NATIONAL PETROLEUM COUNCIL

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Future Transportation Fuels Study

Light-Duty Vehicle Attribute Model

June 20, 2012

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Introduction

This appendix describes a Vehicle Attribute Model that was constructed by the NPC Future Transportation Fuels (FTF) Study Data Analysis Subgroup in support of the study objectives. The model draws on work done by the Study Subgroups in their respective technology areas and seeks to integrate the results into a consistent set of vehicle offerings that reflect how these technologies could present themselves in the vehicle marketplace over time. A range of inputs is considered for each significant technology parameter, and the result is a range of vehicle attribute "cases" that form the basis for subsequent analysis.

Background

The FTF Study addresses questions pertaining to the entirety of US transportation over a time period from the present through 2050. Transportation segments within the Study scope are light duty vehicles (LDVs), heavy duty vehicles (HD), air, rail, and marine. Of these segments, the largest by economic and energy consumption measures is LDVs, or cars and trucks with a gross vehicle weight of less than 8,500 pounds. This segment is the focus of the modeling work described in this appendix.

In order to quantify the impact of LDVs on greenhouse gas emission, oil consumption, economics, or energy security, it is necessary to quantify the individual vehicle attributes, fuel characteristics, the mix of vehicles sold into the fleet, and the number of miles driven over time until a vehicle exits the fleet at end of life. In this study, the VISION tool from Argonne National Lab was used to calculate LDV fleet metrics at the highest level. The VISON tool was pre-loaded with parameters from the Energy Information Administration's Annual Energy Outlook 2010 case tables as the basis for this work. A Vehicle Choice Model from TA Engineering was used to provide VISION with new vehicle sales shares based on vehicle attributes and fuel characteristics. Vehicle attributes and fuel characteristics were provided by separate models constructed by FTF Study Subgroups and linked by a vehicle fuel economy and fuel price handoff. The structure of these models is illustrated in Figure 1.

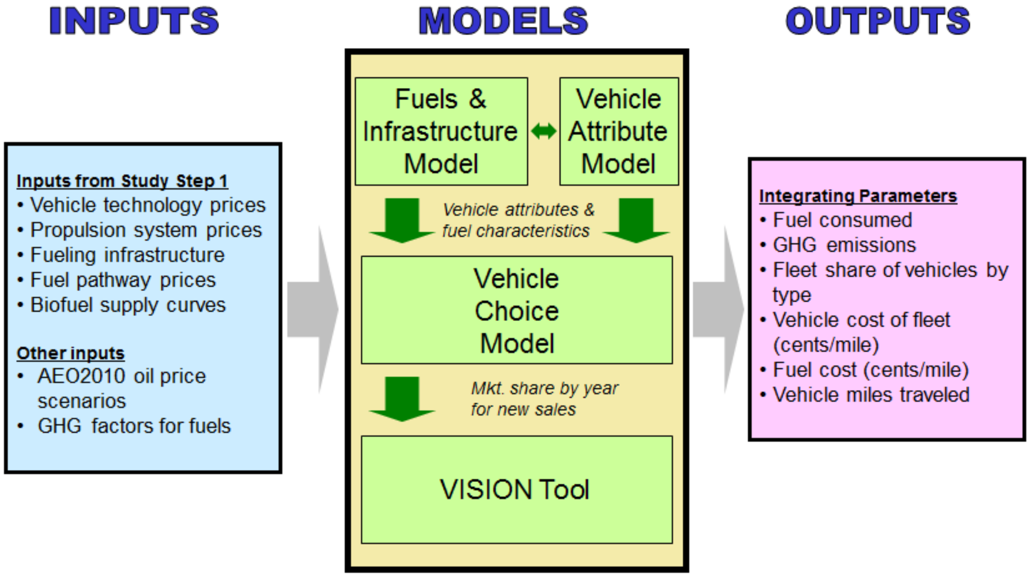


Figure 1 – FTF Study Modeling Structure

Vehicle Classes and Baseline Attributes

Five vehicle classes were chosen to represent the light duty vehicle (LDV) marketplace in the FTF Study: Small Cars, Large Cars, Small SUVs, Large SUVs, and Pickups. The baseline attributes of each vehicle class were defined by mapping from the baseline attributes of the 2008 conventional vehicle as defined in the Annual Energy Outlook 2010 (AEO2010) Reference Case. Table 1 shows the assignments chosen to map the 12 vehicle segments in AEO2010 to the five vehicle segments in the FTF Study. The mapping from the FTF vehicle classes into the two VISION tool classes of Car and Truck is also shown in the right-most columns of the table.

AEO2010		NPC FTF	VISION
Vehicle Classes	2008 Sales Mix	Vehicle Classes	Vehicle Classes
Two Seater Car	4%	Small Cars	Car
Mini-compact Car	3%		
Subcompact Car	29%		
Compact Car	64%		
Midsize Car	71%	Large Cars	
Large Car	29%		
Small Van	10%	Small SUVs	Truck
Small Utility	90%		
Large Utility	79%	Large SUVs	
Large Van	21%		
Small Pickup	18%	Pickups	
Large Pickup	82%		

Table 1 – Mapping of Vehicle Classes

2008 sales mix ratios were used to assign vehicle attributes to each FTF vehicle class from multiple AEO2010 vehicle classes on a sales-weighted basis. Figure 2 shows the resulting 2008 conventional vehicle attributes by FTF vehicle class.

	FE (mpg)	RPE	Weight (lbs)	Power	
				(hp)	(kW)
Small Cars	32.3	$22,781	3,010	173.6	129.5
Large Cars	30.3	$27,425	3,504	206.8	154.2
Pickups	22.3	$20,430	5,239	277.5	206.9
Small SUVs	25.6	$23,959	4,150	204.4	152.4
Large SUVs	22.8	$32,339	5,239	268.4	200.2

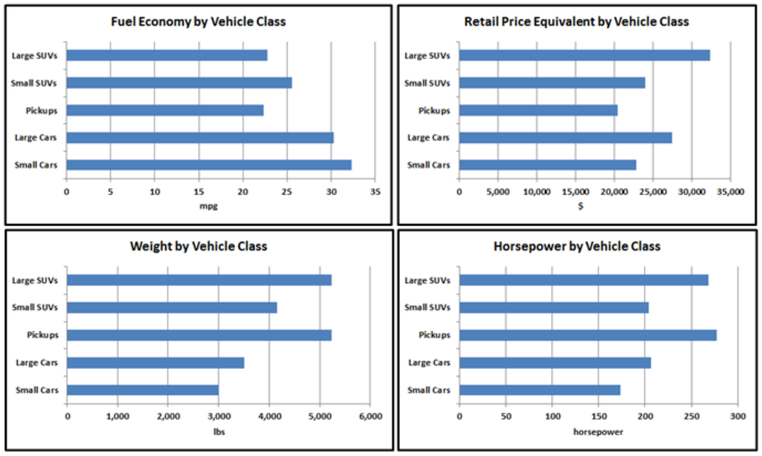


Figure 2 – Baseline: 2008 Conventional Vehicle as Mapped from AEO2010

Model Outputs

The Light Duty Vehicle Attribute Model provided The Vehicle Choice Model (VCM) and VISION tool with the following vehicle attributes

1. **Test Fuel Economy**
   This is the fuel economy that a vehicle would be expected to deliver on a combined city/highway fuel economy test cycle. Test fuel economy is typically 25% higher than “on-road” or “sticker” fuel economy. The VISION tool uses a correction factor to estimate on-road fuel economy as it calculates fleet metrics such as fuel consumption, energy feedstock use, and GHG emissions.

2. **Retail Price Equivalent**
   Retail Price Equivalent (RPE) is intended to reflect industry-average production costs plus rates of profit and overhead expense. In other words, RPE represents the consumer’s cost, the average additional price consumers would pay.

3. **Electric Utility Factor**
   This is the percentage of miles over which a plug-in hybrid electric vehicle uses electric plug energy rather than gasoline (or biofuel) energy. A utility factor of 100% would mean the vehicle is charged regularly, never drives beyond its battery range, and never uses gasoline. At the other extreme, a utility factor of 0% would indicate that the vehicle is never charged, and all of its energy comes from gasoline.

Each of these attributes is calculated for each vehicle class for every fifth year from 2015 to 2050. The VCM and VISION interpolate between these five-year points to derive year-by-year attribute values.

Model Scope and General Methodology

An overarching goal of this modeling work was to normalize assumptions across different vehicle and fuel pathways. As a first step, common vehicle classes and common baseline vehicle attributes were established as described above. The next step was to identify shared vehicle subsystems and ensure that common subsystem characteristics were applied over time to each pathway. Figure 3 shows the pathways included in the study, along with their respective vehicle subsystems and fuel and infrastructure elements.

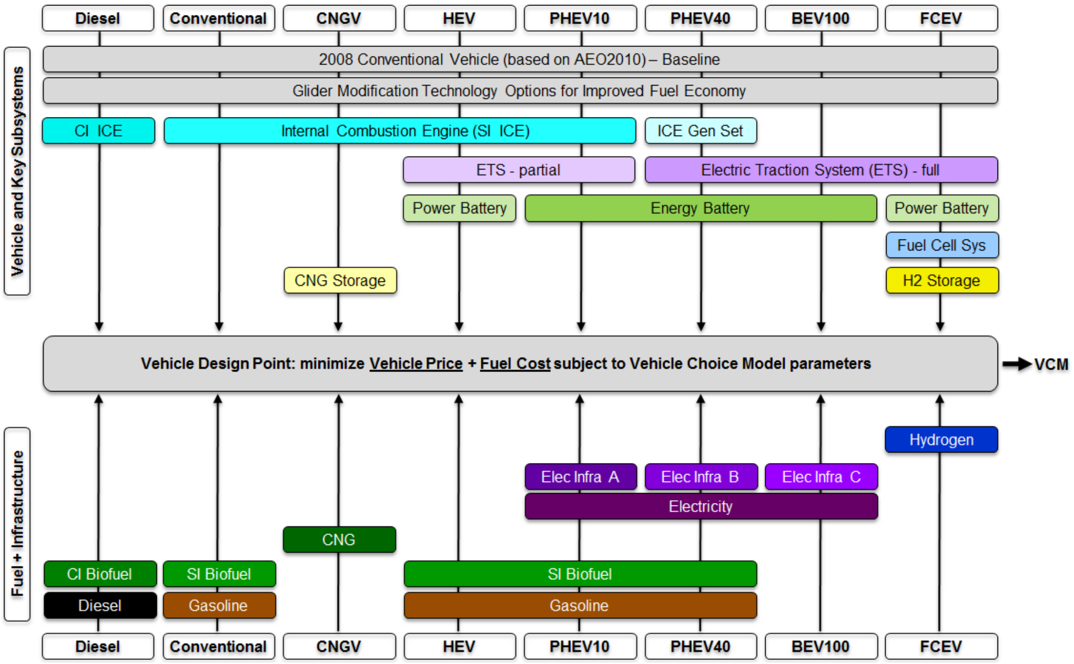


Figure 3 – Pathways and Model Structure

There are eight vehicles pathways in total in the study, listed at the top and bottom of Figure 3 from left to right:

1. **Diesel**
   Vehicle with a compression ignition (CI) engine that uses diesel fuel or a substitute derived from biomass. For purposes of this study, the Diesel vehicle is assumed capable of using any mix of diesel and CI biofuel

2. **Conventional** – Gasoline Vehicle
   Vehicle with a spark ignition (SI) engine that uses gasoline fuel or a substitute derived from biomass. For purposes of this study, the Conventional vehicle is assumed capable of using any mix of gasoline and SI biofuel

3. **CNGV** – Compressed Natural Gas Vehicle
   Vehicle with a spark ignition engine that uses natural gas fuel stored onboard at 3,600 psi (24.8 MPa). CNG fuel storage system is sized for 300 miles of on-road driving range

4. **HEV** – Hybrid Electric Vehicle
   Vehicle with spark ignition engine and a battery plus electric motor for power assist. Uses same fuel as Conventional vehicle, with same assumptions on biofuel flexibility

5. **PHEV10** – Plug-in Hybrid Electric Vehicle 10
   Vehicle with spark ignition engine and a battery plus electric motor for power assist. Uses same fuel as Conventional vehicle, with same assumptions on biofuel flexibility. Onboard battery

recharges from the engine or through external electric plug and stores energy for 10 miles of on-road driving

6. **PHEV40** – Plug-in Hybrid Electric Vehicle 40
   Vehicle with full electric drive and a spark ignition engine / generator. Onboard battery recharges from the engine or through external electric plug and stores energy for 40 miles of on-road driving. Engine / generator uses same fuel as Conventional vehicle, with same assumptions on biofuel flexibility

7. **BEV100** – Battery Electric Vehicle 100
   Vehicle with full electric drive powered by an onboard battery. Battery recharges only through external electric plug and stores energy for 100 miles of on-road driving

8. **FCEV** – Fuel Cell Electric Vehicle
   Vehicle with full electric drive and a fuel cell system that uses gaseous hydrogen fuel stored onboard at 70 MPa (10,150 psi). Fuel tank is sized for 300 miles of on-road driving range. Battery is included for power assist and is similar in function to the HEV battery

In the middle of Figure 3 is a box labeled “Vehicle Design Point.” Vehicle subsystem characteristics and fuel prices are inputs to this box, and vehicle attributes are outputs for handoff to the Vehicle Choice Model (VCM). This box represents the core of the Vehicle Attribute Model, where vehicle price and vehicle fuel operating cost are balanced to produce the combination of vehicle attributes that competes best in the VCM marketplace model. The VCM model parameters are used as the basis for this tradeoff, allowing the model to produce the best possible vehicle for any given set of technology constraints and fuel prices.

Apart from the three attributes of price, fuel economy, and utility factor, all vehicles are assumed to be equivalent. Other attributes, such as acceleration or interior passenger and cargo space, were not assigned any discriminating preference in specific choice of propulsion system or fuel. Given freedom to create a clean sheet design, all vehicle pathways can satisfy marketplace requirements for these attributes. The only exception to this is the limited range of the BEV100. This pathway cannot satisfy all market requirements due to its limited driving range and long recharge time. This limitation is handled within the VCM by application of market share constraints.

Where vehicle pathways share a key technology, the characteristics of that technology are held common, but each pathway is allowed to choose its optimal degree of adoption. An example of this is adoption of technologies for fuel economy improvement. Each pathway has the same “menu” of options for glider (chassis and body) technologies, and each option has the same price point for each pathway, but different motivations result in different degrees of adoption. Conventional vehicles, for example, may adopt efficiency technology to offset fuel costs when gasoline prices are sufficiently high, while the BEV100 may adopt efficiency technology in order to reduce its onboard battery energy requirement and minimize vehicle price.

Key Modeling Parameters

Key parameters for the Vehicle Attribute Model include the mass compounding multiplier, the relationship between vehicle mass and fuel consumption, the relationship between technology cost and retail price equivalent, and technology price learning curves. For conventional vehicles, HEVs, and diesel vehicles, assumptions on mass compounding, mass impact on fuel consumption, and retail price markup were all included in the reference sources used to estimate the range of fuel economy technology impact on RPE. The range of assumptions used by different sources is included in the range of technology prices used in this FTF Study. Technology price curves were developed as described below.

CNGV, PHEV40, BEV100, and FCV attributes were developed using a modular approach with common parameter assumptions to ensure consistency. The first of these assumptions is the mass compounding factor. As propulsion system hardware and fuel or energy storage are added or deleted from the baseline conventional vehicle, the net mass effect on the vehicle must be determined in order to compute its resultant fuel economy. As an example, if battery mass is increased for greater energy storage capacity, then support structure, suspension, brakes and tires must be adjusted to compensate for this increased mass. Propulsion system power must also be increased to ensure that specified vehicle acceleration performance is maintained. All of these secondary effects lead to additional, or compounded, mass and price on the vehicle. In this Vehicle Attribute Model, a mass compounding factor of 1.5x was applied, meaning that for every pound of primary mass added there is an accompanying half pound of secondary mass. The price associated with this secondary mass was set at $4.29 per pound for 2008. This price was derived by dividing the price difference between the 2008 baseline Large SUV and Small Car by their mass (weight) difference.

A second key assumption establishes the relationship between vehicle mass and fuel consumption (the inverse of fuel economy, or gallons per mile). Literature indicated that this relationship depends on whether the vehicle employs regenerative braking. Much of the propulsion energy over the urban drive cycle is used to accelerate the mass of the vehicle from a stopped or slowed condition. If a vehicle does not have regenerative braking, then all of this propulsion energy ends up as waste heat dissipated in coast-down or braking. If a vehicle does have regenerative braking then about half of this energy can be recaptured and stored, mitigating the overall impact of mass on fuel consumption. Parameters derived from the literature are

1. 10% change in mass ➔ 6% change in fuel consumption
   For vehicles without regenerative braking (Conventional / Diesel / CNGV)

2. 10% change in mass ➔ 4% change in fuel consumption
   For vehicles with regenerative braking (HEV / PHEV / BEV / FCEV)

In this study, the PHEV, BEV100, and FCEV were all assumed to have regenerative braking, so 10% change in mass was assumed to provide a 4% change in fuel consumption. HEVs also use regenerative braking, but their fuel economy functions were based directly on literature values, so this mass to fuel consumption ratio was not applied to them in the modeling.

A third key assumption establishes a relationship between factory cost and retail price equivalent. In many cases the literature provided a retail price equivalent directly, and in these cases the only modification made was to convert to 2008 dollars, which are the common currency for the FTF Study. In other cases, literature provided data on a factory cost basis, which is the manufacturer's cost to produce or purchase. To adjust factory cost to retail price equivalent, a standard markup of 30% was applied.

The final key assumption is a pair of improvement rates, or learning curves. History has shown that as volumes of a product are produced over time there is improvement in the product design, materials, and production process. This improvement results in lower price and reduction in mass. While the vehicle subsystem prices used in the Vehicle Attribute Model are anchored to literature values, the literature did not in all cases provide the required 5-year data points from 2015 to 2050. In these cases, two improvement rate curves were applied to fill in the gaps. These two curves are shown in Figure 4. The "3-2-1" curve was applied to new technologies where rapid improvement could be expected over the first decade of production, and a more moderate "1-1-1" curve was applied to mature technologies with an established history of mass production. The application of these curves to specific technologies is described in the individual pathway sections that follow.

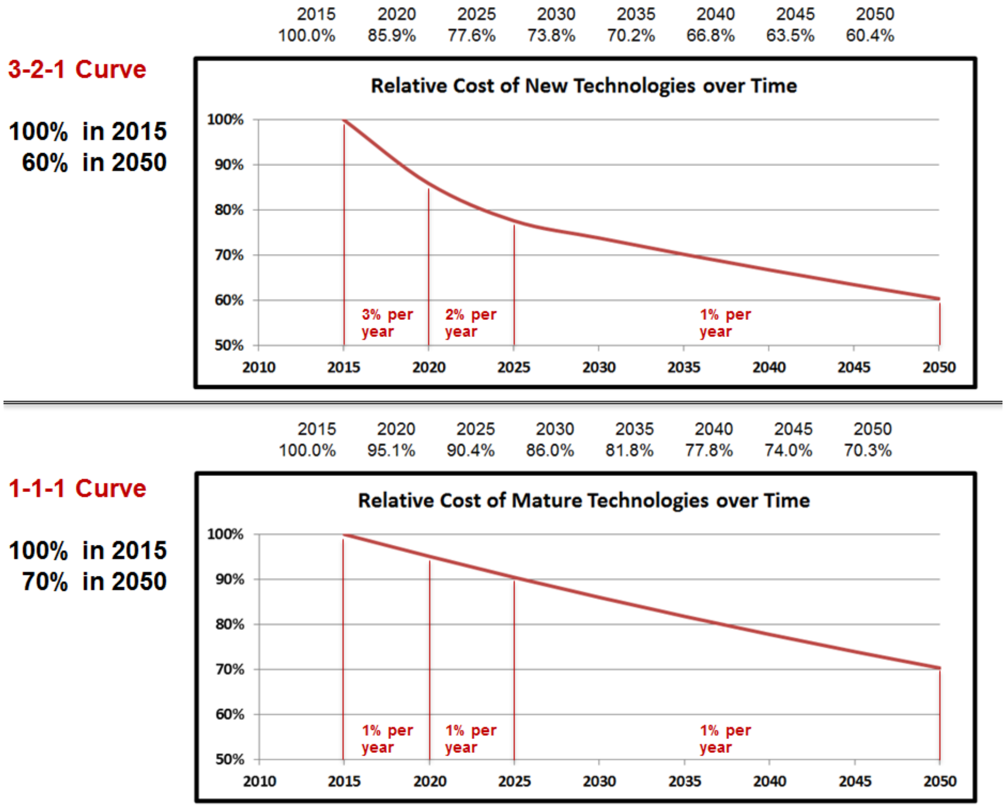


Figure 4 – "3-2-1" and "1-1-1" Improvement Curves

Vehicle Pathways

Conventional and HEV Pathways

As described in the Engines-Vehicles chapter of the FTF Study report, the key characteristic of the Conventional and HEV pathways is a pair of curves that define the upper and lower bound prices of technologies to improve vehicle fuel economy. These two price curves, along with three oil price curves, result in six cases for each of the Conventional and HEV pathways in the Vehicle Attribute Model.

The model begins with the baseline 2008 vehicle as described above. The attributes of this baseline vehicle are held constant over time, with the exception of price. Based on industry experience, the price of the baseline vehicle was assumed to decrease by 1% per year in real terms, beginning in 2008. The vehicle prices for the initial 2015 modeling point were thus taken as 93% of the 2008 prices shown above.

In the literature, the prices of fuel economy improvement through hybridization fell on common curves with the prices of other fuel economy improvement options such as reduced resistance, improved aerodynamics, and lightweighting of the chassis and body, or "glider." For purposes of this modeling work, the Conventional Vehicle and HEV were differentiated by segmenting these common curves into lower and higher fuel economy regions. As shown in Figure 5 using Small Car in 2015 as an example, the region where the fuel economy ratio to the 2008 baseline vehicle is 1.4 or less represents the Conventional Vehicle and the region above a ratio of 1.4 represents the HEV. This line of differentiation was increased by 1% per year from 1.4x in 2015 to 2.0x in 2050. Conventional Vehicle fuel economy was further constrained in the Vehicle Attribute Model by taking the values for conventional vehicle fuel economy in the AEO2010 Reference Case as floor values.

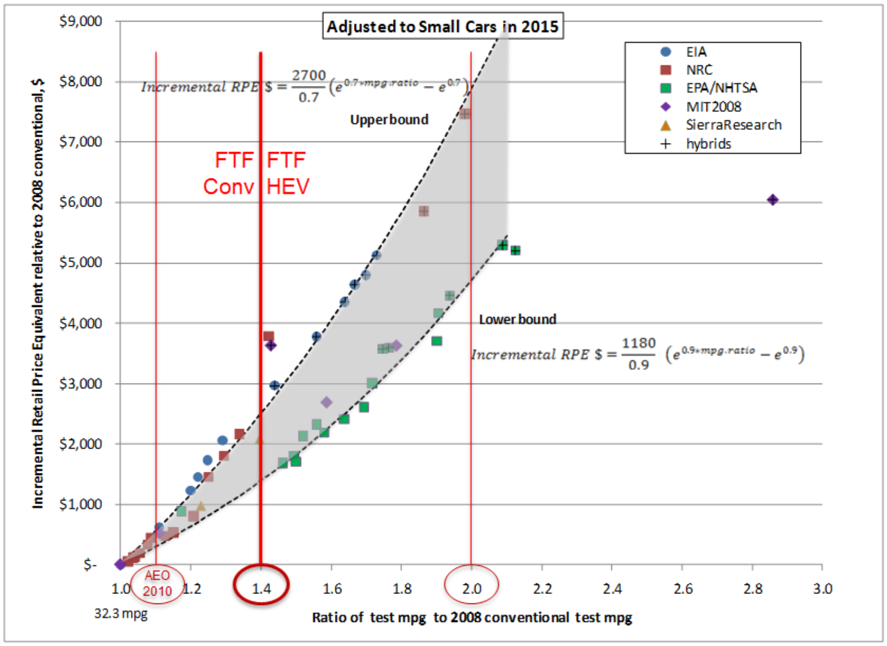


Figure 5 – Price vs. FE for Conv and HEV Small Cars in 2015

HEV fuel economy was defined in the Model by a floor value at the Conv / HEV differentiation line and an upper limit that starts at 2.0x the 2008 baseline vehicle fuel economy in 2015. This upper limit was increased by 1% per year to 2.8x the 2008 baseline vehicle fuel economy value in 2050. The intent in applying this upper limit to HEV fuel economy was to stay within the bounds of improvement options identified in the literature.

The upper and lower bound fuel economy price curves were also adjusted over time by applying the 1-1-1 improvement curve to the upper bound and the 3-2-1 improvement curve to the lower bound, making fuel economy technology more affordable with time.

Within the Conventional and HEV price curve regions described above, each point on a curve represents a possible vehicle design point with unique price and fuel economy. To choose a specific design point to pass to the Vehicle Choice Model (VCM), the VCM utility function was referenced for weighting of the respective utilities of vehicle price and fuel cost-per-mile. This weighting in the VCM default case equates one dollar of vehicle price with one dollar of fuel cost over 47,500 discounted test miles. (A “discounted test mile” is mileage that is paired in a computation with test fuel economy and has been discounted to reflect the present value of future fuel expenditures.) The design point that minimizes the sum of vehicle price plus fuel cost for 47,500 discounted test miles is chosen for each of the six cases of upper/lower fuel economy technology price x low/ref/high oil price. The same six cases are also run using an alternate VCM parameter of 140,000 discounted test miles. These two discounted test mile values represent 3-year and 17-year time horizons for consideration of fuel operating cost.

An example of the methodology for selecting vehicle and HEV design points is shown in Figure 6, which is based on 2035, Small Car, 47500 discounted test miles, and reference and high oil prices. At reference oil price, Conventional Vehicle price + 47500 miles of fuel expenditure has a minimum at the 1.41 fuel economy ratio, so this is the optimal vehicle design point. Similarly, the optimal design point for Conventional Vehicles at high oil is at a fuel economy ratio of 1.58. In 2035, the HEVs have a minimum fuel economy ratio of 1.71, and this becomes the optimal HEV design point for small cars in 2035 under both reference and high oil.

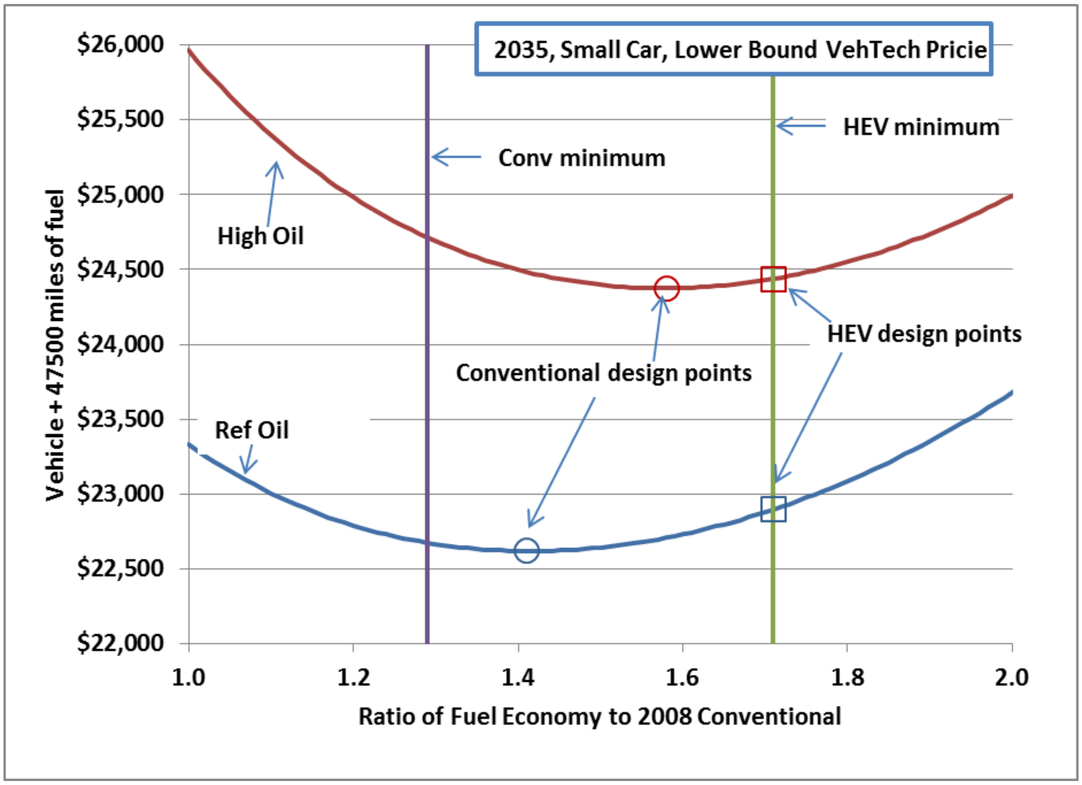


Figure 6

Diesel Pathway

The Diesel pathway is similar to the Conventional / HEV pathways. The only differences are

- Unique Diesel upper and lower price of fuel economy technology curves
- Full curve is used – no Diesel HEV pathway was included in the Study
- Diesel fuel prices instead of gasoline fuel prices

BEV100 Pathway

Like the Conventional and HEV pathways, the BEV100 pathway modeling also uses a pair of curves that define the price of technologies to improve vehicle fuel economy. These curves are a subset of the curves used for the Conventional and HEV pathways – they include all of the same glider technology options but none of the powertrain technology options. The BEV100 modeling also uses upper and lower bound curves for battery price, which is a significant portion of the overall vehicle price. The price of electricity from the plug is the Transportation Electricity price from AEO2010 and for consistency is tied to the AEO2010 low/ref/high oil price cases that are used throughout the Study modeling work. In addition to the plug price, there is a component of electricity price that reflects the capital cost of fixed infrastructure, and this price component differs depending on whether the vehicle is charged predominantly at home ("home charging") or can be charged as needed outside the home as well ("ubiquitous charging").

There are 24 total cases for the BEV100 that reflect all combinations of upper/lower glider technology prices, upper/lower battery prices, low/ref/high oil prices, and home/ubiquitous charging.

The BEV100 modeling begins with the common 2008 baseline vehicle, adjusted to 2015 retail price equivalent as in the Conventional, HEV, and Diesel modeling work. The next step is to recalibrate the vehicle fuel economy from miles per gallon of gasoline in the tank to miles per gallon gasoline equivalent (gge) from the electric plug. Within the Vehicle Attribute Model, gge is defined as 33.7 kWh. This is based on the lower heating value of gasoline and is consistent with current EPA fuel economy labeling practice. However, the VISION tool defines a gge as 36.6 kWh based on the higher heating value of gasoline. The conversion from miles per 33.7 kWh to miles per 36.6 kWh is made in the handoff from the Vehicle Attribute Model to the Vehicle Choice Model. Within the Vehicle Attribute Model, gge electricity is always equal to 33.7 kWh.

To recalibrate fuel economy, the tank-to-wheels efficiency of the baseline conventional vehicle in 2008 was assumed to be 20%. The corresponding electric plug-to-wheels energy pathway was broken down into three elements, and efficiencies were assigned to each element:

1. Plug-to-battery charging efficiency – 85%
   Based on EPA labeling assumption. Efficiency will vary depending on charging power level and ambient conditions. Field data is now being gathered from initial deployments of plug-in vehicles but was not available on a national level over a full year of seasons for this analysis.

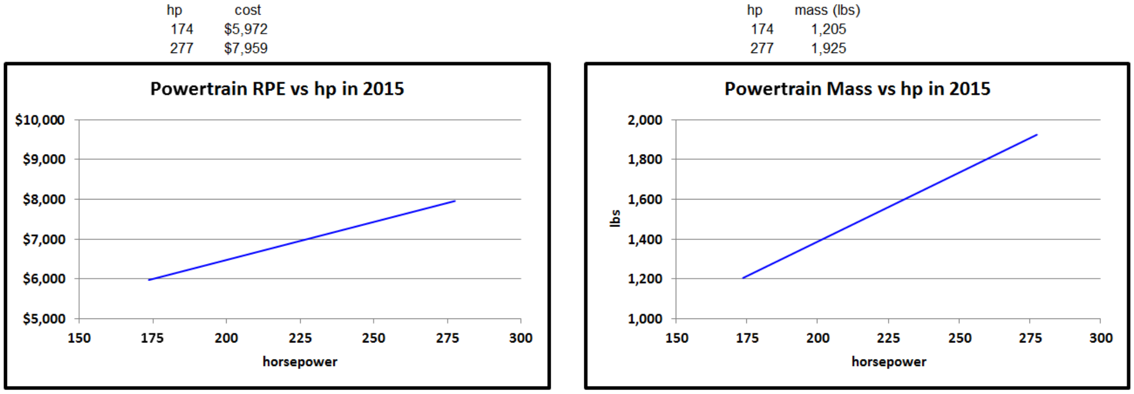
2. Battery-to-DC – 95%
   Based on expert opinion, including discussion within Electric Subgroup. This is the discharge efficiency of the battery. Efficiency will vary with power level, but there is general consensus that this efficiency will be very high when averaged over the full drive cycle.

3. DC-to-torque at the wheels efficiency – 90%
   Based on expert opinion, including discussion within Electric SG. This comprehends losses in conversion from DC to three-phase AC and from AC through the electric machine and gearbox.

A final factor added to the plug-to-wheel efficiency calculation is energy capture from regenerative braking. It was estimated by the Engines-Vehicles Subgroup that half of braking energy could be recaptured over the drive cycle, and this equates to about 11% of total tractive energy (energy applied to tractive force or accessories). Referencing the conventional vehicle energy flow from the Engines-Vehicles chapter and applying the three efficiency elements above, the total BEV100 plug-to-wheel efficiency ratio came to 4.0x the baseline Conventional Vehicle tank-to-wheel efficiency. This put the Small Car baseline test fuel economy in 2015, for example, at 130 mpgge.

The 4.0x ratio was held constant over time on the premise that no increase in efficiency occurs without an associated price increase. Price reduction takes priority over efficiency improvement in the model as technical improvements are made on the electric drivetrain over time. However, in cases where subsystem mass is reduced over time there is an efficiency gain realized at the vehicle level. Plug-to-wheels efficiency parameters remain constant, but miles per unit of energy delivered to the wheels increase as vehicle mass is reduced. There is also an opportunity to improve vehicle-level efficiency through application of glider technology options, as will be described later.

The next step after efficiency recalibration is to remove the conventional powertrain, which consists of the gasoline fuel system, engine, transmission, and exhaust system. The mass and price of these powertrain pieces is not provided in the AEO2010 Reference Case tables, so literature was referenced to derive equations for price and mass as a function of horsepower. Figure 7 shows the values used for 2015 over the range of horsepower levels from Small Car to Large SUV. Consistent with treatment of the baseline vehicle, the powertrain delete prices are reduced by 1% per year over time, and the mass is held constant over time.



hp	cost
174	$5,972
277	$7,959

hp	mass (lbs)
174	1,205
277	1,925

Figure 7 – Powertrain Delete Retail Price Equivalent and Mass Values for 2015

An electric traction system (ETS) was added in place of the deleted powertrain to create an "electric glider." The ETS includes power electronics, the electric motor or electric machine, and the gearbox. The ETS was sized in kilowatts (kW) to match to horsepower of the deleted conventional powertrain. Argument could be made that this ETS is somewhat oversized, since electric traction delivers superior off-the-line (from a standing start) acceleration. However, the Vehicle Attribute Model did not attempt to weigh the value of off-the-line acceleration against highway passing acceleration or hill climbing power. For simplicity, all vehicle pathway powertrains were sized to match the 2008 conventional baseline vehicle. The price and mass for the ETS over time were drawn from the Electric chapter of this report and are shown in Figure 8.

	2015	2020	2025	2030	2035	2040	2045	2050
Price ($/kW)	23.40	22.25	21.16	20.13	19.14	18.20	17.31	16.46
Mass (lbs/kW)	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75

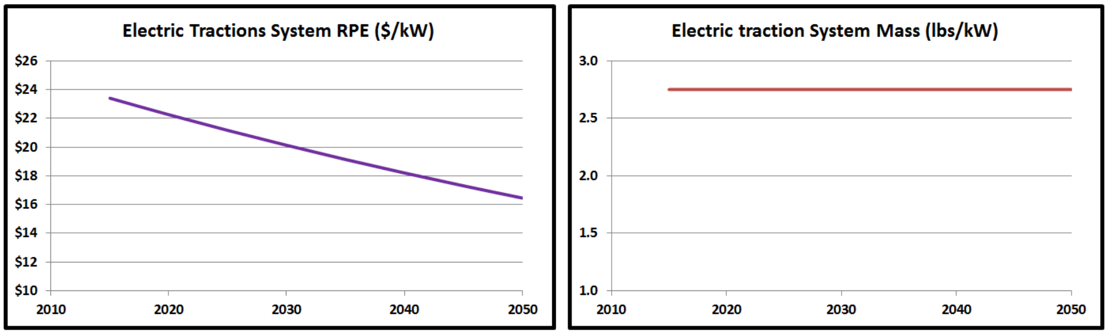


Figure 8 – Electric Traction System Retail Price Equivalent and Mass over Time

The final step in the BEV100 modeling was addition of the battery and adoption of glider fuel economy improvement technologies. These steps must be coupled because the BEV100, by definition, always provides 100 miles of on-road driving range. This means that as glider fuel economy technologies such as lightweighting are adopted to improve efficiency, the battery energy should be reduced to maintain the range at 100 miles. Reducing the battery energy reduces its price and mass, and mass decompounding amplifies these reductions. The model comprehends this feedback mechanism and solves for battery size for each level of fuel efficiency technology adoption. It then chooses the degree of glider fuel economy improvement that minimizes the total of vehicle price plus fuel cost over the number of discounted test miles implicit in the VCM parameters. It should be noted that while the ETS sizing is not explicitly revisited or adjusted to reflect the final vehicle mass, it is implicitly adjusted through mass compounding or decompounding and the associated price adjustment. Figure 9 provides details on the battery sizing calculation.

For each point in the range of possible electric glider fuel economy values:

$$\text{range (miles)} = [\text{battery usable energy (kWh)}]\left[\frac{\text{distance driven (miles)}}{\text{battery usable energy (kWh)}}\right] = (\text{kWh})\,(\text{fuel economy}) = (\text{kWh})\left(\frac{1}{\text{fuel consumption}}\right) \quad \{\,1\,\}$$

$$\text{fuel consumption (kWh / mile)} = (\text{glider fuel consumption})\left(1 + \text{kWh}\ \frac{\%\ \text{increase in fuel consumption}}{\text{kWh}}\right) \quad \{\,2\,\}$$

Combining { 1 } and { 2 } :

$$\text{range} = (\text{kWh})\left(\frac{1}{(\text{glider fuel consumption})\left(1 + \text{kWh}\ \frac{\%\ \text{increase in fuel consumption}}{\text{kWh}}\right)}\right) \quad \{\,3\,\}$$

And solving for battery size:

$$\text{kWh} = \left(\frac{(\text{range})\,(\text{glider fuel consumption})}{1 - (\text{range})\,(\text{glider fuel consumption})\left(\frac{\%\ \text{increase in fuel consumption}}{\text{kWh}}\right)}\right) \quad \{\,4\,\}$$

Figure 9 – BEV100 Battery Sizing Equations

Battery characteristics for this final step are drawn from the Electric chapter. The literature-based chapter data presents battery cost upper and lower bounds per nominal kWh at the pack assembly level. The Electric chapter also provides projections for battery usable state-of-charge (SOC). SOC indicates the percentage of nominal battery energy capacity that is actually used in vehicle operation. SOC is less than 100% because battery durability depends on depth of discharge as well as the number of charge / discharge cycles, and vehicle manufacturers will choose the SOC that best balances battery pack cost with durability requirements. SOC is applied to the pack cost per nominal kWh to derive a pack cost per usable kWh. These costs are then increased by 30% as described above to adjust from factory cost to retail price equivalent. The resulting prices over time are shown in Figure 10, along with the corresponding mass values.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Price - High	$1,463	$1,048	$660	$591	$526	$502	$479	$455	$433
Price - Low	$877	$629	$397	$355	$315	$301	$288	$273	$260
Mass - High		27.7	26.9	26.1	25.3	25.3	25.3	25.3	25.3
Mass - Low		27.7	23.1	20.2	18.7	17.8	16.9	16.1	15.3

Figure 10 – BEV100 Battery Retail Price Equivalent and Mass over Time

The glider fuel economy technology options for the BEV100 are identical to the glider fuel economy technology options for the Conventional and HEV pathways. They are a subset of the Conventional / HEV curves shown in Figure 10 that include all of the same glider technology options but none of the powertrain technology options. Consistent with the Conventional and HEV pathway modeling, the BEV100 upper and lower bound price curves were also adjusted over time by applying the 1-1-1 improvement curve to the upper bound and the 3-2-1 improvement curve to the lower bound, making fuel economy technology more affordable with time. The degree of fuel economy improvement available from glider technology was limited to 1.2x relative to the 2008 baseline vehicle to stay within the range of literature values. The glider fuel economy technology price curves for Small Cars in 2015 are shown in Figure 11.

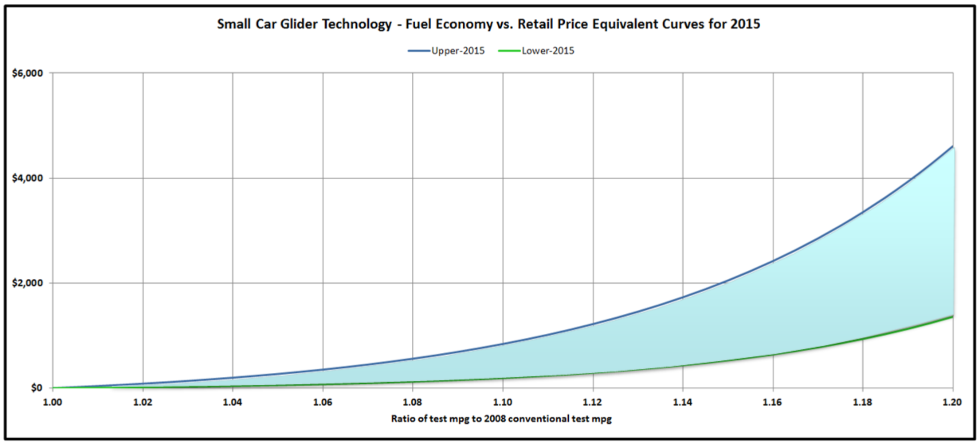


Figure 11 – Price of glider fuel economy technology for Small Cars in 2015

In addition to the vehicle itself, the full price for the BEV100 includes the price of the home-use Electric Vehicle Service Equipment (EVSE). This EVSE is the charging equipment sold with the vehicle and ranges from a simple cord set for 120V charging to a garage-mount panel for 240V or higher charging levels. Electric infrastructure beyond the home-use EVSE itself, such as panel upgrades, wiring, outlet relocation and EVSE installation, is included in the price of electricity rather than the vehicle price. Table 2 shows home-use EVSE prices for the BEV100.

2015	2020	2025	2030	2035	2040	2045	2050
$842	$761	$723	$688	$654	$622	$592	$563

Table 2 – BEV100 Home-use EVSE Prices over Time

The BEV100 was modeled for all five of the FTF Study vehicle classes. However, only the Small Car, Large Car, and Small SUV results were passed to the Vehicle Choice Model. A BEV100 Large SUV or Pickup is technically feasible, but the Electric Subgroup concluded that the BEV100 range limitation would limit its market share in these segments to the point where scale economies would not be reached and macro-level transportation sector effects would not be material.

PHEV10 Pathway

The PHEVs are combinations of elements from the HEV and BEV100. The PHEV10 is closer to the HEV in powertrain configuration, as the electric traction system (ETS) is assumed to be limited to power assist of the engine and not necessarily capable of fully propelling the vehicle over its full duty cycle. For this modeling work, the optimized HEV was taken as the PHEV10 starting point and battery energy was added to provide 10 miles of on-road driving range. The battery price and mass per nominal kWh were identical to those used in the BEV100 modeling, but a narrower SOC window, as defined in the Electric chapter, was applied to arrive at price and mass per usable kWh. The result, shown in Figure 12, was a PHEV10 battery that is slightly more expensive and heavier than the BEV100 battery on a per-usable kWh basis.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Price - High	$1,829	$1,300	$812	$722	$639	$589	$543	$516	$491
Price - Low	$1,096	$780	$488	$433	$383	$353	$326	$310	$295
Mass - High		34.4	33.1	31.9	30.7	29.7	28.7	28.7	28.7
Mass - Low		34.4	28.4	24.7	22.7	20.8	19.1	18.2	17.3

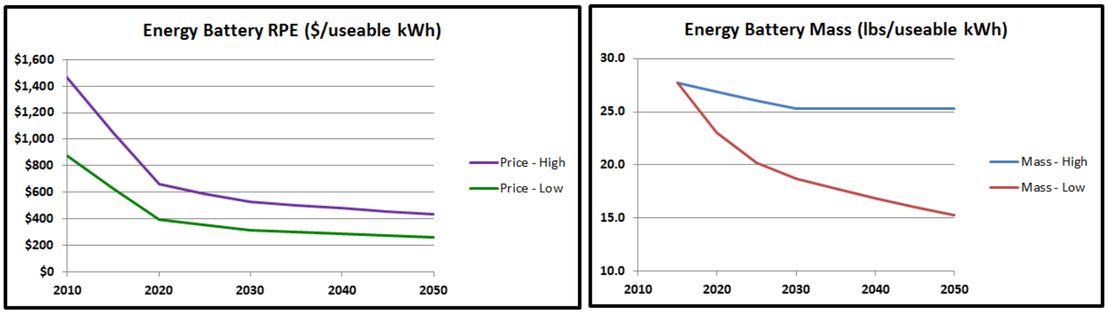


Figure 12 – PHEV10 Battery Retail Price Equivalent and Mass over Time

A unique parameter for the PHEVs is the electric utility factor, which represents the percentage of miles driven on plug energy vs. gasoline (or liquid biofuel) energy. For the PHEV10, a utility factor of 27% was applied in the home charging cases and a utility factor of 50% was applied in the ubiquitous charging cases. These utility factors do not influence the design point for the PHEV10, since it is built off of an HEV that was optimized with all miles driven on gasoline. However, the utility factors do influence overall fuel economy and the fuel cost per mile calculated in the Vehicle Choice Model.

The PHEV10 prices for home-use Electric Vehicle Service Equipment (EVSE) are lower than those for the BEV100 due to prevalence of 120V charging with a simple cord set rather than higher voltage / higher power options. The PHEV10 home-use EVSE prices are shown in Table 3.

2015	2020	2025	2030	2035	2040	2045	2050
$429	$388	$369	$351	$334	$317	$302	$287

Table 3 – PHEV10 Home-use EVSE Prices over Time

PHEV40 Pathway

The PHEV40, like the PHEV10, combines elements of the HEV and the BEV100. While the PHEV10 modeling work builds off of an HEV baseline, the PHEV40 modeling work follows the BEV100 modeling steps, but with a couple of key differences. The first difference is in the handling of the baseline powertrain. Like all of the pathways, the PHEV40 begins with the 2008 conventional baseline vehicle with price adjusted to 2015 via 1% per year reduction. However, where the BEV100 modeling deleted the conventional powertrain, the PHEV40 keeps the conventional powertrain in place but scales it to a smaller size. This scaling is possible because the role of the conventional engine is no longer to propel the vehicle directly, but to act instead as an engine / generator set to sustain onboard electric power after battery energy has been exhausted. In this modeling work, the engine / generator set is assumed to retain 75% of the conventional powertrain price and mass. The PHEV40 then adds a full electric traction system, identical to that of the BEV100.

The battery state-of-charge window for the PHEV40 is identical to that of the PHEV10, and the price and mass per usable kWh is as shown in Figure 12 for the PHEV10 pathway. The PHEV40 does have unique utility factors of 65% in the home charging cases and 80% in the ubiquitous charging cases. As expected, the larger battery capacity means a higher utility factor, or higher percentage of miles driven on plug energy, for the PHEV40 in comparison to the PHEV10. The PHEV40 also has a unique set of home-use EVSE prices, which again reflect a unique mix of charging power levels and associated equipment. The PHEV40 home-use EVSE prices are shown in Table 4.

2015	2020	2025	2030	2035	2040	2045	2050
$635	$574	$546	$519	$494	$470	$447	$425

Table 4 – PHEV40 Home-use EVSE Prices over Time

The PHEV40 optimization of glider fuel economy technology adoption and corresponding adjustment of battery size is performed as described in the BEV100 section above. The only difference, other than the 40 vs. 100 mile battery range, is that the fuel cost per mile reflects a mixture of plug energy and gasoline (or biofuel) energy miles rather than plug energy only. After computing the optimal efficiency design point, both plug energy (charge depleting) and gasoline (charge sustaining) fuel economy values are passed to the Vehicle Choice Model.

FCEV Pathway

The FCEV pathway uses the same pair of curves as the BEV100 / PHEVs to define the price of fuel economy improvement technologies. These curves represent glider technology options, and the FCEV, like all of the other vehicle technology pathways, is built off of the common glider. There are also upper and lower bound curves for technologies unique to the FCEV, which include the fuel cell system (fuel cell stack plus balance of plant), a battery for power assist, and the hydrogen storage system. The price of hydrogen fuel has an upper and lower bound that is based on modeling work done by the Hydrogen Subgroup. Hydrogen fuel price is not tied to the AEO2010 low/ref/high oil price cases because it was found to be more sensitive to station capital cost, scale, and utilization than to natural gas feedstock costs. There are 8 total cases for the FCEV that reflect all combinations of upper/lower glider technology prices, upper/lower FCEV system technology prices, and upper/lower hydrogen prices.

The FCEV begins with the common 2008 baseline vehicle, adjusted to 2015 retail price equivalent as in the modeling work for other pathways. The next step is to recalibrate the vehicle fuel economy from miles per gallon of gasoline to miles per kilogram (kg) of hydrogen. In this modeling work, one kg of hydrogen was taken to be a gallon gasoline equivalent, or gge. The lower heating values of a kg of hydrogen and a gallon of gasoline are within 1% of each other, and the Gibb's free energy of a kg of hydrogen, which is relevant to the fuel cell stack power output, is also within several percent of the lower heating value of gasoline.

To recalibrate fuel economy, the tank-to-wheel fuel efficiency of the baseline vehicle in 2008 was assumed to be 20%. The corresponding FCEV tank-to-wheel efficiency was taken as 50% based on analysis and references from the Hydrogen chapter. As in the BEV100 and PHEV cases, energy capture from regenerative braking was factored in on top of the once-through efficiency. The result was a total tank-to-wheel efficiency ratio of 2.7x the baseline conventional vehicle efficiency. This put the Small Car test fuel economy in 2015, for example, at 88 mpgge.

The 2.7x ratio was held constant over time on the premise that no increase in efficiency occurs without an associated price increase. Price reduction takes priority over efficiency in the model as technical improvements are made to the fuel cell propulsion system over time. However, in cases where subsystem mass is reduced over time there is an efficiency gain realized at the vehicle level. Tank-to-wheels efficiency parameters remain constant, but miles per unit of energy delivered to the wheels increase as vehicle mass is reduced. There is also an opportunity to improve vehicle-level efficiency through application of glider technology options.

The FCEV model follows the same initial steps as the BEV100 model, with removal of the powertrain from the 2008 conventional baseline vehicle and the addition of a full electric traction system. At this point the FCEV “electric glider” is identical to that of the BEV100.

As described in the Hydrogen chapter, all current-generation FCEVs use a battery to supplement the fuel cell stack. Power from the battery enables faster vehicle start-up from cold, provides quick response for transients, keeps the fuel cell stack in a more favorable operating window, and recaptures braking energy. The FCEV battery role is similar to that of the HEV battery. It requires a prescribed level of power but has minimal energy storage requirements. AEO2010 did not provide details on the price and mass of the HEV battery, so literature sources were used to gather this detail for use in the FCEV modeling work. Based on published specifications of existing FCEVs, battery power levels were set to 20% of the total propulsion system power level. Figure 13 shows the battery price and mass over time. Note that in this case the battery units are kW (power). This differs from the kWh (energy) units used in the BEV100 / PHEVs modeling work.

	2015	2020	2025	2030	2035	2040	2045	2050
Upper	$66	$57	$51	$49	$47	$44	$42	$40
Lower	$44	$38	$34	$33	$31	$30	$28	$27
Mass (lbs/kW)	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8

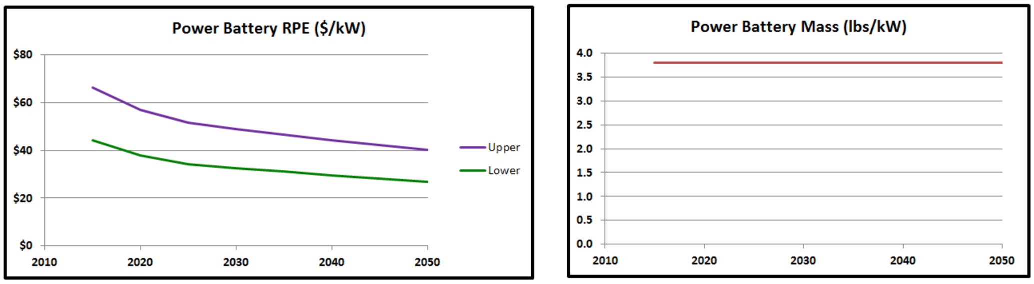
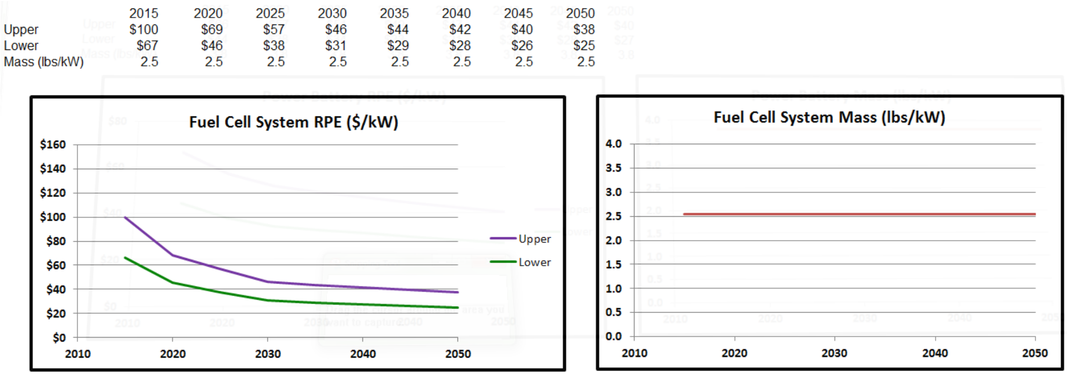


Figure 13 – FCEV Battery Retail Price Equivalent and Mass over Time

The fuel cell system (FCS) is sized to provide equivalent power to the conventional powertrain that it replaces. This ensures that the FCEV has adequate power even when the battery charge is depleted. With the battery for power assist, it could be argued that this FCS is somewhat oversized, but there are several factors that support this choice of a full-power FCS in the modeling. One factor is that this sizing provides an allowance for degradation of the fuel cell stack. The stack, like batteries, will degrade in performance over time, but the design intent of the FCEV will be to ensure adequate performance all the way to the end of vehicle life. Another factor to support this FCS sizing is that the FCEV has a more complex high-voltage architecture than the BEV100 or PHEVs due to its dual high-voltage power sources, the battery and the FCS. Detailed work on electrical system architecture options was beyond the scope of this model, and the power electronics prices on the FCEV were not increased over those of the BEV100 or PHEVs to reflect this added complexity, so the conservative sizing of the FCS provides some allowance to compensate for this simplified approach.

The FCS price and mass upper and lower bounds were drawn from the Hydrogen chapter of the report and are shown in Figure 14. In addition to improvement curves, the FCS prices also reflect a ramp-up from lower volumes in 2015 to "full volume" production by 2030. The same volume ramp-up was applied to the hydrogen storage system described below, as these subsystems are unique to the FCEV and have not yet been produced at more than demonstration scale.



	2015	2020	2025	2030	2035	2040	2045	2050
Upper	$100	$69	$57	$46	$44	$42	$40	$38
Lower	$67	$46	$38	$31	$29	$28	$26	$25
Mass (lbs/kW)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5

Figure 14 – Fuel Cell System Retail Price Equivalent and Mass over Time

The final step in FCEV modeling was addition of the hydrogen storage system (HSS) and adoption of glider fuel economy improvement technologies. As with the batteries for BEV100 and PHEV40, these steps were coupled to achieve the optimal balance between vehicle efficiency and onboard energy storage. In the FCEV case, the onboard hydrogen storage is sized to deliver 300 miles of on-road driving range, with the assumption that 95% of target density is achieved on average when fueling at a hydrogen station. HSS price and mass were broken down into detail fixed and per-kg components by the Hydrogen Subgroup. This detail was needed in order to normalize the characteristics of composite wrapped pressure vessels across the FCEV and CNGV pathways that use different pressure levels and different sizing of the same underlying technology. Figure 15 shows the price and mass of an example 6kg HSS over time. This HSS size might be typical of a larger FCEV.

	2015	2020	2025	2030	2035	2040	2045	2050
Cost - Upper	$12,524	$8,604	$7,109	$5,778	$5,495	$5,226	$4,969	$4,726
Cost - Lower	$6,216	$4,270	$3,528	$2,868	$2,727	$2,594	$2,466	$2,346
Mass - Upper	259	259	259	259	259	259	259	259
Mass - Lower	259	246	234	223	212	202	192	182

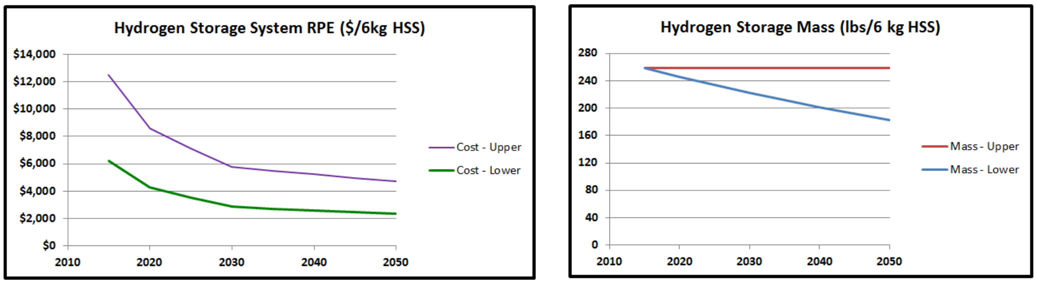


Figure 15 – Retail Price Equivalent and Mass of 6 kg Hydrogen Storage System over Time

CNGV Pathway

The CNGV pathway is similar to the Conventional Vehicle pathway from an engine and glider fuel economy option standpoint, and it is similar to the FCEV pathway in its approach to fuel storage system sizing. On the engine side, one difference is that there are modifications required to the engine and fuel delivery system to change the powertrain from liquid fuel (gasoline or biofuel) combustion to gaseous fuel (natural gas) combustion. On the fuel storage side, CNGVs with their lower storage pressures have the additional option of steel tanks that would not be practical on an FCEV. There are 12 total cases for the CNGV that reflect all combinations of upper/lower powertrain plus glider technology prices, upper/lower CNGV system prices that include composite/steel fuel storage tanks, and CNG fuel prices tied to low/ref/high oil price cases.

While CNGV efficiency is similar to that of conventional vehicles, the CNG Subgroup concluded from survey of existing CNGVs that there is some difference. The fuel economy of the 2008 baseline conventional vehicle was recalibrated to be 7% higher when burning CNG fuel, and this gain was increased further as the CNG fuel storage system mass was subtracted out of this baseline starting point.

CNGV system prices, excluding fuel storage, consist of engine hardening, fuel injection modification and onboard diagnostics and certification. CNGVs are produced only in small volumes in the US today, and this results in high costs for parts logistics and assembly. In the Vehicle Attribute Model, CNGVs were assumed to remain at low volume through 2015 but reach higher volumes by 2020 such that standard parts flow and factory assembly processes would apply. From 2020 on there are no incremental assembly costs relative to Conventional Vehicles and no or minimal custom diagnostics or calibration costs relative to Conventional Vehicles. Figure 16 shows upper and lower CNGV system prices over time for all of the system elements except fuel storage.

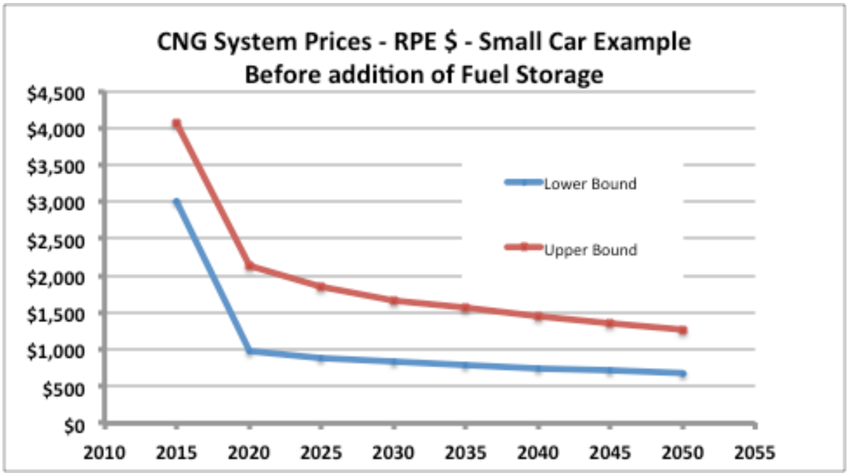


Figure 16 – CNGV System Retail Price Equivalent

CNGVs have two fuel storage system technology options: steel tanks, which are lower in cost but heavier, and composite tanks, which are higher in cost but lighter in weight. To limit model cases, upper and lower bound price and mass were not assigned to each of these two storage options. Instead, composite tanks were used to define the upper-bound prices and steel tanks were used to define the lower-bound prices. Composite CNG storage price assumptions were aligned with price assumptions for the composite hydrogen storage system, with adjustments for storage pressure as appropriate for 3600 psi CNG. The CNG storage price and mass curves over time are shown in Figure 17, for an assumed 10 Gasoline Equivalent Gallon (gge) storage system.

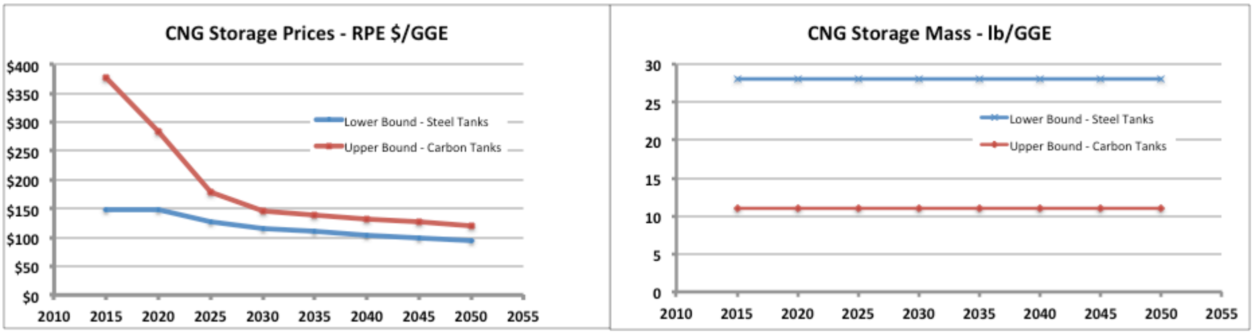
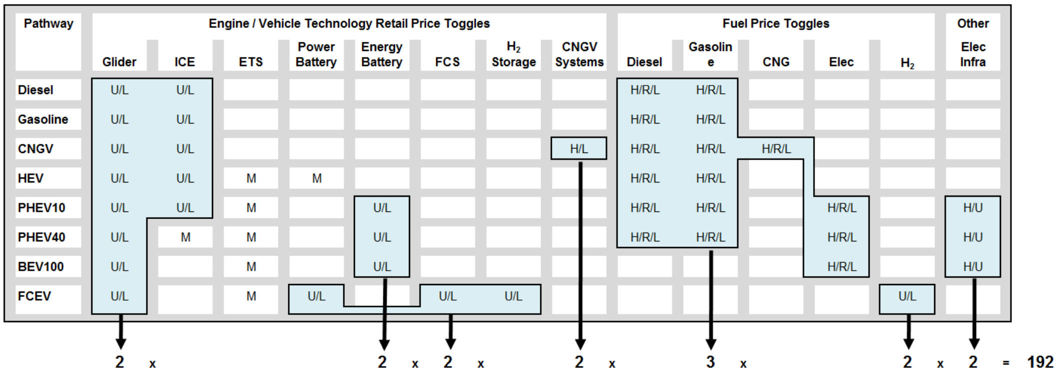


Figure 17 – CNG Storage Retail Price Equivalent and Mass over Time

The final step of CNGV optimization is similar to that of the FCEV pathway. The CNGV storage system sizing is balanced with fuel economy technology adoption, with the requirement that the vehicle deliver 300 miles of on-road driving range. An additional constraint placed on the CNGV during this optimization was that the degree of fuel economy technology adoption is not allowed to be less than that of the corresponding conventional vehicle in AEO2010.

Model Output Cases

Across the full range of vehicle pathways there are 192 unique cases defined by unique sets of vehicle and fuel input parameters. These cases are summarized in Figure 18. This figure shows the full array of "toggles" and their possible combinations.



Pathway	Engine / Vehicle Technology Retail Price Toggles								Fuel Price Toggles					Other
	Glider	ICE	ETS	Power Battery	Energy Battery	FCS	H_2 Storage	CNGV Systems	Diesel	Gasoline	CNG	Elec	H_2	Elec Infra
Diesel	U/L	U/L							H/R/L	H/R/L				
Gasoline	U/L	U/L							H/R/L	H/R/L				
CNGV	U/L	U/L						H/L	H/R/L	H/R/L	H/R/L			
HEV	U/L	U/L	M	M					H/R/L	H/R/L				
PHEV10	U/L	U/L	M		U/L				H/R/L	H/R/L		H/R/L		H/U
PHEV40	U/L	M	M		U/L				H/R/L	H/R/L		H/R/L		H/U
BEV100	U/L		M		U/L							H/R/L		H/U
FCEV	U/L		M	U/L		U/L	U/L						U/L	

2 x 2 x 2 x 2 x 3 x 2 x 2 = 192

H2 = hydrogen; U/L = upper/lower; H/R/L = high/reference/low oil price cases from AEO2010; H/U = home charging only or ubiquitous charging (home + public/private)

Figure 18 – Vehicle Attribute Model Case Combinations

It should be noted that all toggles move together across technology pathways (vertically in Figure 18). For example, if the price of glider and ICE technologies is set to the upper bound, then it is set to the upper bound for all pathways together to ensure consistency. The Vehicle Choice Model (VCM) applies this requirement when using Vehicle Attribute Model results in its marketplace model. The time horizon for weighting of vehicle price and fuel cost-per-mile is not included above as a toggle; changing this parameter from 47,500 to 140,000 discounted test miles generates 192 additional cases, for a total of 384 cases.

Shown in Figures 19 and 20 are two examples of model outputs for the Small Car vehicle class and a time horizon of 47,500 discounted test miles. Vehicle price plus fuel cost for 47,500 discounted test miles is plotted on the left half of each figure, and grams of carbon dioxide per mile is plotted on the right half. Figure 19 depicts the case in which all technology prices are at their upper bound and all fuel prices are at their lower bound. Figure 20 reverses these settings and puts all technology prices at their lower bound and all fuel prices at their upper bound. The carbon footprint plots do not include advanced biofuels in the liquid fuel mix, and electric charging is set to "home." While these two output examples are for individual cases, the downstream analysis based on the VCM and VISION tool results focused on clusters of cases rather than individual cases.

Note: this example is 1 case of 384 cases that are generated in the Vehicle Attribute Model

Note: this example is 1 case of 384 cases that are generated in the Vehicle Attribute Model

Figure 19 – Example Small Car Outputs with Technology Prices High and Fuel Prices Low

Note: this example is 1 case of 384 cases that are generated in the Vehicle Attribute Model

Note: this example is 1 case of 384 cases that are generated in the Vehicle Attribute Model

Figure 20 – Example Small Car Outputs with Technology Prices Low and Fuel Prices High

Model Technical Notes

The Vehicle Attribute Model was constructed entirely within Microsoft Excel 2007. It uses a series of macros to cycle through the range of cases for each vehicle pathway and writes the resultant vehicle attributes into an output table for handoff to the Vehicle Choice Model (VCM). The Vehicle Attribute Model workbook also includes a number of tools that can be used to query the data on an individual pathway, or “Swimlane,” basis. Many of the key inputs, including fuel prices and technology prices, are generated in separate work that is exogenous to the Vehicle Attribute Model. Sources of these inputs are noted within the model, and include both literature sources and FTF Study Subgroup analysis work.

Complete Model Output Tables

Model output tables can be found in the Vehicle Attribute Model file Inputs.xls