low oil price cases (except as noted below)
  - Gasoline at $2.22 and $5.05 per gallon
  - Diesel at $2.32 and $4.82 per gge
  - Electricity at 11.7¢ and 11.9¢/kWh
  - The variation in the prices of NG is assumed to be a function of the pressurization required, i.e. lower prices associated with lower pressure NG for sorbent tanks ($1.84 per gge, as previously discussed) and higher prices for CNG. For CNG, EIA's "Natural Gas Heavy-duty Vehicle Potential" Case shows $2.57 per gge (20.17 per MBtu), slightly higher than the price from the "Natural Gas Heavy-duty Vehicle Reference" Case. $2.57 was assumed to be the higher price point for CNG
  - Hydrogen at $2.50 and $5.00 per gge (including taxes): the high value is based on an analysis using current (not future) technology and relatively high natural gas prices from AEO 2009 (Department of Energy's Record No. 12024).

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[6] Advanced tank concept being investigated by DOE's Advanced Research Projects Agency (ARPA-E) – see FOA 672 at https://arpa-e-foa.energy.gov/Default.aspx?Archive=1

[7] EIA personnel suggested using prices from their Natural Gas HDV case instead of the reference case for AEO 2012 because they updated their assumptions when developing the Natural Gas HDV case after the release of the AEO 2012 reference case.

The PHEV10 and EREV40 can be charged without modification to existing outlets. For the BEVs, a sensitivity case was added, with the low/medium/high pre-installation prices of the electric vehicle supply equipment (EVSE)[8] that is external to the vehicle at $400, $500 and $600, respectively. EVSE installation costs are additional and assumed to be 50% of the equipment costs. Table 3 summarizes the major vehicle-related assumptions used in this analysis.

Table 3. Technical Parameters from Autonomie Modeling and Unit Cost Assumptions for Year 2035 LDVs (medium values shown with low/high between parentheses)

	Batteries, Total kWh for PHEVs, EREV & BEVs	Battery Power, kW	Natural gas or H2 on board, kWh	Power of Engine or Fuel Cell, kW	Power of Motor & Generator, kW	Battery Cost, $/kW for HEVs, or $/Total kWh for PHEVs, EREV & BEVs	Cost of Natural gas or H2 Tank, $/kWh	Fuel Cell Cost, $/kW
ICEV Gasol				114 (99 - 134)				
ICEV Dies				95 (79 - 110)				
ICEV NG			217 (183 - 266)	104 (90 - 124)			$4.3 ($3.0 - $5.7)	
HEV Gasol		29.0 (25.3 - 33.6)		73 (63 - 84)	100 (85 - 112)	$25 ($20 - $28)		
PHEV10 Gasol	3.4 (2.4 - 4.7)			74 (63 - 85)	101 (87 - 114)	$280 ($240 - $320)		
EREV40 Gasol	13.8 (10.4 - 18.8)			70 (60 - 80)	175 (153 - 197)	$130 ($110 - $145)		
FCEV		36.3 (31.8 - 41.6)	132 (108 - 163)	77 (64 - 91)	94 (80 - 105)	$25 ($20 - $28)	$9.4 ($8.4 - $11.5)	$35 ($32 - $38)
BEV100	28.4 (23.4 - 34.3)				114 (93 - 130)	$81 ($75 - $84)		
BEV300	89.4 (71.6 - 110.1)				118 (88 - 144)	$81 ($75 - $84)		

Note: The 2012 gasoline ICEV has a 137-kW engine

Cost of Ownership Results (excluding insurance, maintenance and taxes; based on prices of vehicles = 1.5 × manufacture costs)

The potential for improvements in technology to reduce the costs of ownership of advanced powertrain vehicles and fuels to levels comparable to conventional options is summarized graphically in the following figures for the different types of mid-size cars. For plug-in vehicles, retail electricity prices projected by EIA were used as the fuel costs.

Figure 2 shows the results of the 5-year life cycle analysis without EVSE costs.

[8] The conductors, including the ungrounded, grounded, and equipment grounding conductors; the electric vehicle connectors and attachment plugs; and all other fittings, devices, power outlets or apparatuses installed specifically for delivering energy from the premises wiring to the electric vehicle (http://www.energy.ca.gov/papers/98-09-23_Kateley.pdf)

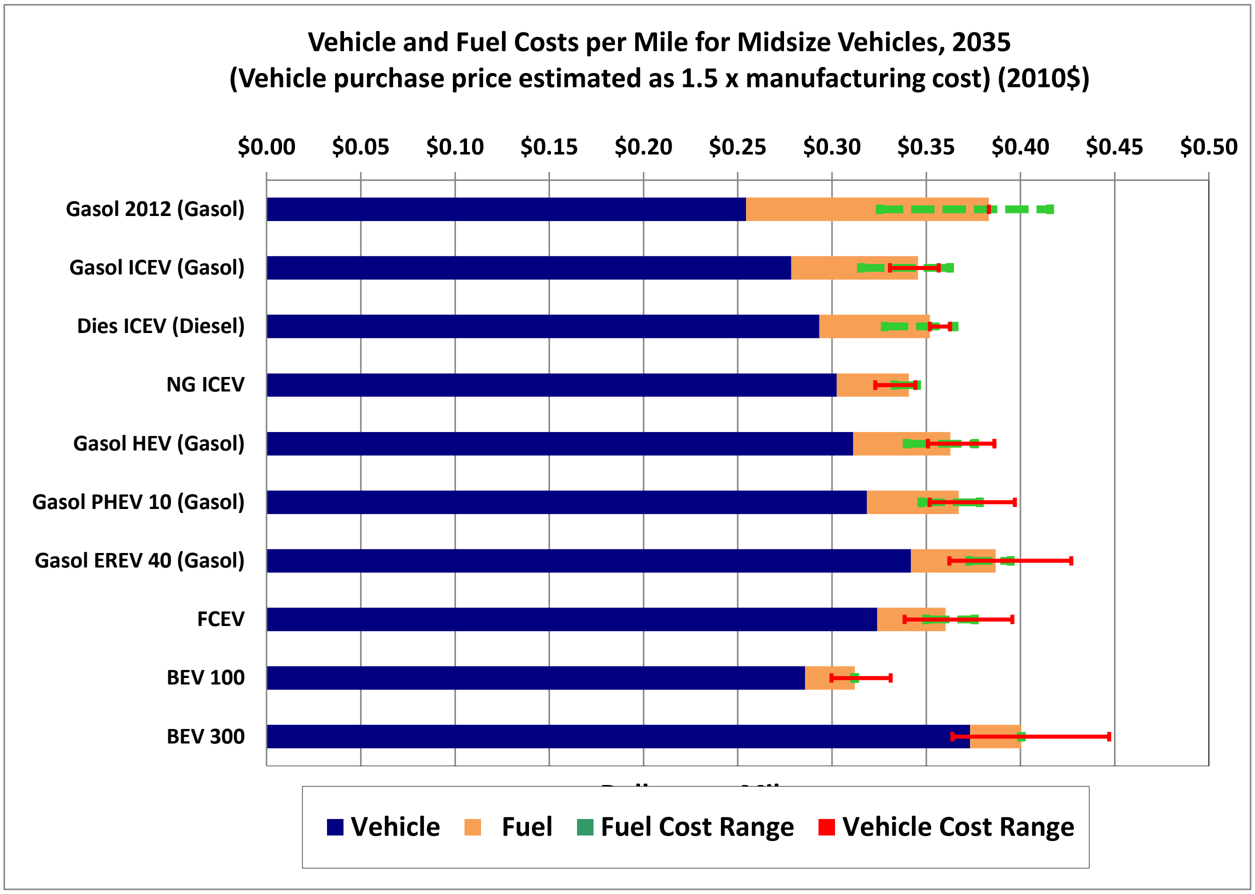

Figure 2. Ownership Costs for Future Mid-Size Car (2035, $/mi). Lifecycle costs estimated assuming 14,000 mi are driven each year over a 5-yr ownership period (based on vehicle price = 1.5 × manufacture cost; excluding insurance, maintenance, and taxes) and resale value at 25% of original price

Figure 3 shows the results of the 15-year life cycle analysis, also without EVSE costs.

The low/high error bars (sensitivity bands) illustrate uncertainties associated with projecting the performance of future vehicles and future fuel costs. The green sensitivity bands show the effects of variations in the fuel costs, and the red sensitivity bands show the effects of non-fuel- related uncertainties (corresponding to aggressive and conservative levels of success), including manufactured component costs and ranges of fuel economy of the associated vehicles:

- The reference or "Medium Optimism" case 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)
- Vehicle technology sensitivity: The "low" vehicle sensitivity case includes more optimistic 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 more optimistic 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 prices sensitivity: The fuel price sensitivity cases show the effect 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 For the five-year ownership scenario, the 25% resale values were arrived at after examining information from Top Ten Used Car Values (2012 Models) from Kelly Blue Book. http://www.kbb.com/new-cars/best-resale-value-awards/best-resale-top-10-

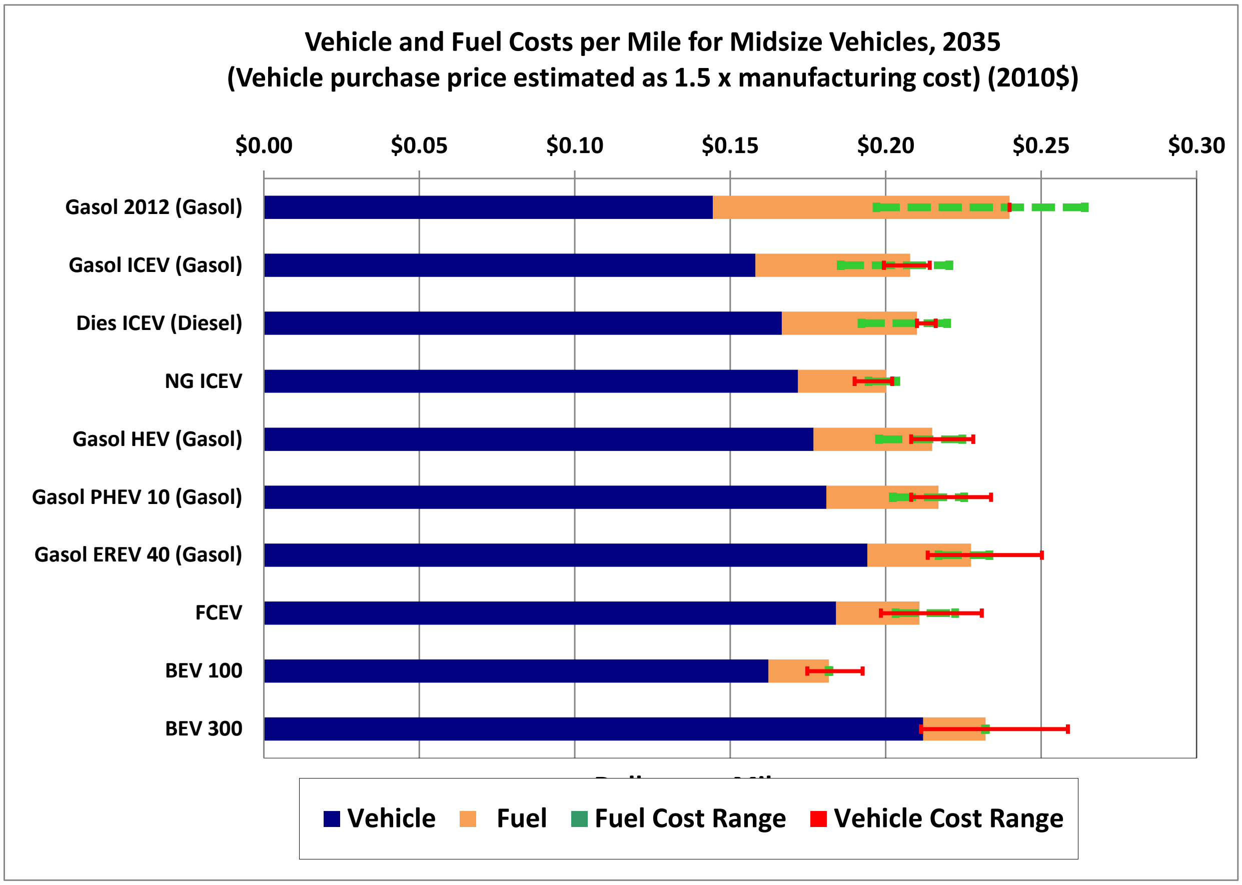

Figure 3. Ownership Costs for Future Mid-Size Car (2035, U.S. \$/mi). Lifecycle costs estimated assuming 10,000 miles are driven each year over a 15-year ownership period (based on vehicle price = 1.5 × manufacture cost, excluding insurance, maintenance, and taxes) and no residual resale value

Notes for Figures 2 and 3

- Costs are expressed in constant 2010 dollars, based on a net discount rate of 7%
- Costs are for high-volume sales (100,000 per year for batteries and 500,000 per year for fuel cells)
- Calculations do not include financing, maintenance, property tax, and insurance.
- Vehicle costs and fuel economies were estimated by 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, including the effect of adding EVSE costs to BEV results (shown in the last row).

Table 4. Life-cycle Costs for Medium-Optimism (Base) Case, 2035 Mid-size Cars, 5-Year

Midsize	Gasoline ICEV	Diesel ICEV	N Gas ICEV	Gasoline HEV	Gasol PHEV10	Gasoline EREV40	FCEV	BEV100	BEV300
Cost/Mile (Vehicle)	$0.278	$0.293	$0.303	$0.311	$0.319	$0.342	$0.324	$0.286	$0.373
Cost/Mile (Fuel)	$0.067	$0.059	$0.038	$0.052	$0.049	$0.045	$0.036	$0.026	$0.027
Total Cost/Mile	$0.346	$0.352	$0.341	$0.363	$0.367	$0.387	$0.360	$0.312	$0.400
Total Cost/Mile with EVSE for BEVs								$0.323	$0.411

Table 5. Life-cycle Costs for Medium-Optimism (Base) Case, 2035 Mid-size Cars, 15-Year

Midsize	Gasoline ICEV	Diesel ICEV	N Gas ICEV	Gasoline HEV	Gasol PHEV10	Gasoline EREV40	FCEV	BEV100	BEV300
Cost/Mile (Vehicle)	$0.158	$0.167	$0.172	$0.177	$0.181	$0.194	$0.184	$0.162	$0.212
Cost/Mile (Fuel)	$0.050	$0.043	$0.028	$0.038	$0.036	$0.033	$0.027	$0.019	$0.020
Total Cost/Mile	$0.208	$0.210	$0.200	$0.215	$0.217	$0.227	$0.211	$0.182	$0.232
Total Cost/Mile with EVSE for BEVs								$0.187	$0.237

The record and analytic approach was peer reviewed by experts at ANL and NREL. 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. The method used to estimate the cost of operation over assumed vehicle ownership periods was first published in 2011 under a request-for-information (http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/costs_mile_rfi.pdf). Feedback from industry on the RFI was incorporated in the current analysis.

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