

## CHAPTER TWO

# LIGHT-DUTY VEHICLES

### INTRODUCTION

The light-duty (LD) vehicle segment of the U.S. transportation sector accounts for nearly two-thirds of total transportation energy consumption, the vast majority of which is petroleum based. Personal mobility measured in vehicle miles traveled has been growing steadily for decades, and for a large part of the population, the mobility that comes from owning a vehicle is necessary for daily life.

This chapter begins with an overview of the U.S. LD vehicle market—size/scale, production methods, business model structure, vehicle segments/classes, and an overview of the timeline required for new technology adoption. A significant part of this study was an integrating analysis to quantify and compare the economic interaction of the various LD fuel-vehicle systems considered by this study. This chapter describes results of the LD vehicle integrated analysis.

The analysis is based on ranges of assumptions and input data drawn from publicly available information. The results provide a number of ranges as calculated outputs (e.g., ranges of vehicle and fuel expenditures, ranges of greenhouse gas [GHG] emissions, ranges of vehicle shares, and ranges of fuels shares)—not projections or forecasts—from which insights about fuel-vehicle systems have been drawn. The findings are drawn from the calculated outputs and the directional trends observed with the fuel-vehicle systems. The chapter concludes with a discussion of the key findings and insights drawn from the analysis. The focus of this chapter is on results pertaining to fuel-vehicle system fleet shares and economics in 2050. The analytical results related to GHG emissions and energy secu-

rity can be found in the chapters that specifically address those topics.

This work suggests that there are opportunities for alternative fuel-vehicle systems to earn meaningful presence in the United States by 2050. Alternative fuel-vehicle systems are defined as follows:

- Advanced Biofuels – liquid internal combustion engine (ICE) vehicles fueled by cellulosic biofuels
- CNGVs – ICE vehicles fueled by compressed natural gas (CNG)
- PHEVs – plug-in hybrid electric vehicles fueled by gasoline/biofuel blends and electricity from the grid
- BEVs – battery electric vehicles fueled by electricity from the grid
- FCEVs – fuel cell electric vehicles fueled by hydrogen from natural gas.

Fuel price assumptions have a large impact on the economic competitiveness of the alternative fuel-vehicle systems. Substantial improvements in the fuel economy of the LD vehicle fleet are possible from many incremental improvements to conventional liquid ICE vehicles and increasing penetration of electrified vehicle systems—hybrid electric vehicles (HEVs), plug-in electric vehicles (PEVs)<sup>1</sup>, and FCEVs. The internal combustion engine is likely to be a dominant propulsion system because it can be used in gasoline, biofuels, natural gas, hybrid, and plug-in hybrid vehicles. CNGVs could be the strongest competitor to liquid ICE vehicles. While there are significant uncertainties, the analysis identified several alternative fuel-vehicle systems that appear

<sup>1</sup> PEV is a term that refers to both plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs).

to be competitive and provide significant economic value under certain conditions.

## BACKGROUND

### Description of Current Light-Duty Vehicle Industry and Market

#### Size, Scale, and Transition Time

In 2010, there were approximately 72 million new light-duty vehicles sold around the world. The U.S. auto market, at about 11.6 million vehicles, represented about 16% of the world's LD vehicle total. According to the Energy Information Administration's Annual Energy Outlook 2010 (AEO2010), the global LD vehicle fleet is approximately 830 million and the U.S. fleet is about 230 million.

Six large global company groups (Toyota, GM, Volkswagen, Hyundai-Kia, Ford, and Renault-Nissan) sold over 5 million vehicles each and collectively accounted for ~55% of global sales. Another seven global company groups (Fiat-Chrysler, Honda, PSA, Suzuki, Mazda, Daimler, and BMW) sold between 1.5 and 4.0 million vehicles each, accounting for ~25% of global sales. Numerous small and/or country-specific manufacturers account for the remaining 20% of the market.

Original equipment manufacturers (OEMs) rely on the use of globally common components, systems, designs, and processes to cost-effectively produce high volumes of LD vehicles. Mass-market OEMs use common vehicle and powertrain platforms to manufacture multiple vehicle brands and body-style derivatives that ideally have annual production volumes of many hundreds of thousands. These platforms are typically built in plants around the world to align capacity and supply with expected demand. Significant amounts of engineering hours and capital dollars are required for each vehicle and powertrain platform and each specific vehicle brand and model. These resources are expended years in advance of the start of production and revenue generation.

LD vehicle development lead time, production life cycle, and model longevity are very similar across the global auto manufacturers.<sup>2</sup> It can take

<sup>2</sup> Center for Automotive Research (with support from the Environmental Defense Fund), *How Automakers Plan Their Products: A Primer for Policymakers on Automotive Industry Business Planning*, July 2007.

two to four years to conceptualize and develop a vehicle. Mild updating and refreshing takes the least amount of lead time, while all-new platforms and vehicle models take the most time. Powertrain development lead times are typically longer than those for a vehicle. Vehicle platforms are typically used for at least two life cycles of vehicle models and derivatives. A vehicle model is typically in the market for 4 to 6 years, so a core platform is usually designed and intended to remain in production for 8 to 12 years. OEMs typically manage their product portfolios with a 5- to 10-year horizon, and plan the development and launch of vehicles to match their best assessment of market demand and to balance workload, engineering expense, capital investment, and showroom freshness. The longevity of vehicles in a country's operating fleet varies. An analysis of AEO2010 vehicle survival as a function of age indicates the mileage-weighted average lifetime of cars is 13 years and of light trucks is 14 years. However, a study by Oak Ridge National Laboratory determined that the median lifetime for a 1990 model year automobile was 16.9 years.<sup>3</sup> Further, a recent analysis by R. L. Polk indicates that at recent LD vehicle sales rates and longevity levels it would take 17 years to replenish the entire U.S. inventory.<sup>4</sup>

New vehicle programs are rarely developed from a "clean sheet." Existing platforms, systems, and components are highly leveraged to minimize new engineering expense, capital investment, and development time. New and advanced technology developed by the manufacturers and/or suppliers is typically high risk and high investment, and deployed gradually in brands and vehicle models according to expected market demand and consumer willingness to pay. This also allows for cycles of technology learning during volume ramp-up to lower cost and improve performance. To keep invention off the critical path, the lead time for development of new technology must precede the start of vehicle program timing. Synchronizing new technology development timetables with vehicle program timetables can be difficult. As new technologies evolve and improve in terms of performance and cost, wider applications in a manufacturer's vehicle portfolio are common, assuming market demand. It can take

<sup>3</sup> Oak Ridge National Laboratory, *Transportation Energy Data Book: Edition 29* (prepared for the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy), June 2010.

<sup>4</sup> The Economist Online, "US Cars and Light Trucks," modified February 25, 2012, <http://www.economist.com/node/21548275>

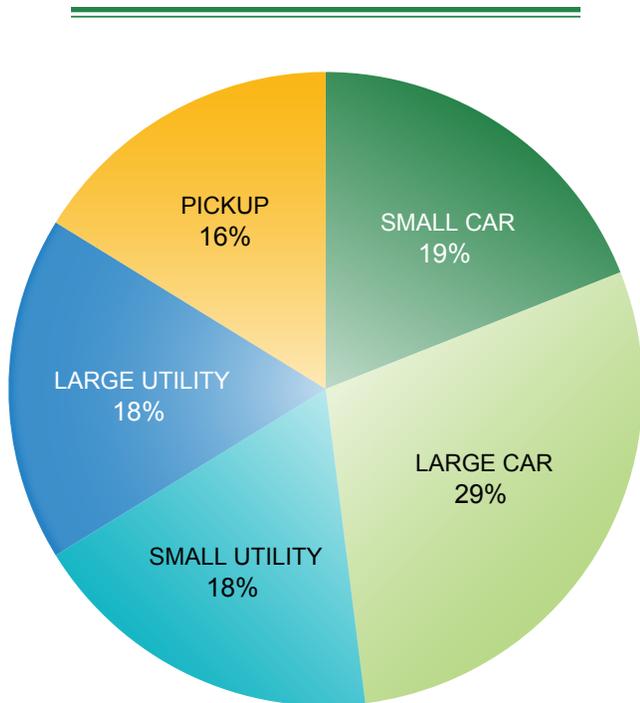
many years to deploy new technology throughout a manufacturer’s full portfolio of products, and a decade or more to significantly penetrate the operating vehicle inventory due to the increased longevity of vehicles in operation.

### Vehicle Segments/Classes

The U.S. LD vehicle market comprises many different vehicle type segments and classes, generally delineated by vehicle size and type, which were consolidated into the five segments shown in Figure 2-1. The integrated analysis for this study included each vehicle segment.

Vehicles that include electrified propulsion systems represent a wide range of technologies. “Mild hybrids” (e.g., Honda Civic hybrid) and “strong hybrids” (e.g., Toyota Prius) run on liquid fuel and provide little or no pure electric motor driving range. These vehicles are referred to as HEVs

and are included in the liquid ICE category. “Plug-in hybrids” draw electric energy from the grid to charge batteries, then use liquid fueled engines for propulsion either together with grid electricity or when battery power reaches a minimum and/or to maintain minimum charge for continued electric operation. These vehicles are referred to as PHEVs and are included in the Electric category. While there are technical similarities between some strong HEVs and low-range PHEVs, the study used the ability to draw energy from the grid as a differentiator. Dedicated battery electric vehicles run on batteries charged from the grid exclusively and are referred to as BEVs. Finally, fuel cell electric vehicles are electric vehicles that carry hydrogen on board as an energy carrier. The hydrogen is converted by the fuel cell into electricity to run an electric motor for propulsion. These vehicles are referred to as FCEVs. Natural gas vehicles are powered by internal combustion engines that run on compressed natural gas stored on board the vehicle. They are referred to as CNGVs.



Note: “Small Car” comprises Two-seater, Mini-compact, Sub-compact, and Compact. “Large Car” comprises Midsize and Large. “Small Utility” comprises Small Van and Small Utility. “Large Utility” comprises Large Utility and Large Van. “Pickup” comprises Small Pickup, Large Pickup, and Commercial Light Truck. Commercial Light Truck is not included in light-duty vehicle sales in the Annual Energy Outlook, but is included in VISION.

Source: Energy Information Administration’s AEO2010 Reference Case.

**Figure 2-1.** 2010 Segment Share of New U.S. Light-Duty Vehicle Sales

Table 2-1 lists the four fuel-vehicle systems evaluated in this study and provides reference to more detailed discussion provided in study chapters. The table provides nomenclature linkage between the fuel-vehicle system chapters and the terms used in the integrated analysis.

### Description of Individual Fuel-Vehicle Systems

The following sections summarize the primary benefits and challenges from each of the fuel-vehicle systems that are discussed in greater detail in the fuel-vehicle system chapters.

#### Liquid ICE

Chapter Nine, “Light-Duty Engines & Vehicles,” addresses technologies to reduce fuel energy consumption of LD vehicles powered by ICEs burning liquid fuels. This includes spark and compression ignition engine technologies, improved drivetrains, hybridization, low rolling resistance tires, improved aerodynamics, and mass reduction.

#### Primary Advantages to the Use of Liquid Fueled ICEs

The principal advantages of conventional liquid fueled ICEs include the maturity and scale of the

Fuel-Vehicle System	Propulsion System	Fuel(s)	Scope of Fuel-Vehicle System Chapter	Fuel-Vehicle System Chapter Title
<b>Liquid ICE</b>	Internal Combustion Engine	Gasoline/Biofuel Blends Diesel/Biofuel Blends	ICE Vehicles Hybrid ICE Vehicles (HEV)	Light-Duty Engines & Vehicles
<b>PEV*</b> <b>PHEV10</b> <b>PHEV40</b> <b>BEV100</b>	Electric Motor and Internal Combustion Engine Electric Motor	Electricity Gasoline/Biofuel Blends (for PHEVs)	PHEVs BEVs Electricity Supply Chain and Charging Infrastructure	Electric
<b>CNGV</b>	Internal Combustion Engine	Compressed Natural Gas	CNGVs Compressed Natural Gas Dispensing Infrastructure	Natural Gas
<b>FCEV</b>	Electric Motor	Compressed Hydrogen	FCEVs Hydrogen Dispensing Infrastructure	Hydrogen

\* PHEV10 allows up to 10 miles of driving in all-electric mode, PHEV40 allows up to 40 miles of driving in all-electric mode, and BEV100 has up to 100 miles of driving range.

**Table 2-1.** Fuel-Vehicle Systems Included in Study

technologies involved, with high-volume, low-cost supply chains and manufacturing capability. The liquid fuels supply chain is also mature, large-scale, and well developed. Fuel availability is ubiquitous, as is the ICE vehicle maintenance and servicing industry. Customers are well versed in the operation and fueling of liquid ICE vehicles. Adding liquid biofuels to the existing system is technically viable and can be done for relatively low incremental cost to the vehicle and fuel-dispensing infrastructure.

Many of the vehicle and propulsion system fuel economy improvement technologies considered for the liquid ICE fuel-vehicle system are applicable to other fuel-vehicle systems. Advances in vehicle-level technologies such as improved aerodynamics, reduced rolling resistance, and lightweighting apply to all fuel-vehicle systems. Advances in ICE vehicle technologies are applicable to both liquid and CNG-fueled engines. Friction reduction, advanced valving, electrifying accessories, direct injection, reduced rolling resistance, and improved aerodynamics each provide incremental fuel economy improvements in the area of 1–6%. Smaller

displacement turbocharged engines and advanced transmissions yield 2–15% each, and start-stop technology can provide 2–8% improvement. The most significant fuel economy improvements come from hybridization (25–55% improvement) and mass reduction (30% reduction may yield up to 28% fuel economy improvement). These are estimates for 2015–2025 according to the literature surveyed, and they are not additive.

### Primary Challenges to the Continued Use of Liquid Fueled ICEs

The principal hurdle to achieving significant fuel economy improvement in this fuel-vehicle system is achieving cost levels that provide an attractive value proposition to consumers. Incremental ICE improvements such as stratified charge/lean burn, homogeneous compressed charge ignition, clean diesel, exhaust heat recovery, and fuel flexibility require cost reduction to become attractive to consumers and be used more widely on new vehicles. Achieving the maximum potential of fuel economy increase from downsizing and turbocharging

requires an increase in the minimum octane number of U.S. gasoline or vehicles dedicated to the use of high concentration alcohol-gasoline blends. Increasing gasoline octane increases refinery energy use and GHG emissions and should be evaluated by considering vehicle and refinery impacts. Higher octane can also be achieved by blending ethanol with regular gasoline. The use of advanced lightweight materials yields more fuel economy improvement, but requires significant reduction of material and manufacturing costs for mass-market applications. Hybridization, including batteries, motors, controllers, and regenerative braking, are more expensive and face significant cost barriers.

For maximum benefit, multiple technologies must be developed and deployed as systems. It will take many years for some of these advanced engine/vehicle/fuel technologies to achieve material penetration in the overall U.S. LD vehicle fleet due to adoption hurdles, long development times, vehicle life cycles, and vehicle longevity in the market.

Beyond fuel economy improvements, there are further opportunities to reduce GHG emissions and improve U.S. energy security through low-carbon fuels, such as those derived from cellulosic biomass. These system options, advantages, and hurdles are discussed in detail in Chapter Six, “Greenhouse Gases and Other Environmental Considerations,” and Chapter Twelve, “Biofuels.”

## **Biofuels**

### **Primary Advantages to the Use of Biofuels**

Biofuels offer an option for diversifying fuel supply while continuing with high-volume, low-cost, and mature ICE technology. Conventional biofuels are commercial today and provide a GHG benefit over fossil fuels. Today the United States has capacity to produce approximately 14 billion gallons (910,000 barrels/day) of ethanol from renewable resources, namely corn-derived dextrose. Cellulosic biofuels are liquid fuels derived from biomass such as stover, switch grass, timber, and other agricultural waste and algae. Cellulosic biofuels offer the potential for a large increase in feedstock supply and greater GHG reduction than conventional biofuels. Fueling infrastructure hurdles are lower for biofuels than for other alternative fuels and modifications to fuel-vehicle systems and ICEs are relatively minor.

### **Primary Challenges to the Use of Biofuels**

There are different challenges for today’s commercial biofuels and cellulosic biofuels. Feedstock logistics and fuel production technology is well established for conventional biofuels but are limited by feedstock supply. Continued development of the biomass supply depends on improving crop yields per acre for corn, arable land availability, and co-product production and utilization. Yields on corn have doubled over the past 20 years, and this trend is expected to continue with another doubling over the next 20 years. Cellulosic biofuels have technical barriers to reach economic competitiveness and scale. In addition, there are infrastructure challenges in feedstock collection, processing plant scale and in some cases in distribution and dispensing. These issues are discussed in greater depth in Chapter Four, “Priorities for Technology Investment.”

Although the U.S. Renewable Fuel Standard (RFS) includes a requirement for the use of cellulosic biofuels, there is to date no commercial production of cellulosic biofuels. According to a recent study from the National Academies, there are questions about the ability to achieve the Renewable Fuel Standard, and questions about whether the RFS will be “effective in addressing global greenhouse-gas emissions because the extent of emissions reductions depends to a great degree on how the biofuels are produced and what land-use or land-cover changes occur in the process.”<sup>5</sup>

Significant research efforts are underway to increase the yields of energy crops such as switchgrass and miscanthus. Infrastructure development to collect, store, transport, and process biomass is critical to the wide scale adoption of biofuels. While there are no major technical issues with developing the infrastructure for crop residues and energy crops, there is a significant capital requirement needed to build out this infrastructure and balance the biomass supply with demand. It should also be recognized that there will be additional demands on the biomass resource beyond liquid transportation fuels including power generation, chemical feedstocks, and products.

There are two major platforms for conversion technology, biological conversion and

<sup>5</sup> National Research Council of the National Academies, *Renewable Fuel Standard: Potential Economic and Environmental Impact of U.S. Biofuel Policy*, 2011.

thermochemical conversion, each with several separate pathways under development. The successful development of these pathways will allow for the commercial deployment of cellulosic biofuels including ethanol, isobutanol, and other “drop in” biofuels. In the biological pathway, some of the key challenges include:

- Increasing the efficiency and reducing the cost of enzymatic or chemical hydrolysis to produce fermentable sugars.
- Improving the ability of microorganisms to ferment all sugars, in particular C5 sugars (xylose and arabinose).
- Increasing the efficiency of cellulosic biomass logistics, which are not well suited to feeding large centralized plants. Development of smaller more intensified technologies or local economical densification technologies will be key to building out the cellulosic biofuels industry.

Several technical challenges also exist with the thermochemical pathways. They include:

- Improving pyrolysis technology to produce a bio-crude that is lower in oxygen content, has lower acidity, and is thermally stable.
- Improving gasification technology to produce a clean syngas.
- Improving catalysts for upgrading pyrolysis oils to produce fuel products including higher selectivity and longer lifetimes.

Success in overcoming the technical challenges of advanced biofuels presents a significant opportunity in reducing GHG emissions, as well as providing an economic fuel that provides more “drop-in” capability for vehicles and infrastructure than other alternatives.

## **Natural Gas**

A compressed natural gas vehicle (CNGV) shares common powertrain architecture with the liquid ICE vehicle using a spark ignition engine, but it uses natural gas fuel stored onboard at 3,600 pounds per square inch (24.8 megapascals) in place of gasoline. With no significant technology barriers, economic drivers and the availability of refueling infrastructure determine the adoption of natural gas in transportation. Creating sufficient demand to quickly migrate to fully OEM-produced vehicles will result

in substantial cost improvements from today’s low volume “final vehicle modifier” approach.

## **Primary Advantages to the Use of Natural Gas for Transportation**

CNGVs offer an option for diversifying fuel supply while continuing with high-volume, low-cost and mature ICE technology. In cases where CNG is priced significantly lower than gasoline, the fuel savings can offset the incremental costs of CNG storage and offer a positive value proposition to the consumer. CNGV technology is applicable across all LD vehicle segments, and there are few technical challenges to implementation. CNGVs operating on natural gas offer reduction in GHG footprint, as described in Chapter Six, “Greenhouse Gases and Other Environmental Considerations,” and further reduction is possible using renewable natural gas supply.

The United States has large domestic natural gas resources that are accessible at relatively low cost using the latest drilling technologies, and there is already an extensive transmission and distribution system in place delivering gas to industrial, commercial, and residential customers. Resource opportunities are more fully developed in the 2011 NPC study, *Prudent Development: Realizing the Benefits of North America’s Abundant Natural Gas and Oil Resources*.

CNGVs can be configured with bi-fuel (CNG/gasoline) capability to help in the transition period when CNG fuel dispensing infrastructure is not adequately developed in a given market region. While not included in the integrated analysis due to higher cost, home CNG fueling is an option that some consumers may use as an alternative to station fueling. Station CNG fuel can be dispensed with an interface (hose and nozzle) and fueling time similar to gasoline.

## **Primary Challenges to the Use of Natural Gas for Transportation**

Primary LD vehicle market technical and commercial challenges that need to be addressed are: limited make-model availability and limited refueling infrastructure. CNG on-vehicle storage cannot match gasoline on-vehicle storage in cost, mass, package size, or range potential. CNG storage system costs will remain significantly more expensive than gasoline, even with volume production and with vehicle

driving range held to 300 miles as was done for this analysis. This fuel storage system cost must be offset by lower fuel prices or other value propositions for the customer to select a CNGV over a conventional liquid ICE vehicle. CNGV fuel economy will be reduced by the mass of the storage tanks, especially in the case where lower-cost steel tanks are selected over higher-cost, lighter carbon fiber composite tanks. Packaging enough CNG fuel onboard for sufficient vehicle range represents a significant space claim in the vehicle architecture. Unless careful consideration of CNG storage is accounted for in vehicle designs, this may require either a sacrifice of interior space or elimination of features.

CNG fueling may benefit from the availability of pipeline distribution to the station site, but CNG dispensing is more costly than gasoline dispensing. Although new modular dispensing technologies are available for station island upgrades, generally CNG dispensing presents larger physical equipment and electric power footprint needs at the fueling station. The United States does not have wide-scale availability of CNG fueling today, so there are transition challenges to work through before the market can be ready for larger volume sales of CNGVs. This transition for LD vehicles may be assisted by a supply of natural gas refueling along freight corridors for heavy-duty vehicles. CNG dispensing requires significant capital equipment at the station site, and the costs per gallon gasoline equivalent of CNG dispensing will remain high until the station becomes well utilized.

## *Electricity*

### **Primary Advantages to the Use of Electricity for Transportation**

There are several advantages to the use of electricity as a transportation fuel. Because of the high efficiency of an electric motor, plug-in electric vehicles can be two-to-three times more efficient than a comparable gasoline vehicle on a tank-to-wheels basis, thus electricity as a fuel is in most cases less expensive per mile than gasoline. Battery electric vehicles (and plug-in hybrid electric vehicles when driving in electric mode) also emit zero tailpipe emissions, which is becoming increasingly important in congested urban areas. Additionally, compared to conventional liquid ICE vehicles, these vehicles also reduce well-to-wheels GHG emissions, and there is opportunity to reduce emissions even

further by using low carbon electricity generation technology such as renewable electricity or through the use of carbon capture and sequestration. As electricity can be produced from a variety of primary energy sources, its use as a fuel helps to diversify transportation energy use.

Electricity as a transportation fuel also has the advantage of existing generation and distribution infrastructure, as there is already a ubiquitous electricity supply chain in the United States. Over 60% of all housing in the United States has an attached garage or carport, and adding a dedicated circuit for a 110V outlet to charge a PHEV has minimal cost. In terms of electricity supply, even if a large percentage of the vehicle population were “electrified,” and new electricity generation capacity were needed, it would represent a small percentage of capacity additions already planned for in existing long-term asset planning processes of electric supply entities.

### **Primary Challenges to the Use of Electricity for Transportation**

These advantages, however, do not come without challenges—both at the vehicle level and at the infrastructure level. The challenges at the vehicle level are centered on the battery, and include cost, energy density, degradation, and longevity.

- **Cost.** As stated above, PEVs, which includes both BEVs and PHEVs, provide an operating cost savings. However, the cost of the battery leads to substantially higher upfront vehicle price when compared to a conventional liquid ICE vehicle. This cost must be reduced for more wide-scale adoption.
- **Energy Density.** The lower energy density of batteries relative to liquid fuels is somewhat compensated for by the high efficiency of electric motors, and for PHEVs by the addition of a gasoline engine, but for BEVs, the lower energy density leads to a limitation in vehicle range.
- **Degradation & Longevity.** There are two facets to battery longevity. The first is the actual calendar life of the battery. It is currently unknown whether batteries used in PEVs will last for the life of the vehicle, and battery replacement is likely to remain a significant expense. The second facet of longevity is the degradation of power and energy storage capacity that occurs over time. The gasoline engine in PHEVs can compensate for this, but

BEVs will experience reduced power and vehicle range. Battery innovation, therefore—improved energy density, reduced degradation, and certain calendar life—is most likely necessary for the wide-scale adoption of BEVs.

For vehicle charging, while PHEVs can easily re-charge the battery overnight using a standard 110V outlet, drivers of BEVs will most likely need to charge at a higher power level (240V). This requires the purchase and installation of a separate charging unit, which could be a barrier to vehicle purchase if the expense is high (e.g., if new panel capacity is needed, or there is no existing 240V connection in the garage). For both PHEVs and BEVs, drivers in urban areas with on-street parking and drivers who live in multiple dwelling units (MDUs) such as apartments, both types of charging (110V and 240V) will be difficult to realize, as the installation cost can be high and the driver typically lacks the authority to install a charging unit.

As these vehicles have just begun to enter the market, market acceptance of a limited-range vehicle is uncertain. It is possible that “range anxiety” and the inability to use the vehicle for all trips will prove to be a barrier to adoption, but it is also possible that the advantage of home refueling and lower operating costs will outweigh the range limitation.

## **Hydrogen**

The hydrogen fuel cell electric vehicle has full electric drive and is powered by a fuel cell system that uses gaseous hydrogen fuel stored onboard at pressures of 10,150 pounds per square inch (70 megapascals). For purposes of this study, the hydrogen fuel storage system has been sized for 300 miles of on-road driving range, which is comparable to current gasoline vehicles. A battery is coupled with the fuel cell system for power assist and is similar in function to the battery in a hybrid electric vehicle.

### **Primary Advantages to the Use of Hydrogen**

The FCEV emits no tailpipe emissions other than water, and it offers the excellent acceleration, low noise, and low vibration driving that is characteristic of all electric drive vehicles. In addition, the efficiency of electrochemical energy conversion in the fuel cell system is much higher than that of an internal combustion engine. This increased efficiency is the enabler for competitive driving range and

competitive fuel operating cost-per-mile. A majority of the major automotive manufacturers (General Motors, Ford, Toyota, Honda, Nissan, Daimler, and Hyundai) are planning commercial introduction of FCEVs beginning in 2015 in targeted geographies (e.g., United States, Germany, Japan, and South Korea). Most FCEV electric drive components are shared with hybrids, PHEVs, and BEVs, and FCEVs will share some benefit of component cost reduction as these vehicle volumes increase over time. Hydrogen fuel cell electric propulsion systems can be applied to all LD vehicle classes, and they also offer the benefit of rapid refueling.

Hydrogen fuel is an “energy carrier” in the sense that it can be produced from any energy source, including renewables, using multiple conversion pathways. It is produced at large scale for industrial applications today, and in many places this industrial production base can be leveraged to meet early hydrogen fueling needs; however, new production facilities will be needed as demand grows. Using hydrogen produced from natural gas, hydrogen in an FCEV reduces per-mile GHG by approximately 50% compared to a conventional liquid ICE vehicle and could be priced competitively when distribution and dispensing equipment is well utilized. Further reduction in hydrogen GHG emissions is possible using lower carbon feedstocks or carbon capture and sequestration, but with potentially higher costs.

### **Primary Challenges to the Use of Hydrogen**

FCEV propulsion technology development has progressed significantly over the past several decades, but two remaining challenges are durability and cost. Demonstrated on-road durability is less than 100,000 miles and needs to increase by a factor of two to meet the vehicle lifetime expectations of today’s consumers. Laboratory testing of the latest fuel cell stack materials indicates that this challenge may soon be overcome, but full durability (150,000+ miles) has yet to be demonstrated. FCEVs are expected to enter the market with a significant price premium. Several generations of product, along with increases in the scale of production, can bring FCEV prices down to a competitive level.

While hydrogen production is already large-scale and mature, the distribution and dispensing of hydrogen for use by consumers as a vehicle fuel is relatively new and limited. Large-scale central

production with over-the-road distribution to stations is judged to be a lower cost option than smaller distributed production in the near term and is the baseline for this study. The key challenge is refueling equipment capital cost and physical footprint (including setback distances). These hurdles could be addressed through advances in compression and storage technologies used at a dispensing location. The costs of dispensed hydrogen will remain high until stations become well utilized, and high utilization requires concentration of FCEVs in early infrastructure areas. Areas with ample hydrogen fuel availability will be ideal for the deployment of FCEVs.

## METHODOLOGY

The analysis models used for this chapter pull inputs from the individual fuel-vehicle system chapters to develop consistent vehicle and dispensed fuel costs for each fuel-vehicle system. All systems are then compared on an economic basis (vehicle price plus fuel costs over a given time horizon) as inputs are varied to calculate the new vehicle shares and the resulting fleet of fuel-vehicle systems in 2050. The characteristics (e.g., vehicle and fuel expenditures, GHG emissions, and fuel demand) of each fleet (made up of different portfolios of fuel-vehicle systems) are then calculated and analyzed. Detailed information about the models, inputs, and methodology is available on the NPC website.

## Foundational Assumptions

The purpose of this analysis was to evaluate various portfolios of fuel-vehicle systems that might result if technology development is aggressively accelerated. This analysis was based on six foundational assumptions. These assumptions are considered foundational because varying any one of these would result in materially different findings than those reached in this analysis. The analysis assumes that:

- Priority technology hurdles for each fuel-vehicle system are overcome.<sup>6</sup>
- Fuel dispensing infrastructure is available, and its cost is reflected in the fuel cost.
- Consumer purchase decisions are based only on economics.

<sup>6</sup> The priority technology hurdles for each fuel-vehicle system are discussed in Chapter Four, “Priorities for Technology Investment.”

- Vehicles are designed to minimize the new vehicle price plus fuel costs over a given time horizon.
- ICE vehicles meet or exceed the vehicle fuel economy projected in AEO2010.
- Each fuel-vehicle system benefits from sustained investment and development.

Realizing all of these assumptions may prove very difficult. For example, Chapter Four, “Priorities for Technology Investment,” highlights twelve priority technology hurdles that need to be overcome for all fuel-vehicle systems to achieve wide-scale commercialization. While some of the hurdles discussed in the technology chapter may be readily overcome, others may not be overcome for decades, if ever. Similarly, Chapter Five, “Infrastructure,” provides a detailed discussion of infrastructure hurdles for each fuel-vehicle system and identifies potential options for addressing them.

## Inputs and Assumptions

### Baseline Inputs

The modeling analysis relied on AEO2010 data (Reference Case, High Oil Price Case, and Low Oil Price Case) as the basis for inputs such as gasoline, diesel, electricity, and natural gas costs, electricity grid mix, and minimum gasoline and diesel vehicle fuel economy.<sup>7</sup> The range of dispensed costs for each fuel, including taxes, was calculated on a normalized basis in this analysis. Future Corporate Average Fuel Economy requirements were not explicitly considered in this analysis; however, AEO2010 fuel economy projections were used as a minimum constraint for future fuel economy calculations and reflect fuel economy regulations through 2016.

When considering the economic viability of a fuel-vehicle system, the period of time over which economics are evaluated can have a material impact on the degree to which the system is economically competitive. The total vehicle price is always considered when calculating fuel-vehicle system market shares; however, fuel expenditure time horizons vary. The assumed period of time over which fuel costs are considered by the consumer is an important consideration. While there is no definitive answer to the question of what value consumers place on improved vehicle fuel economy, research supports the view

<sup>7</sup> AEO2010 data were extrapolated out to provide values for 2036–2050.

## ***Fuel Economy Regulations***

In April 2010, the U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) issued a joint final rule to implement a coordinated national program consisting of new requirements for the 2012 through 2016 model year light-duty vehicles. The EPA and NHTSA programs require the total light-duty vehicle fleet to reach an overall fuel economy of 34.1 miles per gallon by the 2016 model year. Further, on December 1, 2011, EPA and NHTSA issued a joint Notice of Proposed Rulemaking to implement new requirements for light-duty vehicles for model years 2017 through 2025, with a goal of 54.5 miles per gallon gasoline equivalent for the U.S. light-duty vehicle

fleet. The exact implementation of this requirement was still in development as of the writing of this report. This goal will also be re-assessed in the 2017 calendar year, to review consumer acceptance, technology maturation, advanced battery and power electronics development, fuel prices, and infrastructure.

In the light-duty vehicle analysis for this study, individual fuel-vehicle system fuel economies are the result of the Vehicle Attribute Model. Overall fleet fuel economy is a result of the Vehicle Choice Model. Consequently, the overall fleet fuel economy is not a measure of current or pending Corporate Average Fuel Economy (CAFE) requirements.

that consumers consider the total fuel expenditure over a relatively short period of time (e.g., 3 years). Alternately, economics can be evaluated considering fuel expenditures over the useful life of a vehicle (17 years).<sup>8</sup> Since fuel costs are a more significant consideration over the long term versus the short term, an increase in adoption of fuel economy technology is expected to be more economical over a 17-year time horizon versus a 3-year time horizon. This analysis is focused on a 3-year time horizon for fuel expenditures, but also considers the sensitivity of using a 17-year time horizon.

### ***Primary Inputs***

For each fuel-vehicle system, the primary inputs from the chapters used in the analysis can be found in Appendix 2A at the end of this chapter. It should be noted that the use of the term “price” for vehicles and vehicle technologies in Table 2-2 and throughout this document is used to represent retail price equivalent, which is intended to reflect industry-average production costs plus rates of profit and overhead expense.

### ***Rate of Improvement for Vehicle Technology Inputs***

Another important input is the assumed rate of improvement (e.g., price/mass reduction over

time) for the technology inputs shown in Appendix 2A. The importance of the assumed rate of improvement for a technology increases as the period of analysis increases. This analysis evaluated technologies over a 35-year period; therefore, the assumed rate of improvement has a significant impact. Rates of improvements were based on publicly available literature where available and are discussed in each fuel-vehicle system chapter as applicable. The following rates of improvements were applied when publicly available literature was not available:

- Mature Technologies – 1% price reduction per year. This reflects incremental “learning curve” improvements in product design, materials, and production processes as a function of time and cumulative production volumes.
- New Technologies – 3% price reduction per year for years 1 to 5; 2% per year for years 6 to 10; and 1% per year thereafter. This assumes that for new technologies, rapid improvements will be realized over the first decade of production, with subsequent improvement rates reducing to match those of more mature technologies.

### ***Assumptions Bias***

Significant effort was made to ensure consistency of the assumptions, inputs, and analysis approach. There are some assumptions, however, that could advantage or disadvantage specific fuel-vehicle

<sup>8</sup> A 17-year period is used by the U.S. Environmental Protection Agency to develop Corporate Average Fuel Economy (CAFE) regulations.

Fuel-Vehicle System	Assumption	Advantage	Disadvantage
<b>Liquid ICE – Gasoline, HEV, Diesel, and Biofuels</b>	Diesel technology prices not available from all sources used		Vehicle Price
	All ICE engines are fully flexible-fuel capable	Vehicle Price	
	Biofuel infrastructure available and fully utilized	Biofuel Share, Vehicle Share	
	Biofuel blend retail price never less than gasoline		Biofuel and Liquid ICE Share
<b>PEV</b>	Batteries last full life of vehicle	Vehicle Price	
	Range degradation is not accounted for in the model	Vehicle Price	
	AEO2010 Reference Case grid mixes (extrapolated to 2050)	Electricity Cost	GHG Emissions
	Infrastructure available and fully utilized	Electricity Cost, Vehicle Share	
	AEO2010 “transportation” electricity price (mix of residential and off-peak electricity rates)	Electricity Cost	
	Rapid adoption rate allowed	Vehicle Share	
	BEV100 not in large trucks		Vehicle Share
BEV100 annual mileage same as liquid ICE	Vehicle Share		
<b>CNGV</b>	AEO2010 price spreads between Natural Gas and Oil (no low/high natural gas price case)	CNG Cost	CNG Cost
	No renewable Natural Gas	CNG Cost	GHG Emissions
	Infrastructure available and fully utilized	CNG Cost, Vehicle Share	
	Rapid adoption rate allowed	Vehicle Share	
<b>FCEV</b>	No renewable Hydrogen	Hydrogen Cost	GHG Emissions
	Infrastructure available and fully utilized	Hydrogen Cost, Vehicle Share	
	Rapid adoption rate allowed	Vehicle Share	

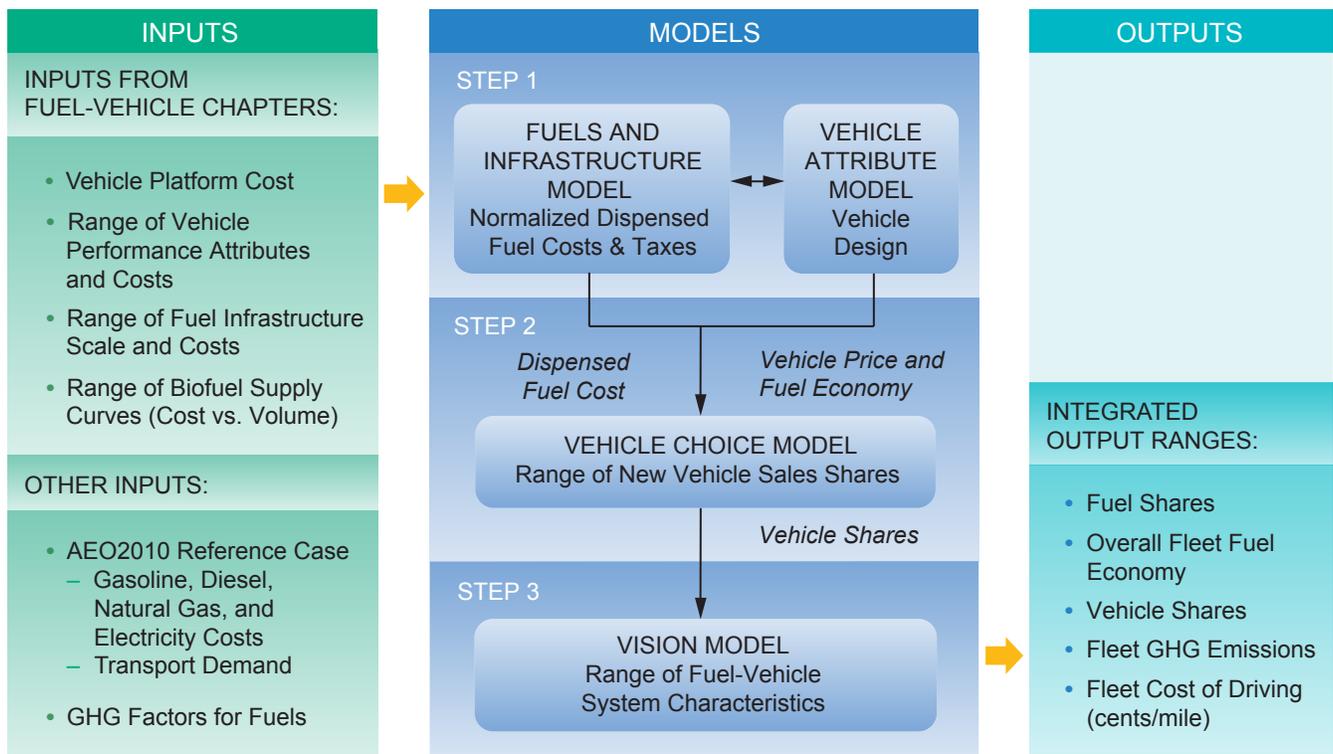
**Table 2-2. Assumptions for Fuel-Vehicle Systems**

systems. Overall, these assumptions tend to favor alternative fuel-vehicle systems relative to conventional liquid fuel ICE vehicles.

Table 2-2 shows the assumptions that apply to the fuel-vehicle systems under consideration. The advantages and disadvantages of each assumption are also presented.

### **Light-Duty Fleet Analysis Process**

The overall approach to the LD vehicle and fleet analysis is depicted in Figure 2-2. The analysis started with primary inputs from each of the fuel-vehicle system chapters of this study. The baseline inputs, primary inputs, and GHG carbon



**Figure 2-2.** Light-Duty Analysis Process

coefficients from GREET<sup>9</sup> were integrated using four models: the Fuels and Infrastructure Model, the Vehicle Attribute Model, the Consumer Vehicle Choice Model, and the VISION model. The four models were used together in the following three steps:

1. The Fuels and Infrastructure Model generates dispensed fuel cost ranges and the Vehicle Attribute Model generates vehicle price and fuel economy ranges under varying technology prices and fuel costs for each fuel-vehicle system. There is a tradeoff between vehicle price and vehicle fuel economy. Adding vehicle technology to increase fuel economy increases the vehicle price. For fuel-vehicle systems with high-cost energy storage, such as the BEV, FCEV, and CNGV, increasing the vehicle efficiency reduces the required stored energy, and thus may reduce the vehicle price. The Vehicle Attribute Model solves for these tradeoffs to minimize the total of vehicle price plus fuel expenditure over a given time horizon.

<sup>9</sup> Details on the carbon coefficients used in this study and GREET are presented in Chapter Six, “Greenhouse Gases and Other Environmental Considerations.”

The Vehicle Attribute Model “pushes” fuel economy technology onto the conventional liquid ICE, diesel, CNGV, and HEV by applying minimum values that increase over time. These values are based on AEO2010 for the conventional liquid ICE, diesel, and CNGV. The HEV is defined in 2015 to have a fuel economy ratio of 1.4 times or greater compared to a 2008 conventional liquid ICE vehicle. This minimum fuel economy threshold was chosen to differentiate the HEV from the conventional liquid ICE vehicle, as a continuum of electrification options exist, and there is no agreed-upon definition of when a conventional liquid ICE vehicle becomes an HEV. Over time, the minimum ratio increases to 2.0 times in 2050.

For the BEVs, and to a lesser extent the CNGV, PHEV40, and FCEV, energy storage plays a role in fuel economy technology adoption. The BEV is designed in the Vehicle Attribute Model to achieve 100 miles of on-road driving range, and the battery is sized accordingly. Up to a point, the cost of adding fuel economy technology to the BEV can be offset by the savings from downsizing of the battery. While reduced

fuel operating cost is the primary motivation to adopt fuel economy technology on conventional liquid ICE vehicles, it is secondary to the battery sizing tradeoff for the BEV.

2. The ranges of outputs from the Fuels and Infrastructure Model and the Vehicle Attribute Model were used as inputs to the Vehicle Choice Model, which compares combinations of fuel-vehicle systems based on economics and calculates new vehicle market shares over time for each set of inputs. These shares are based on vehicle price plus fuel costs over a given time horizon (3 years or 17 years). Other vehicle criteria (e.g., cargo capacity, acceleration) were normalized across all vehicles types and not used as differentiators when calculating portfolios of fuel-vehicle systems. Operating costs related to insurance, repair, fees, etc., were not included in the analysis. Fuel-vehicle system market share calculations in the Vehicle Choice Model do not use a “winner takes all” approach. Rather, market shares are calculated by preferentially pulling market share toward the fuel-vehicle systems with the lower costs (vehicle plus fuel costs) and making adjustments based on historical purchase trends. A summary of the basic input ranges is shown in Appendix 2A: Range of Primary Input Values for Fuel-Vehicles.

The maximum rate of penetration for a fuel-vehicle system was left at the default values in the Vehicle Choice Model. These values allowed market penetration of new fuel-vehicle systems at significantly higher rates than those of any historical fuel-vehicle system and are considered aggressive because they allow fuel-vehicle system market adoption at rates faster than the auto manufacturing industry business models support. For example, in the case of a vehicle fleet (portfolio) of only liquid ICEs and CNGVs, the default values allow CNGVs to capture up to ~80% of new vehicle sales by the year 2020.

3. Vehicle shares from the Vehicle Choice Model were input into VISION to compute the impact on U.S. fleet criteria such as GHG emissions, fuel demand, vehicle expenditures, and fuel expenditures.

Biofuels were added to the fuels portfolio in VISION based on the biofuels supply and costs developed in Chapter Twelve, “Biofuels.” When

added to the fuels portfolio, biofuels displaced gasoline and diesel and were assumed to be used uniformly across all liquid ICE vehicles. No fuel blending limitations were assumed. The addition of biofuels did not impact fuel expenditures but did impact GHG emissions and petroleum demand.

**The following terms were defined for use within the light-duty modeling framework:**

**Fuel-Vehicle System**

A vehicle with one of the eight propulsion systems chosen for this study together with the fuel(s) that supply its propulsion energy.

**Portfolio**

The collection of all possible “cases” under a defined set of fuel-vehicle systems.

**Case**

One complete set of model outputs within a portfolio. Each case is defined by a unique set of selections across applicable “input ranges” and a consumer choice “time horizon.”

**Input Range**

The model selects discreet sets of values that define the range of inputs considered. There were eight input ranges used in the light-duty vehicle and fuels modeling:

1. Vehicle efficiency technology prices (low/high)
2. CNGV system technology prices (low/high)
3. PEV system technology prices (low/high)
4. FCEV system technology prices (low/high)
5. Hydrogen fuel prices (low/high)
6. Oil prices (low/reference/high)
7. Electric charging availability (home only/ubiquitous)
8. Biofuel supply (no advanced biofuels/low supply/high supply)

**Time Horizon**

A parameter in the Vehicle Choice Model that specifies the time over which fuel expenditures are considered—3 years is the baseline parameter value; 17 years was used for sensitivity analysis.

The outputs of this analysis were ranges of fuel-vehicle system shares in the fleet, fuels shares, GHG emissions, and fleet cost of driving (cents/mile). Fleet cost of driving was added to the VISION model by this study's analysis team. It is computed for each year by first summing up total fuel expenditures and the amortized cost of all vehicles on the road, and then dividing by total miles driven. It is a fleet characteristic and is distinct from the vehicle plus fuel cost consideration used in the Vehicle Choice Model for allocating new vehicle shares.

It should be noted that the models used in this analysis do not have feedback mechanisms to incorporate the impact of changes in fuel supply and demand. For example, the functioning of the free market indicates that high oil prices may not persist if there is low oil demand. However, in the models used in this analysis, the price of oil was not impacted by changes in demand.

### Portfolios of Fuel-Vehicle Systems

The analysis considered combinations of fuel-vehicle systems called "portfolios," as shown in Figure 2-3. For example, the "All In" portfolio allows all

of the alternative systems (Liquid ICE, CNGV, PHEV, BEV, and FCEV) to compete. Portfolios of fuel-vehicle systems were compared to determine the incremental impact of each alternative fuel-vehicle system. The "Liquid ICE plus 1" portfolios provide insight on the impact of only one alternative fuel-vehicle system achieving wide-scale commercialization. The "All In minus 1" portfolios provide insights on the impact of one system not achieving wide-scale commercialization. The output of the modeling is a wide range of shares of fuels and vehicles under varying sets of conditions.

The analysis developed directional insights and findings. For example, the analysis drew insights from how the calculated total cost of driving varied for the fuel-vehicle system portfolios over time as primary inputs changed, recognizing the wide range of uncertainty in the input values and analysis.

## RESULTS AND DISCUSSION

### New Vehicle Price

For each fuel-vehicle system, there is a tradeoff between vehicle price and vehicle fuel economy.

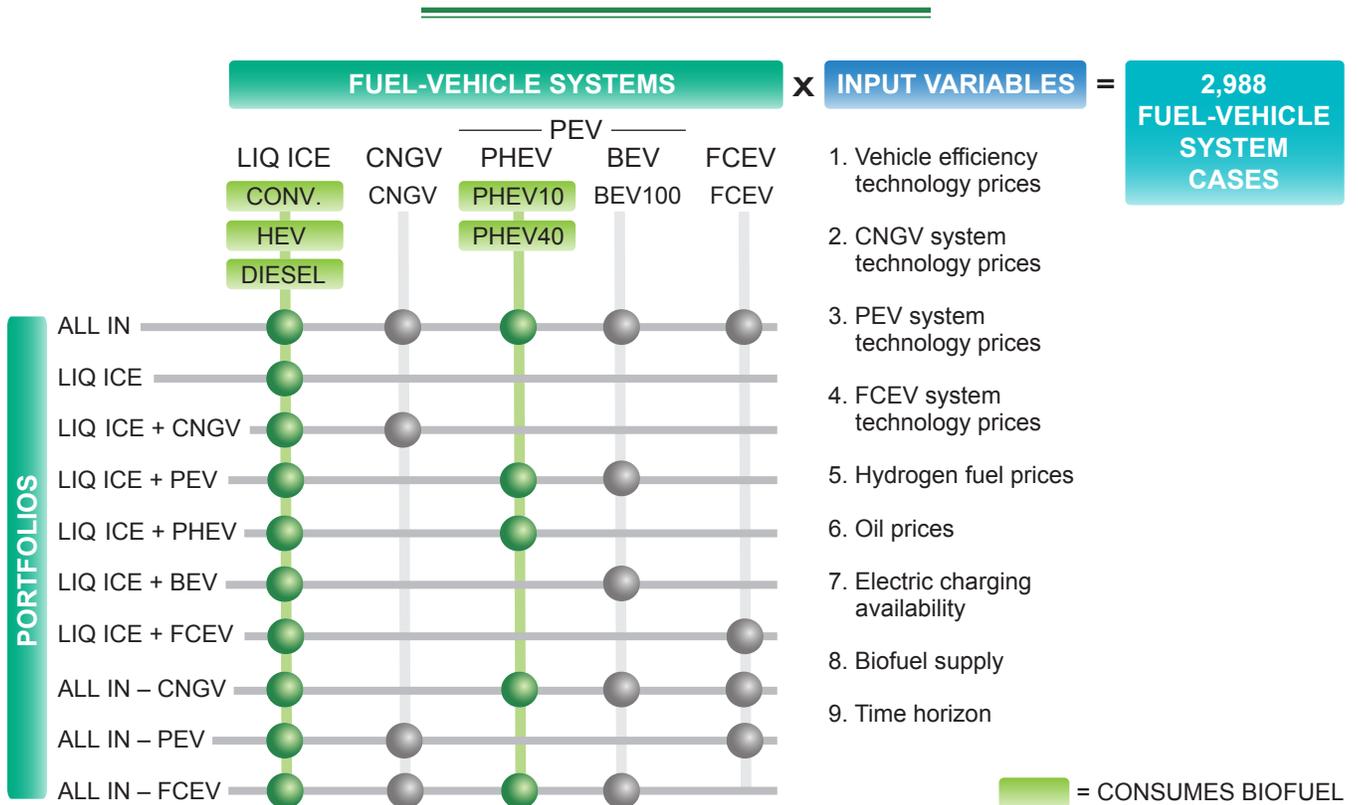


Figure 2-3. Fuel-Vehicle System Combinations Used in Analysis

Adding technology to increase fuel economy also increases the vehicle price. The primary benefit for increased vehicle efficiency technology is reduced fuel consumption. However, there is an additional incentive for adopting vehicle efficiency improvements in fuel-vehicle systems with high-cost of energy storage, such as the BEV, FCEV, and CNGV. Increasing vehicle efficiency in these systems reduces the required stored energy and vehicle cost.

Vehicle price results are provided in Figures 2-4 and 2-5 for the Small Car and Large SUV segments as examples. BEVs were not included in Pickup or Large SUV segments due to battery size and cost constraints, duty cycles, and typical use for these vehicles. Vehicle cost ranges are lower in 2050 than in 2015 for all fuel-vehicle systems due to projected lower cost for key components like batteries and fuel storage and due to learning curves. New fuel-vehicle systems experience greater vehicle price reductions than mature fuel-vehicle systems due to cost reductions in key components and the assumed steeper learning curves of newer technologies as they reach scale. In spite of the larger price reductions for the new fuel-vehicle systems, conventional liquid ICE vehicles remain the lowest retail price equivalent across the full time period evaluated.

## New Vehicle Fuel Economy

**There are opportunities to dramatically improve the fuel economy of light-duty vehicles.** As described in the Methodology section of this chapter, the Vehicle Attribute Model allows each fuel-vehicle system to adopt new fuel economy technology that minimizes the vehicle plus fuel cost. As an example, Figures 2-6 and 2-7 show the calculated on-road fuel economy ranges for small cars and large SUVs in 2015 and 2050. Vehicles with electrified powertrains have the highest fuel economy. Within this group of vehicles, fuel economy increases as electrification increases from HEV to PHEV to BEV. Fuel economy improves between 2015 and 2050 due to reduction in the cost of fuel efficiency technology, increasing fuel prices and the minimum fuel economy constraints described in methodology section. Improvement is smaller for PEV and FCEV vehicles that already have higher fuel economy.

## Fuel Costs

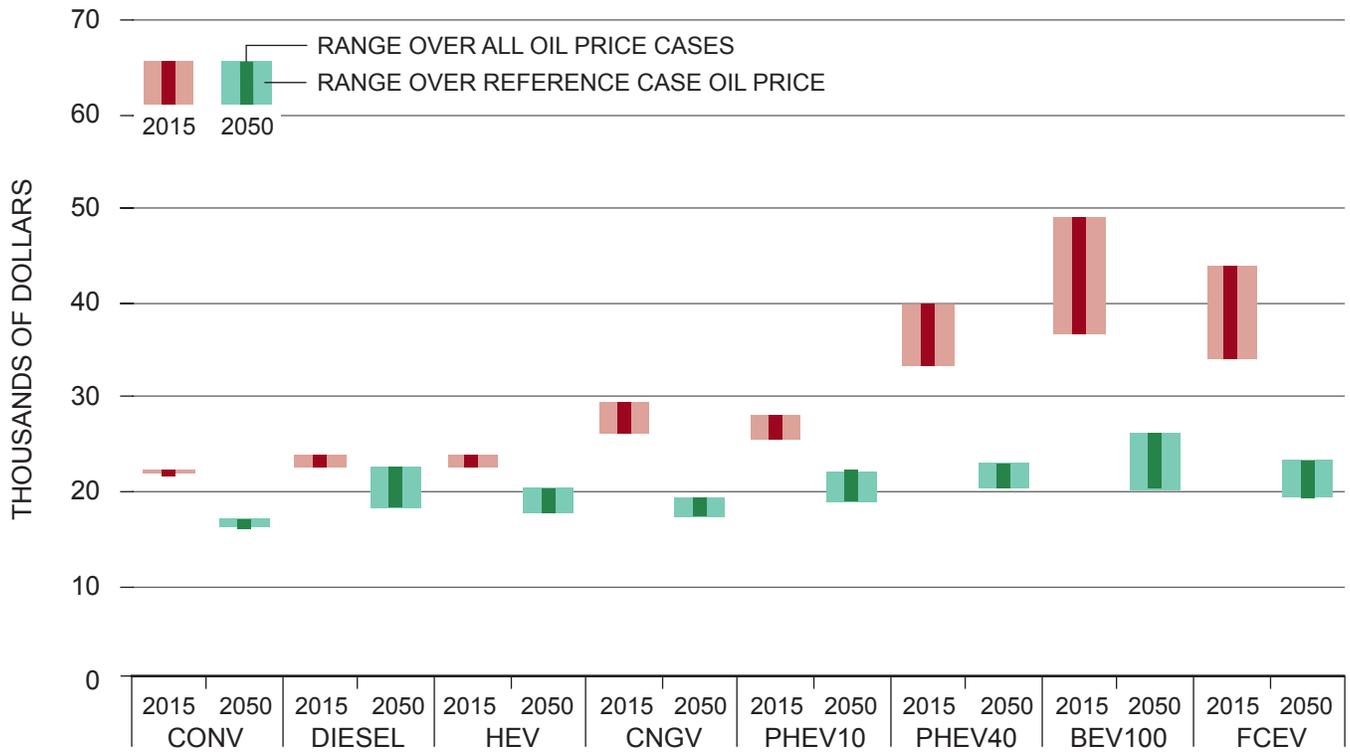
The operating cost of fuel for LD vehicles is determined by the unit cost of the fuel, the fuel economy of the vehicle, and miles driven. As an example, the cost of fuel for a small car for three years is shown in Figure 2-8. The oil price assumptions have a major impact on fuel cost for vehicles operating on gasoline or diesel. The impact of the oil price is seen by comparing the “Range Over All Oil Price Cases” to the “Range Over Reference Case Oil Price” bars in Figure 2-8. At higher fuel costs, some of the impact of fuel costs can be offset by increases in vehicle fuel economy, but would require higher vehicle prices.

CNGVs, PEVs and, to a lesser extent, FCEVs have the lowest fuel costs. CNG fuel costs are lower mainly due to the price advantage (on a \$/BTU basis) of natural gas in AEO2010 projections. On the other hand, PEV and FCEV per-mile fuel costs are lower mainly due to higher vehicle fuel efficiency of these systems. For FCEV, the hydrogen production, distribution, and dispensing costs form a greater fraction of the total fuel costs, versus the feedstock natural gas costs.

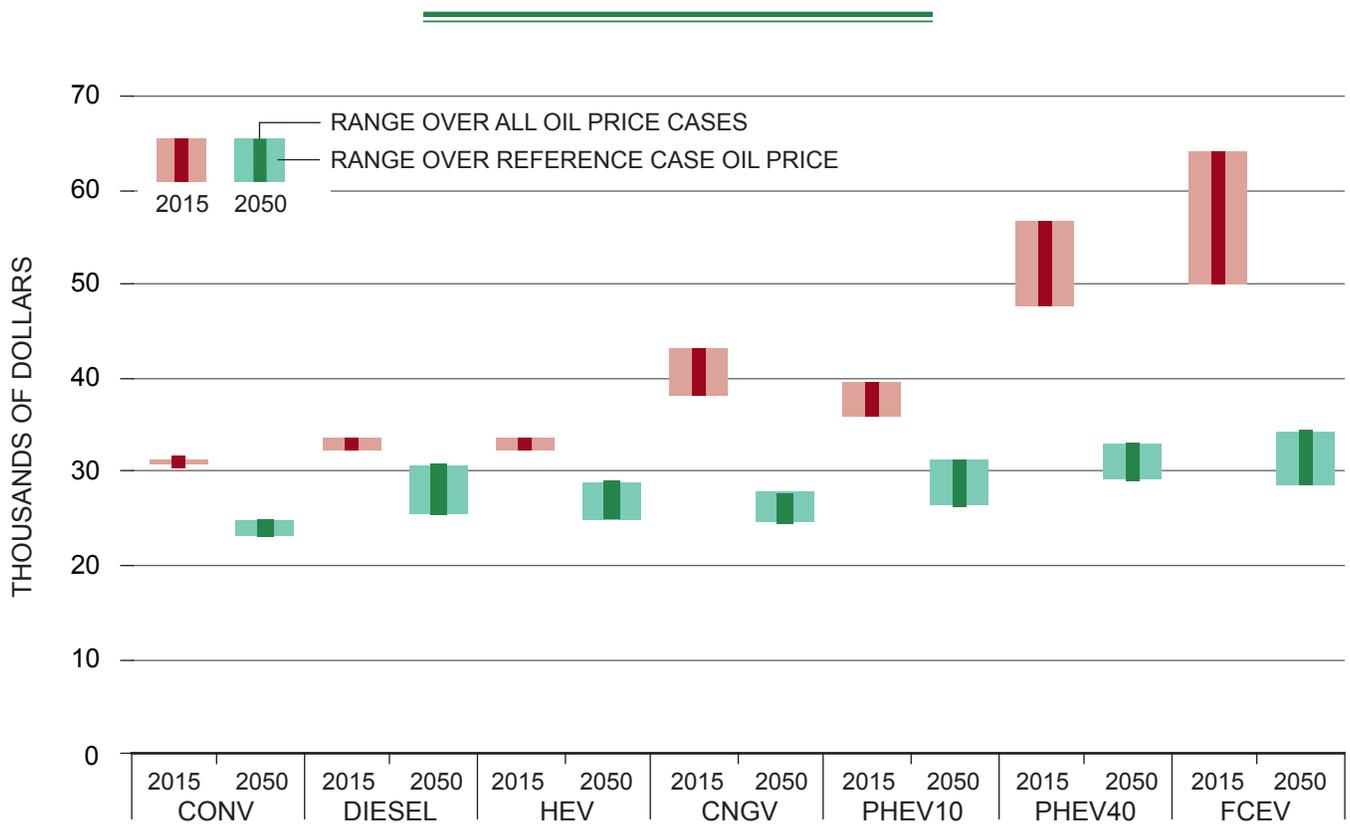
Differences in total fuel expenditures between 2015 and 2050 are due to changes in fuel costs (which include infrastructure costs) and improvements in vehicle fuel economy. In the Reference and High Oil Price Cases, oil and natural gas prices increase faster with time than electricity prices. For diesel and hybrid vehicles, the fuel cost in the Reference Case is slightly higher in 2050 than in 2015, because higher oil price in 2050 is partially offset by increased vehicle fuel economy. For hydrogen FCEVs, fuel costs are lower in 2050 due to projected reductions in the cost of hydrogen infrastructure, and improvements in vehicle technology that provide improved fuel economy.

## New Vehicle plus Fuel Costs

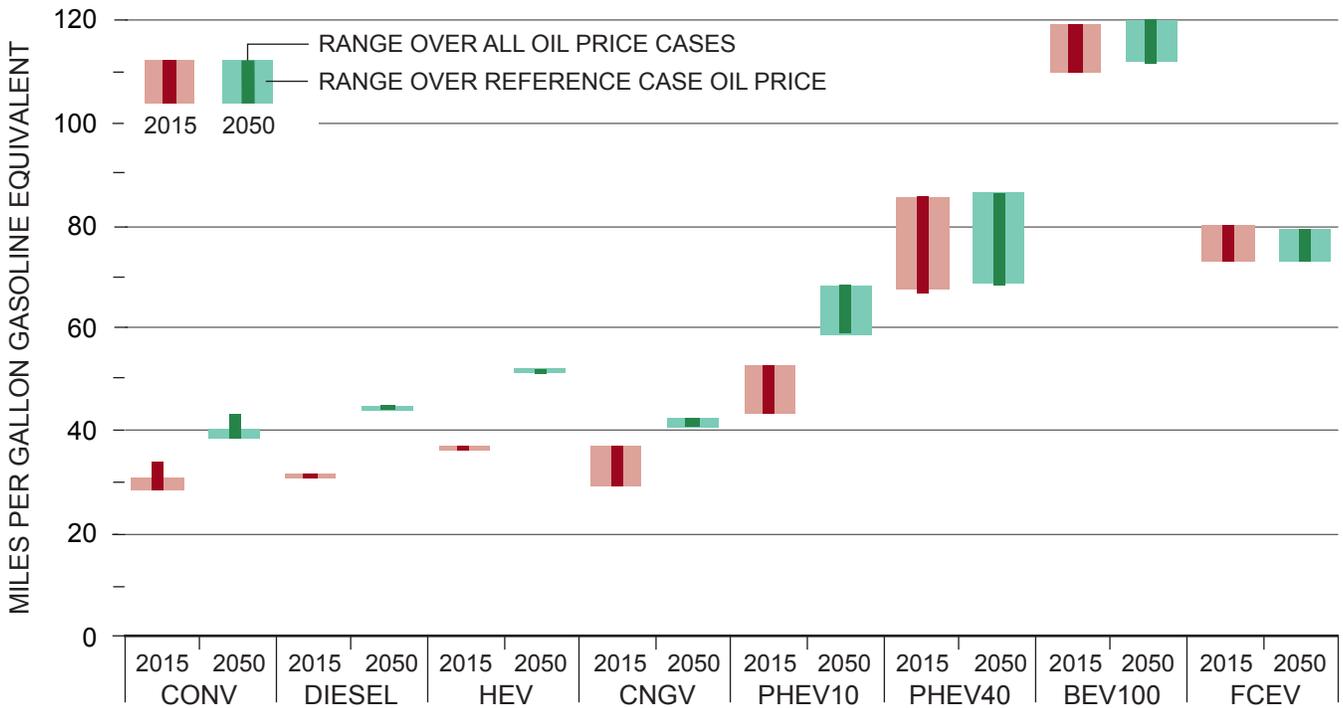
A comparison of small car segment new vehicle prices plus fuel costs for each fuel-vehicle system is shown in Figure 2-9. Liquid ICEs have the lowest vehicle plus fuel costs in 2015 while PHEV40, BEV, and FCEV are the highest, due to high vehicle costs. All vehicles have lower costs in 2050 compared to 2015 due to vehicle technology cost reductions. As discussed previously, costs of new technologies



**Figure 2-4.** Analysis Results – Retail Price Equivalent for Small Cars

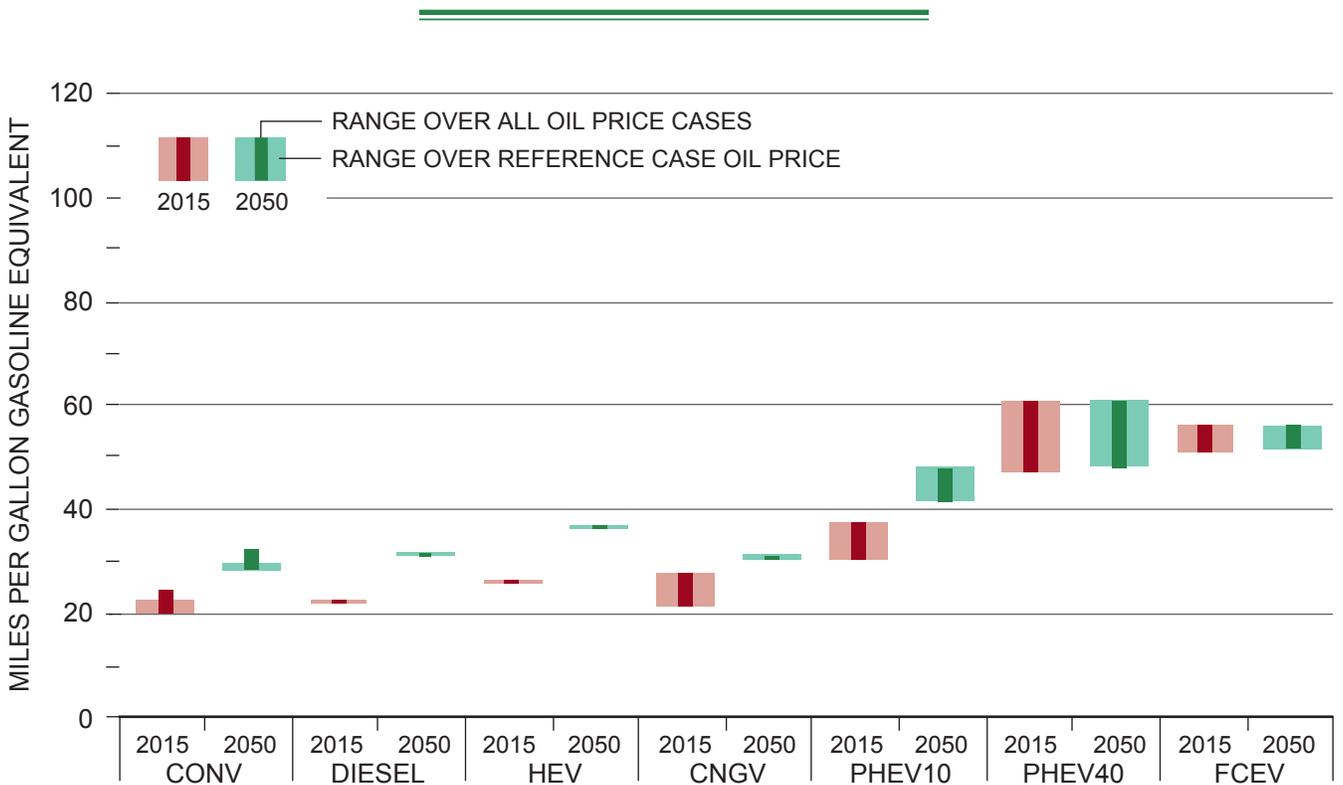


**Figure 2-5.** Analysis Results – Retail Price Equivalent for Large SUVs



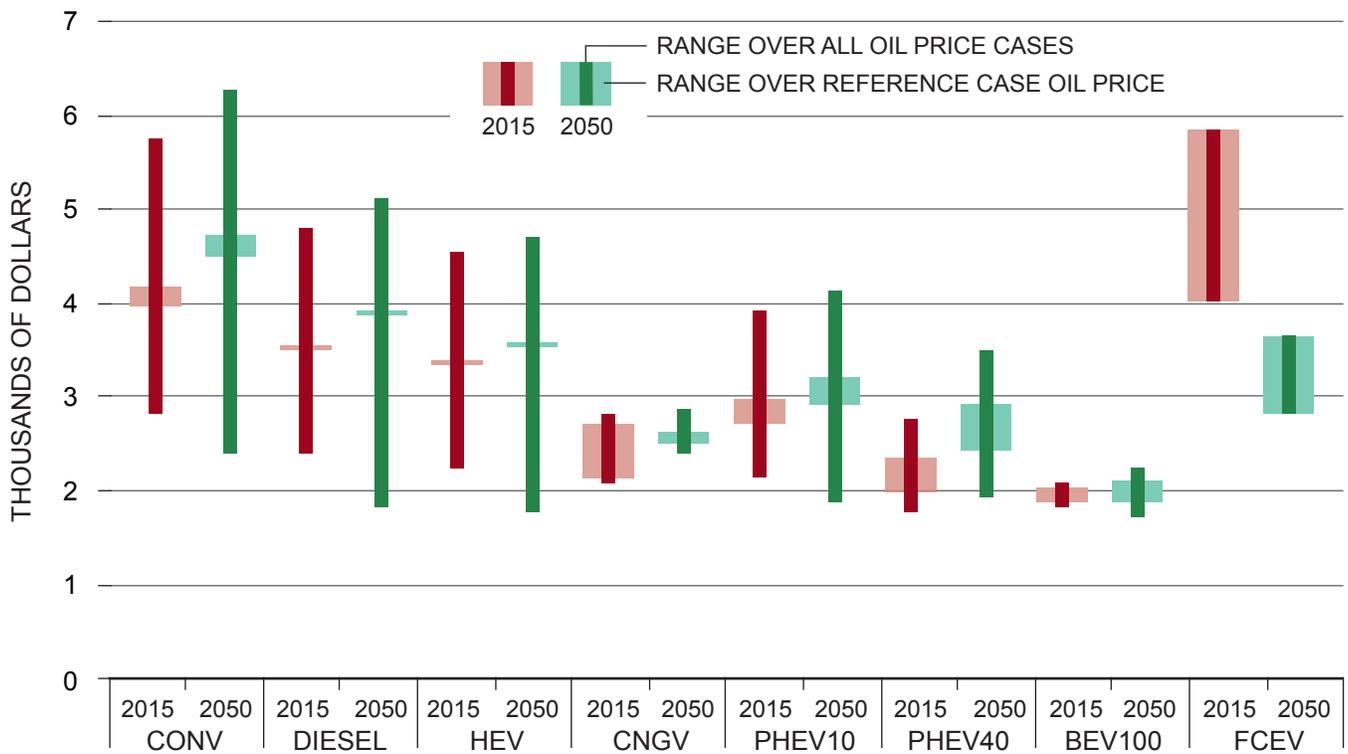
Note: EPA test fuel economy from AEO2010 Supplemental Table 61, converted to on-road fuel economy by multiplying by 0.8.

**Figure 2-6.** Analysis Results – New Vehicle Fuel Economy for Small Cars

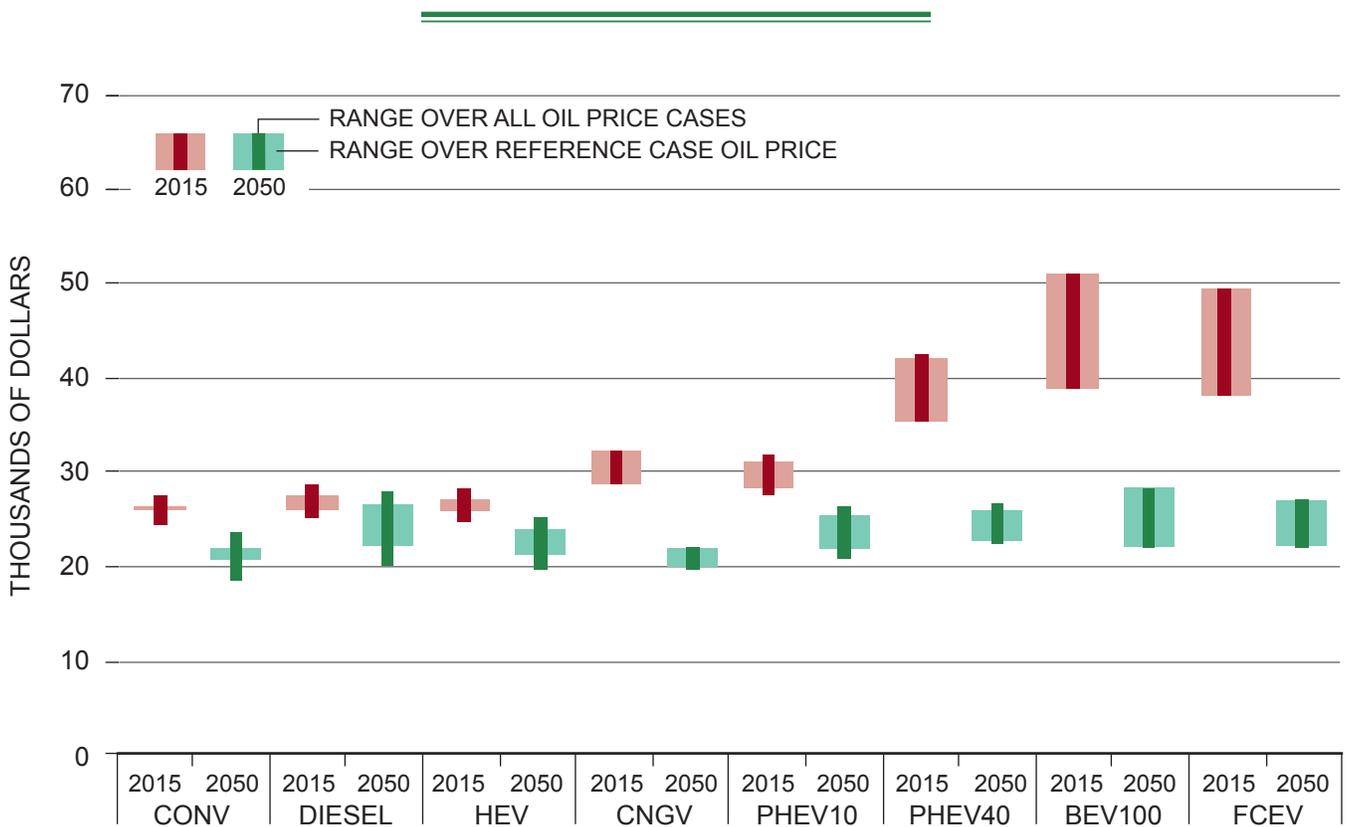


Note: EPA test fuel economy from AEO2010 Supplemental Table 61, converted to on-road fuel economy by multiplying by 0.8.

**Figure 2-7.** Analysis Results – New Vehicle Fuel Economy for Large SUVs



**Figure 2-8.** Analysis Results – Three-Year Fuel Costs for Driving a Small Car



**Figure 2-9.** Analysis Results – Sum of Vehicle Price and Three-Year Fuel Costs for a Small Car

are projected to decline at a faster rate than those of mature technologies; therefore, cost differences between mature and new fuel-vehicle systems narrow by 2050. CNGV and liquid ICE vehicles tend to have the lowest total cost.

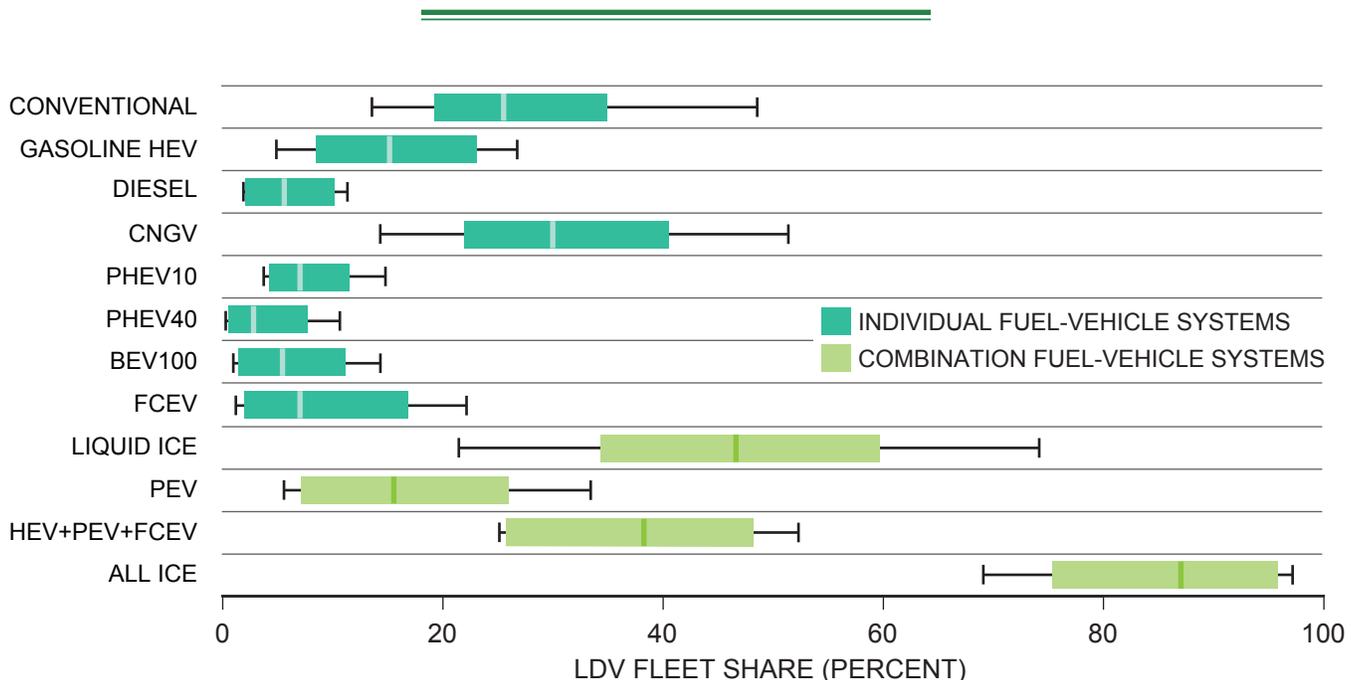
## Fleet Shares

**All of the fuel-vehicle systems demonstrate the potential to achieve wide-scale commercialization by 2050.** Across the 2,988 cases analyzed in this study, the range of shares for each fuel-vehicle system varies widely, because the relative vehicle price plus fuel costs vary. Ranges of shares of the LDV fleet in 2050 where all fuel-vehicle systems compete (“All In” portfolio) are shown in Figure 2-10. All of the vehicle systems achieve wide-scale commercialization by 2050 under certain conditions. Alternative fuel-vehicle systems are more cost competitive in 2050 than in 2015 due to lower vehicle cost premiums. The ranges in the bars reflect uncertainty across the ranges of input variables. Considered individually, PHEV and BEV have relatively low

share but the aggregated PEV share is much more significant.

Internal combustion engines will likely remain a dominant propulsion technology. A diverse set of fuel-vehicle systems could use ICEs in 2050 including conventional liquid ICEs, diesels, HEVs, PHEVs, and CNGVs. As shown in Figure 2-10, the combined share of all vehicles with ICEs is very high. Liquid ICEs (which includes gasoline/biofuels blends and diesel/biofuels blends in conventional liquid ICE vehicles and HEVs) retain a significant share on average. Conventional liquid ICE vehicles have dramatically reduced share compared to today, but are the largest fraction of liquid ICE due to persistently low cost, while HEV share increases with time as HEV price premium decreases. The liquid ICE share has a wide range that is dependent largely on the oil price case assumptions.

**CNGV is the strongest economic competitor to liquid ICE.** When all fuel-vehicle systems compete (“All In”), CNGVs have the highest share of any alternative fuel-vehicle system with a share similar to that of conventional ICEs. CNGVs have a fuel



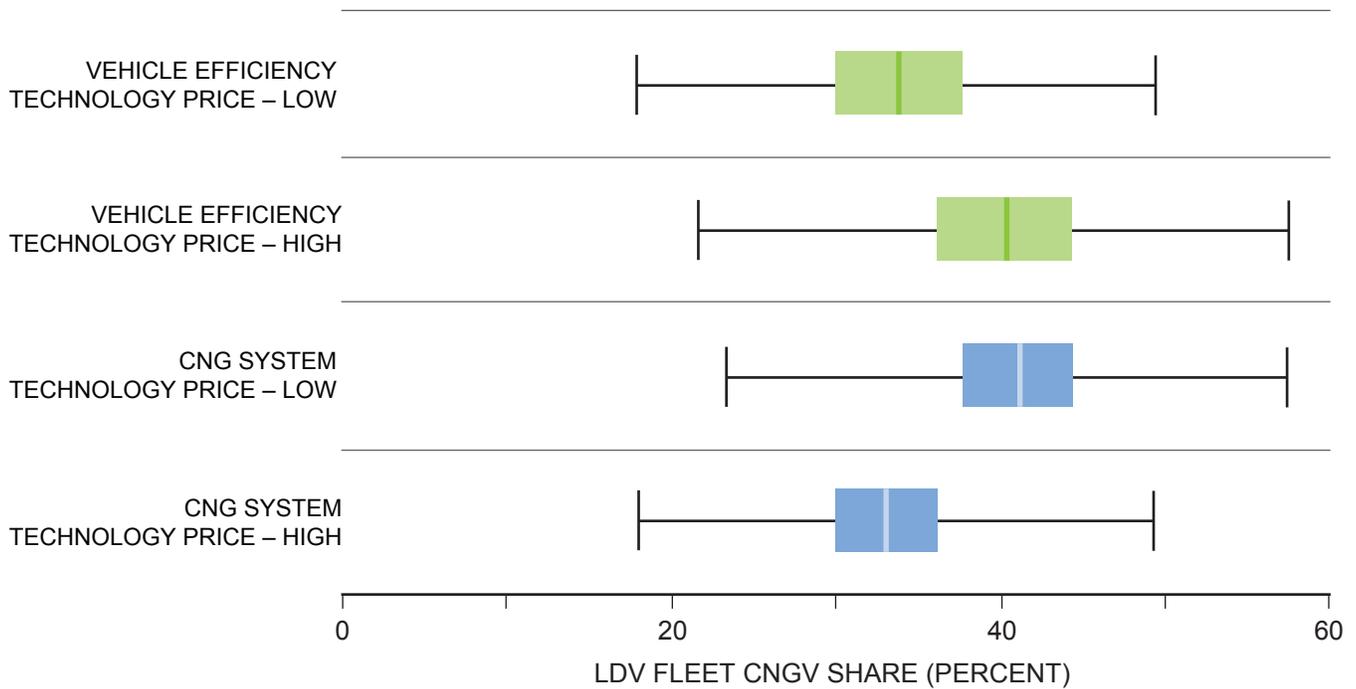
Notes: Brackets denote maximum and minimum for all oil price assumptions; bars represent ranges on Reference Case oil prices; vertical line within bar is average for Reference Case oil prices.

Liquid ICE is sum of Conventional, Gasoline HEV, and Diesel.

PEV is sum of PHEV10, PHEV40, and BEV100.

All ICE includes Conventional, Gasoline HEV, Diesel, CNGV, PHEV10, and PHEV40.

**Figure 2-10.** Ranges of 2050 Light-Duty Vehicle (LDV) Fleet Share including All Fuel-Vehicle Systems (Portfolio = All In)



Note: Brackets denote maximum and minimum for all oil price assumptions; bars represent ranges on Reference Case oil prices; vertical line within bar is average for Reference Case oil prices.

**Figure 2-11.** Ranges of 2050 Light-Duty Vehicle (LDV) Fleet CNGV Share When ICEs and CNGVs Compete (Portfolio = Liquid ICE + CNGV)

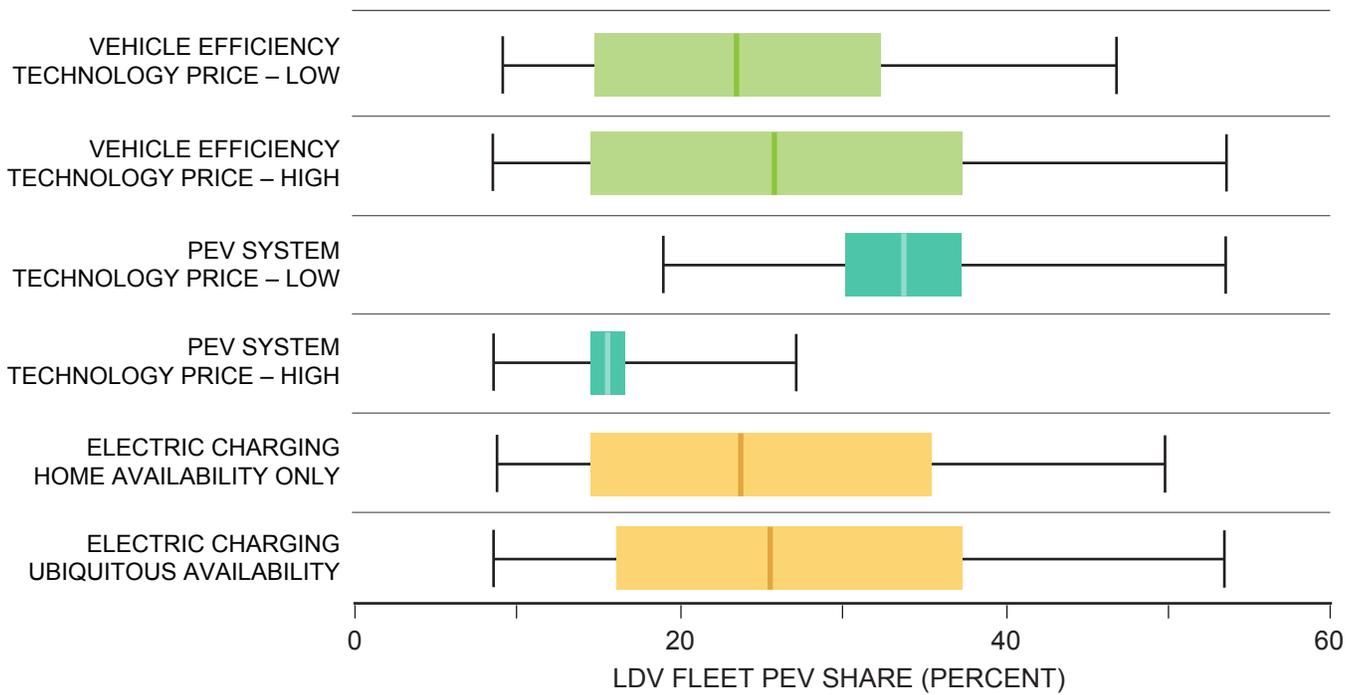
cost advantage that results in lower operating cost and higher share except under the Low Oil Price Case assumptions. Figure 2-11 shows the impact of vehicle-level efficiency technology and CNGV system cost on CNGV share when competing with liquid ICE only. The highest share of CNGV occurs when the CNGV costs (the largest component of which is the vehicle fuel tank) are low.

**Reducing PEV and FCEV systems cost can have a large impact on share.** Figures 2-12 and 2-13 show what drives the PEV and FCEV fuel-vehicle system shares in the liquid ICE+PEV and liquid ICE+FCEV portfolios. When PEV and liquid ICE vehicles compete (Figure 2-12), the cost of the battery has the greatest impact on share. Neither the vehicle-level efficiency technology cost nor the addition of ubiquitous charging stations to residential charging has a material impact.

When FCEVs compete only with liquid ICE vehicles, FCEV share is impacted most by the FCEV technology price, as shown in Figure 2-13. High fuel cell technology costs significantly increase the price of FCEVs, making FCEVs less competitive.

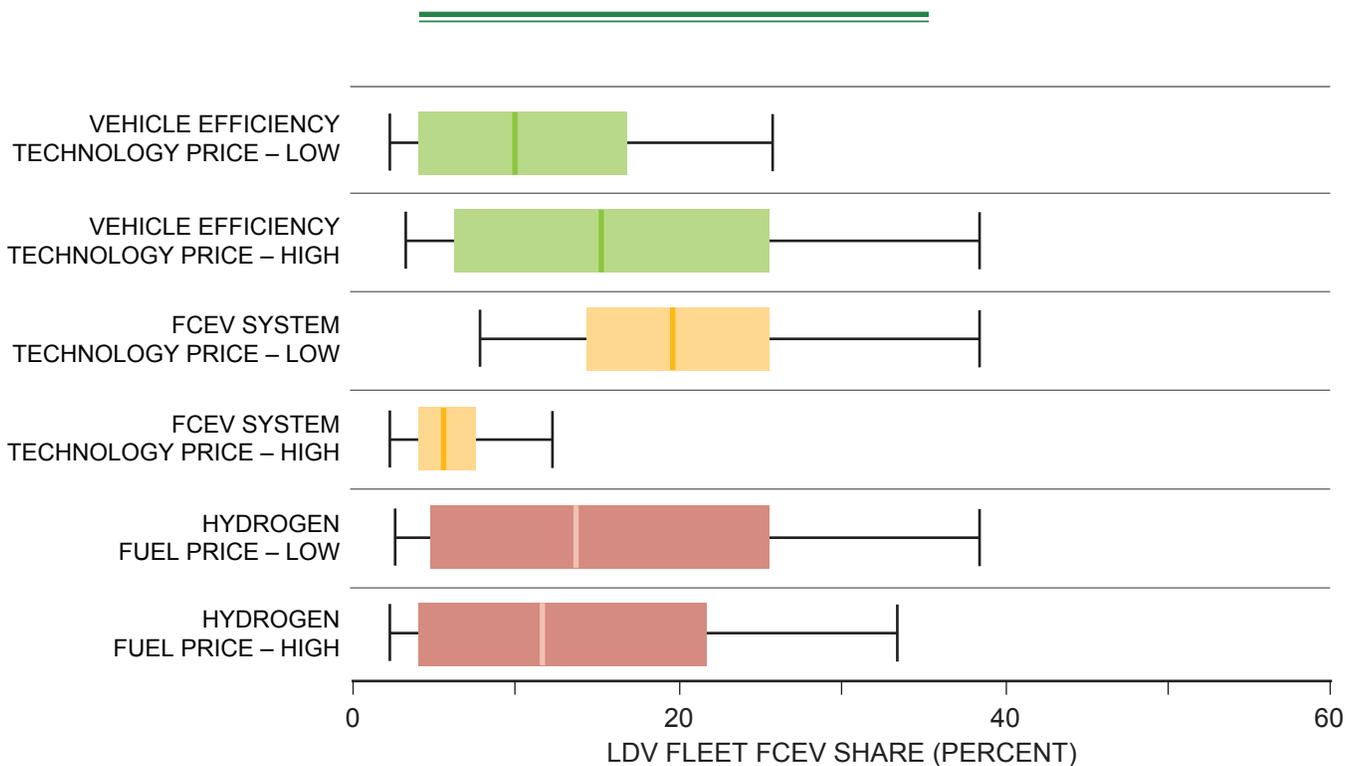
On the other hand, the relatively narrow range of hydrogen fuel costs modeled means hydrogen fuel costs have a relatively low impact on the FCEV's cost of driving and little impact on share. Decreasing vehicle efficiency technology price favors the liquid ICE vehicles more than the FCEVs, and therefore reduces FCEV share.

**Fuel diversification is increased relative to today.** Figure 2-14 shows the range in fuel consumption for each fuel in 2050. The results of the analysis yield ranges of fuels portfolios but with an overall increase in fuel diversification compared to today. The range for oil consumption varies widely depending on the oil price assumption. Other fuels have greater consumption than today, with CNG and biofuel having the most significant increases. The range in share of CNG reflects the assumed price spread between oil and natural gas. Consistent with the long study time horizon, it was assumed that the ICE vehicles can operate with any gasoline/biofuel blend or diesel/bio-based diesel blend. Biofuels take significant share when advanced biofuels are cost competitive. Where large volumes of advanced biofuels



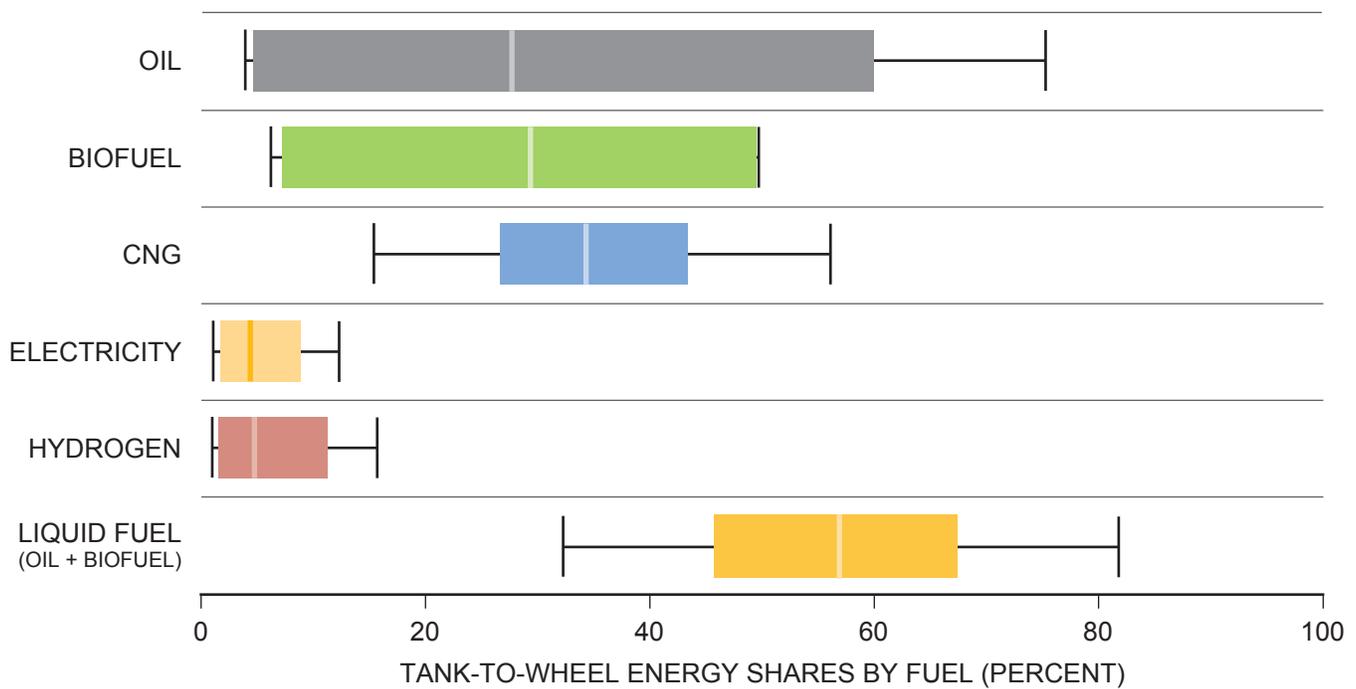
Note: Brackets denote maximum and minimum for all oil price assumptions; bars represent ranges on Reference Case oil prices; vertical line within bar is average for Reference Case oil prices.

**Figure 2-12.** Ranges of 2050 Light-Duty Vehicle (LDV) Fleet PEV Share When ICEs and PEVs Compete (Portfolio = Liquid ICE + PEV)



Note: Brackets denote maximum and minimum for all oil price assumptions; bars represent ranges on Reference Case oil prices; vertical line within bar is average for Reference Case oil prices.

**Figure 2-13.** Ranges of 2050 Light-Duty Vehicle (LDV) Fleet FCEV Share When ICEs and FCEVs Compete (Portfolio = Liquid ICE + FCEV)



Notes: Brackets denote maximum and minimum for all oil price assumptions; bars represent ranges on Reference Case oil prices; vertical line within bar is average for Reference Case oil prices.

**Figure 2-14. Fuel Shares in 2050 (Portfolio = All In)**

are cost competitive, all liquid ICEs, included those in HEVs, and PHEVs, operate on fuel blends with large biofuel fractions.

## Fleet Fuel Economy

As discussed earlier, the fuel economy of LD vehicles increases over time due to a combination of rising fuel costs, fuel economy technology cost reductions, and increasing electrification. Figure 2-15 shows the range of calculated on-road fuel economy of the LD fleet in 2050 grouped by portfolios. The average on-road fleet fuel economy of the 2010 LD vehicle fleet (21 miles per gallon gasoline equivalent<sup>10</sup>) is shown for comparison. The graph shows that the ranges of average values for fleet fuel economy in 2050 are considerably greater than the 2010 LD fleet average.

For liquid ICE, the increase in fleet fuel economy by 2050 results from two factors. First, there is continued increase in the fuel economy of new conventional liquid ICE vehicles and new HEVs over time, resulting either from improved economics (lower

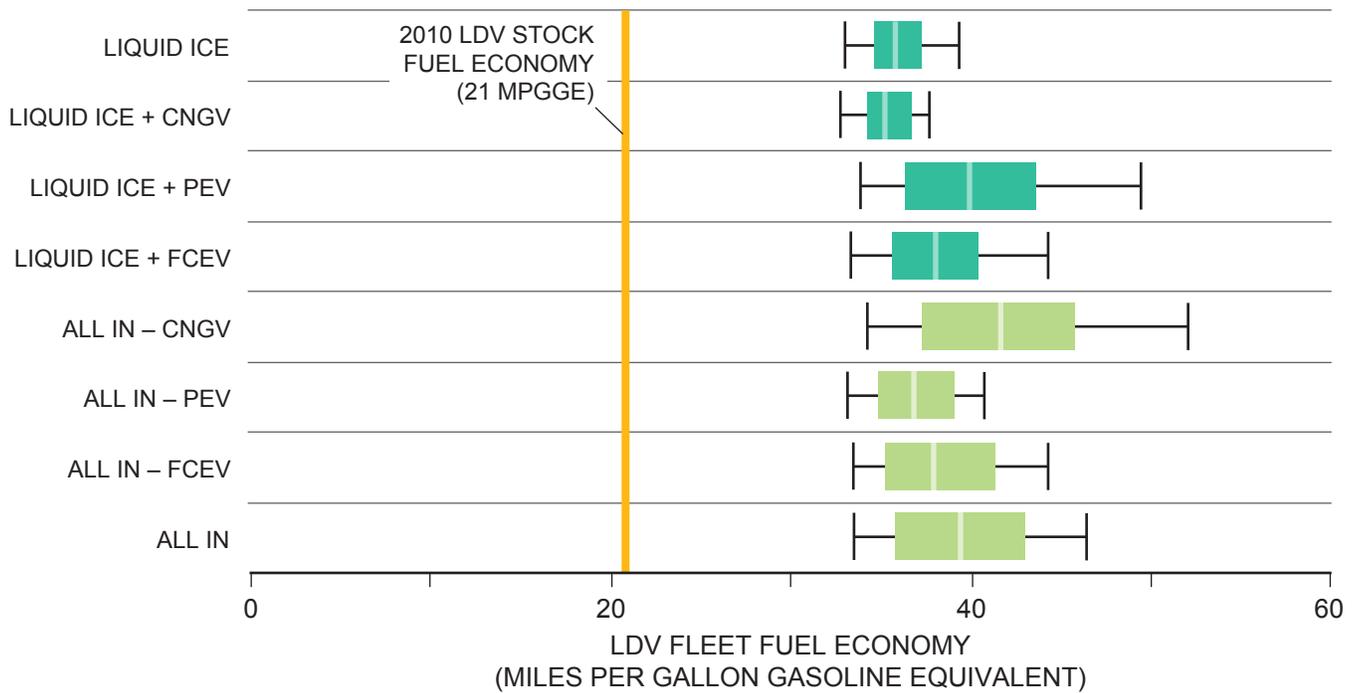
costs of fuel economy technologies and greater adoption due to rising fuel prices) or the minimum fuel economy constraint described in the Methodology section. Secondly, projected increases in fuel costs place greater value on fuel cost savings, increasing shares of more fuel efficient HEVs in the fleet. The net effect is an increase in fleet fuel economy by 60–90%, relative to 2010.

PEVs and FCEVs increase the overall fleet fuel economy up to a maximum of about 140%. This is due to the substantially higher fuel economy of PEV and FCEV fuel-vehicle systems compared to the liquid ICE and CNGV fuel-vehicle systems. In contrast, penetration of CNGVs does not increase the fleet fuel economy. Low CNG fuel costs are a disincentive for the adoption of high fuel economy technology.

## Cost of Driving

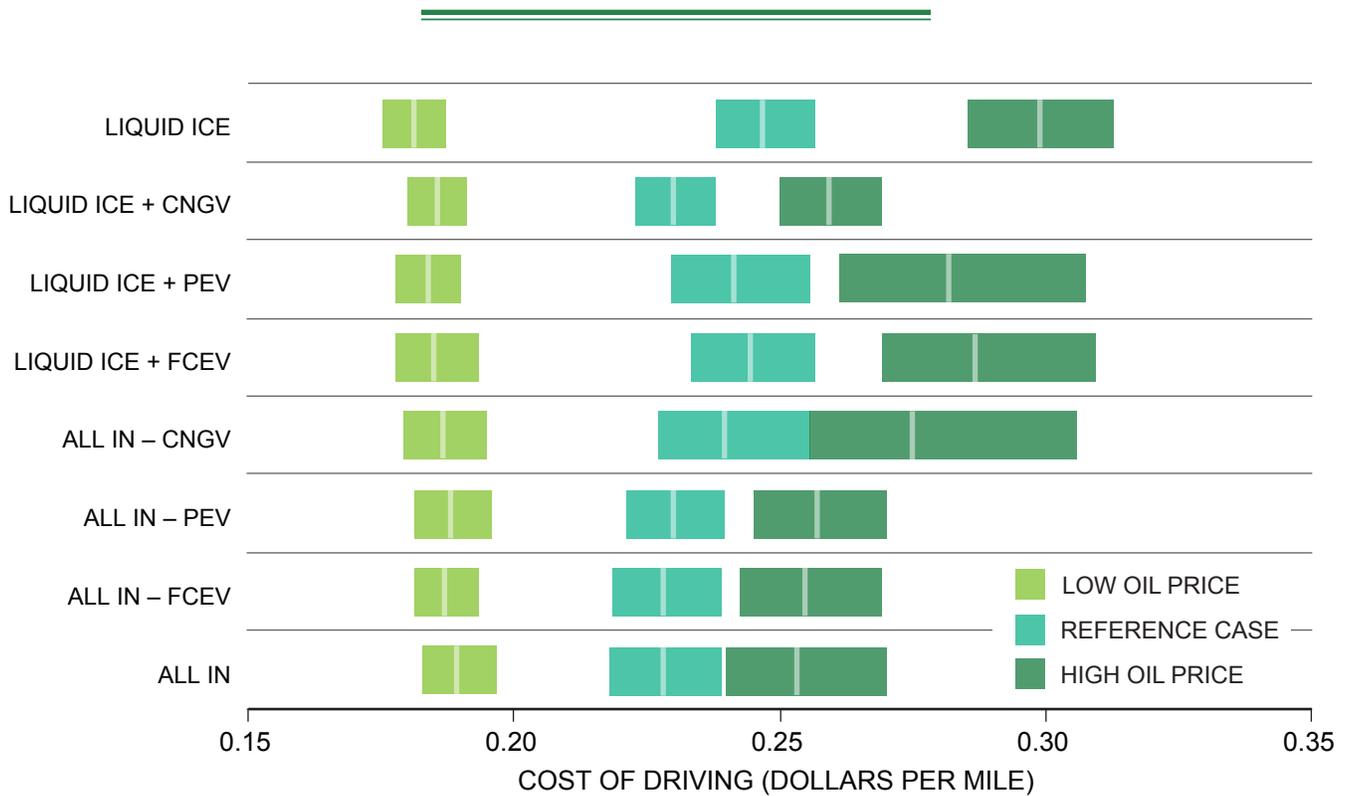
As described in the Methodology section, the cost of driving is computed for each year by first summing up total fuel expenditures, amortizing the cost of all vehicles on the road, and then dividing by total miles driven. The cost of driving results for 2050 are shown in Figure 2-16.

<sup>10</sup> Light-duty vehicle fleet fuel economy in 2010 from VISION 2010, Argonne National Laboratory.



Note: Brackets denote maximum and minimum for all oil price assumptions; bars represent ranges on Reference Case oil prices; line within bar is average for Reference Case oil prices.

**Figure 2-15.** Light-Duty Vehicle (LDV) On-Road Fleet Fuel Economy in 2050



Note: Bars represent ranges for all oil price cases; vertical line within the bar is the average.

**Figure 2-16.** Cost of Driving by Fuel-Vehicle System Combination and Oil Price Cases in 2050

**Petroleum and alternative fuels price assumptions have a significant impact on the cost of driving and alternative fuel-vehicle system share.** The fleet cost of driving increases significantly as oil prices increase. For the liquid ICE portfolio, moving from Reference Case price assumptions to Low Oil Price Case assumptions reduces the cost of driving by about 25%, while moving from the Reference Case price assumptions to High Oil Price Case assumptions increases cost of driving by about 20%. Within Reference and Low Oil Price Cases, the different fuel-vehicle system portfolios all have roughly the same cost of driving. As alternative fuel-vehicle systems are added to liquid ICE, the cost of driving decreases slightly under Reference Case oil price assumptions and increases slightly under Low Oil Price Case assumptions.

Under High Oil Price Case assumptions, adding alternative fuel-vehicle systems has a greater effect on lowering cost of driving, as fuel cost savings can better compensate for the higher vehicle prices. Portfolios with CNGVs have the lowest cost of driving under High Oil Price Case assumptions. This is driven by the large and assumed price difference between oil and natural gas.

**The economic value of alternative fuel-vehicle systems may be substantial.** Alternative fuel-vehicle systems can provide value by reducing the cost of driving compared to conventional liquid ICE vehicles. Each cent/mile saved in 2050 is equivalent to roughly \$50 billion/year. Under High Oil Price Case assumptions, the savings could be roughly \$300 billion per year. Under Low Oil Price Case assumptions, however, the savings could be negative.

The individual fuel-vehicle system chapters and Chapter Five, “Infrastructure,” identify the hurdles to achieving wide-scale commercialization of alternative fuel-vehicle systems. Some of these technology and infrastructure hurdles have cost and investment estimates. These costs should be viewed in context of the economic value that may be created by the wide-scale commercialization of alternative fuel-vehicle systems.

The incorporation of alternative fuel-vehicle systems into the fleet reduces the sensitivity of the fleet cost-of-driving to oil prices. For exam-

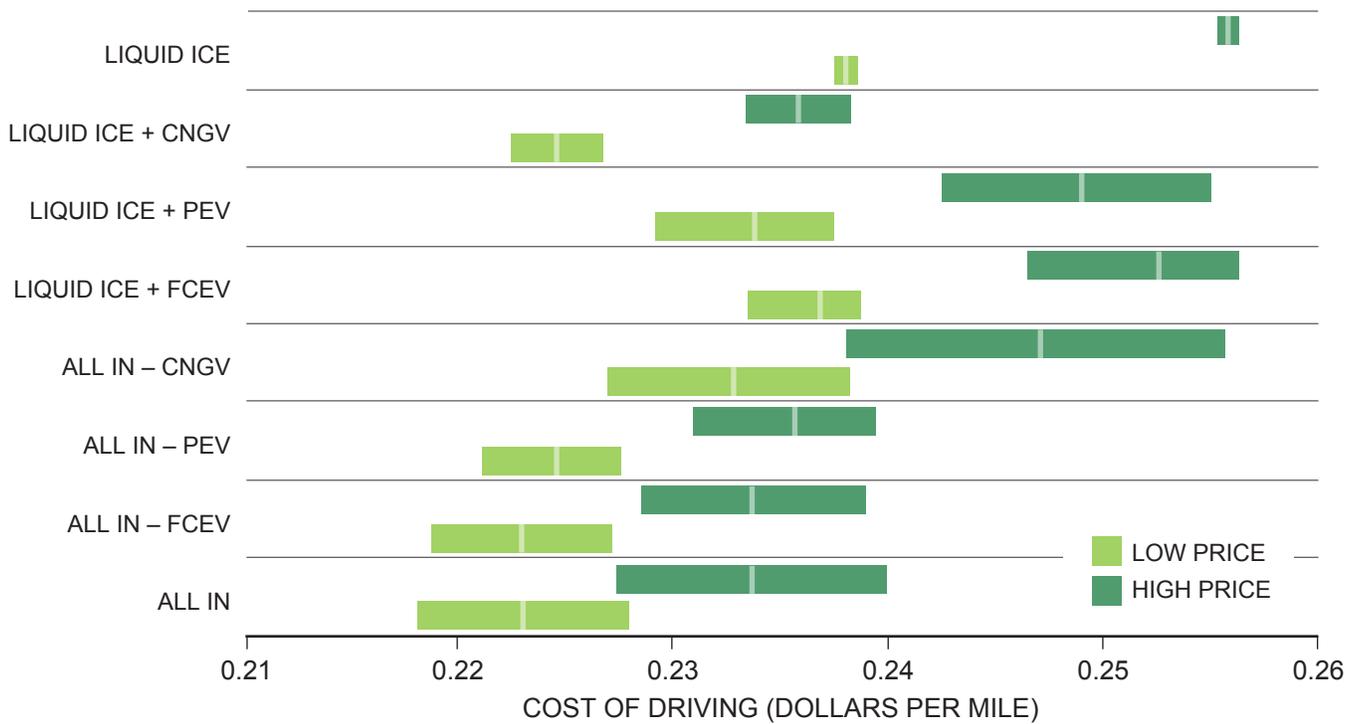
ple, Figure 2-16 shows that if High Oil Price rather than Reference Case assumptions are used, the 2050 cost of driving increases ~20% in fleets with only liquid ICE vehicles (“Liquid ICE”), but only ~10% when all fuel-vehicle systems are included (“All In”). This illustrates that having a diverse portfolio of fuel-vehicle systems can provide some economic resilience to increases in oil prices.

**Lowering the cost of non-powertrain efficiency technologies provides benefits for all fuel-vehicle systems.** Lowering the cost of non-powertrain efficiency technologies (improved aerodynamics, lower rolling resistance tires, and light-weighting) can have a significant positive impact on the cost of driving for all fuel-vehicle systems under Reference Case oil price assumptions, as shown in Figure 2-17. Overall, cost of driving may be reduced by 5–7%.

## Time Horizon for Evaluating Fuel Savings

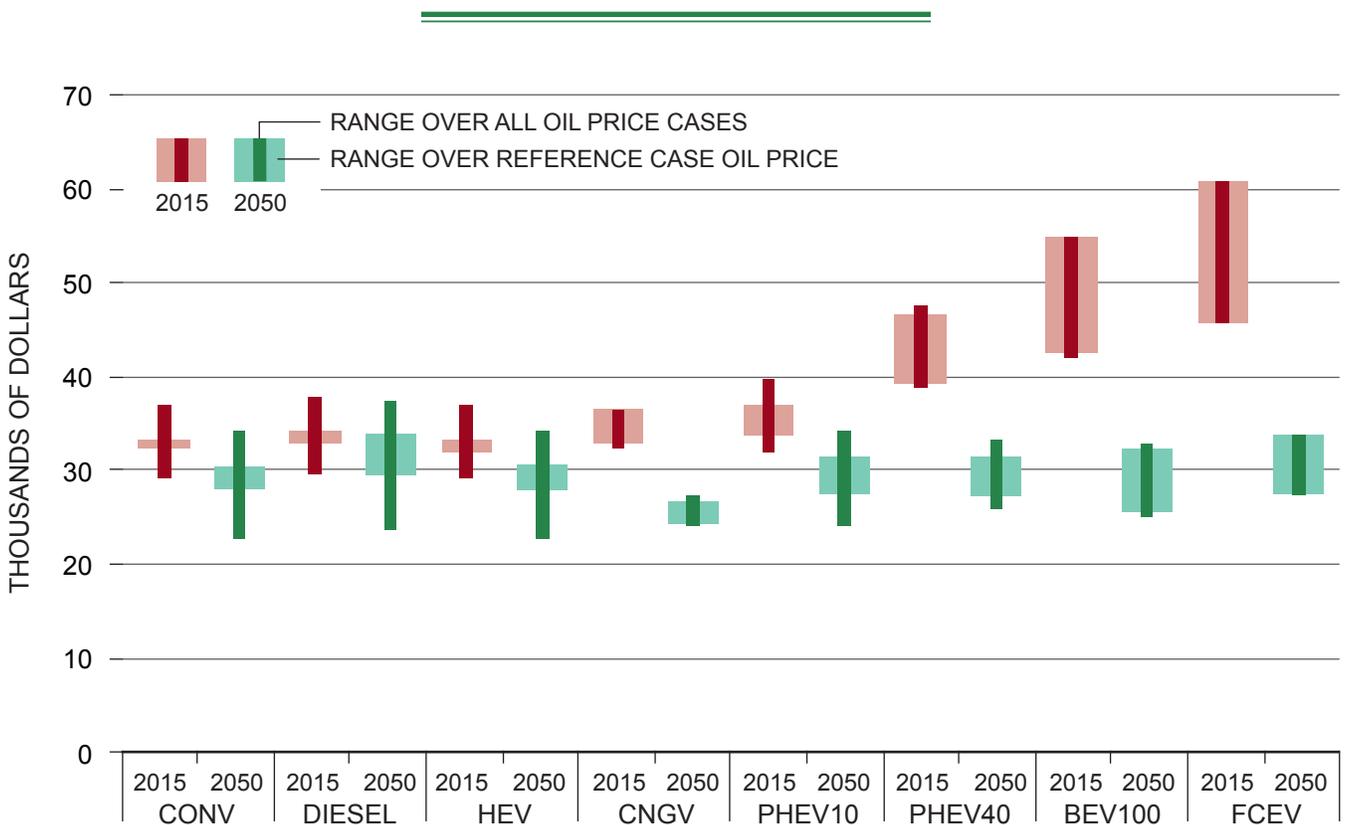
**Vehicle efficiency evaluated over a longer time horizon has a positive impact on fuel economy, cost of driving and wide-scale commercialization of alternative fuel-vehicle systems.** The results discussed thus far in this chapter were based on a 3-year time horizon for evaluating fuel savings, which is roughly aligned with the typical consumer view. If vehicle purchase decisions are assumed to be made based on achieving the lowest total cost over a longer time horizon (e.g., the rough vehicle lifetime of 17 years), greater emphasis is placed on fuel cost savings and less emphasis is placed on vehicle price. This produces greater vehicle fuel economy and greater share of fuel-vehicle systems with lower fuel cost.

Figure 2-18 shows small car segment new vehicle price plus fuel costs for the 17-year horizon for comparison to Figure 2-9 (shown earlier), which used a 3-year horizon. The relative competitiveness of conventional liquid ICE vehicles decreases with a 17-year horizon compared to the 3-year horizon. Based on a 17-year time horizon, 2050 CNGVs tend to have the lowest total cost, and HEV, PEV, and FCEV are more competitive with conventional liquid ICE vehicles.



Note: Bars represent ranges for Reference Case oil prices; vertical line within the bar is the average.

**Figure 2-17.** Impact of Non-Powertrain Vehicle Efficiency Technology Price on Cost of Driving in 2050



**Figure 2-18.** Analysis Results - Sum of Vehicle Price and 17-Year Fuel Costs for a Small Car

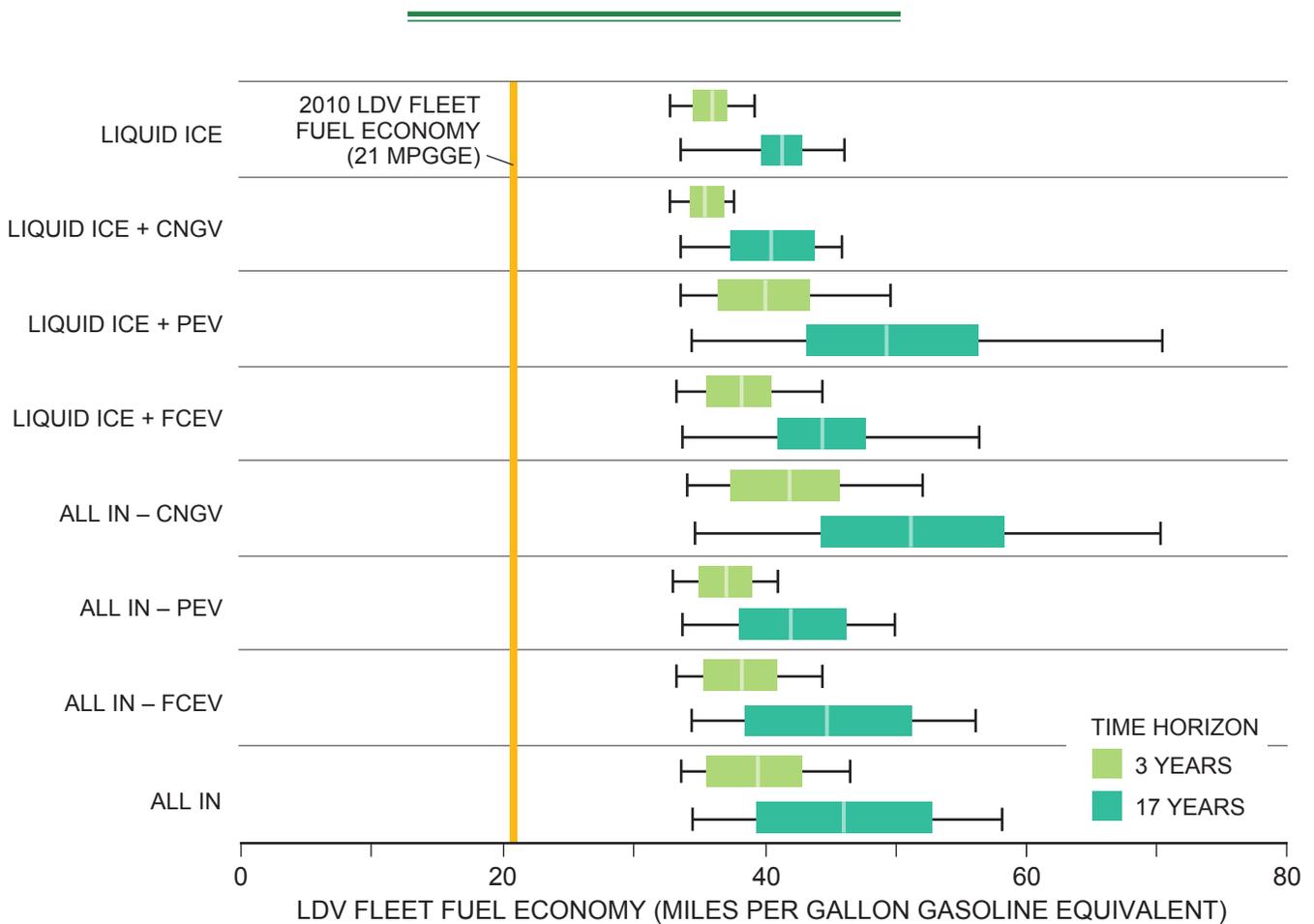
Figure 2-19 compares the fleet fuel economy using the 3- and 17-year horizons. The 17-year time horizon produces a higher fleet fuel economy in 2050 than the 3-year horizon. The fuel economy of each type of fuel-vehicle system entering the fleet is higher, as are the shares of more electrified vehicles (i.e., HEVs, PEVs, and FCEV). In the 17-year view, the liquid ICE fuel economy is more than two times the average fuel economy of the 2010 LD fleet, while a fleet with only PEVs and liquid ICE vehicles (“Liquid ICE + PEV”) has fuel economy ranges from two to roughly two and a half times higher.

Figure 2-20 shows that under Reference Case oil price assumptions when only liquid ICES are present, a 17-year time horizon consideration results in a cost of driving reduced by \$0.01 per mile, which represents approximately 4% of the total

cost of driving. The reduction in the cost of driving is slightly greater when alternative fuel-vehicles are included in the portfolio. For the U.S. vehicle fleet, a \$0.01 per mile reduction in the fleet cost of driving equates to approximately \$50 billion savings per year.

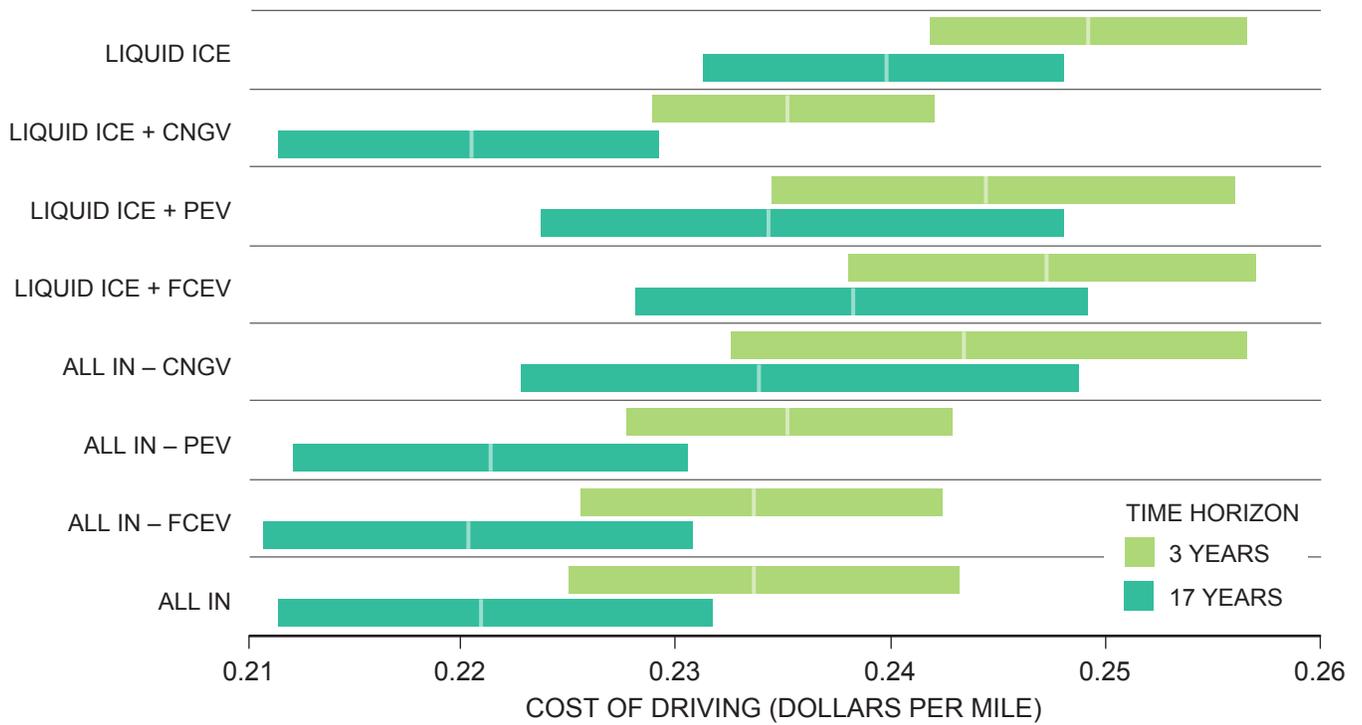
Figure 2-21 compares shares under the 3-year and 17-year view. All of the alternative fuel-vehicle systems show an increase in economic competitiveness in the 17-year horizon, leading to greater fleet share.

The impact of the 17-year view for the alternative fuel-vehicle systems is largest under High Oil Price Case assumptions. As shown in Figure 2-21, CNGVs have the largest share due to the very large fuel cost savings over a 17-year period, assuming CNG costs are persistently lower than gasoline.



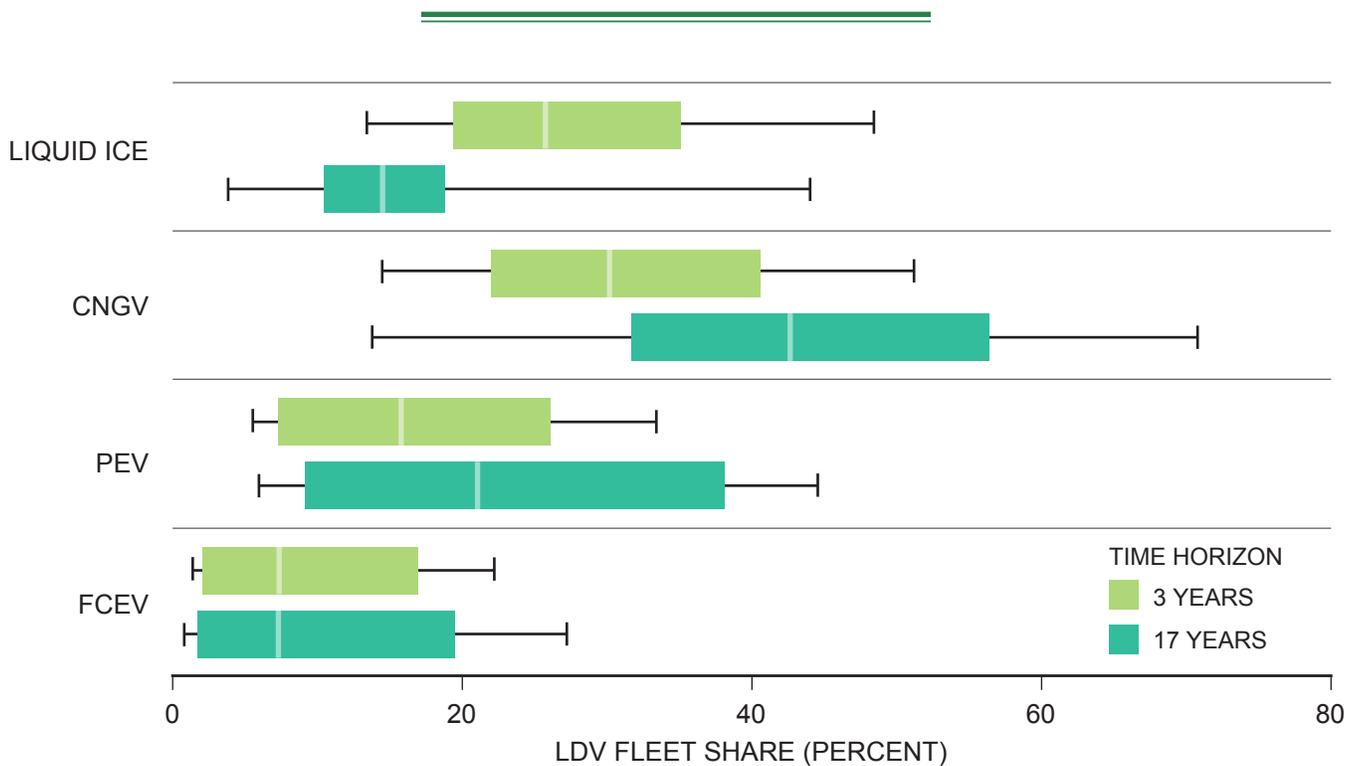
Note: Brackets denote maximum and minimum for all oil price assumptions; bars represent ranges on Reference Case oil prices; vertical line within bar is average for Reference Case oil prices.

**Figure 2-19. Impact of Time Horizon on Light-Duty Vehicle (LDV) Fleet Fuel Economy in 2050**



Note: Bars represent ranges for Reference Case oil prices; vertical line within the bar is the average.

**Figure 2-20.** Impact of Time Horizon on Cost of Driving in 2050



Note: Brackets denote maximum and minimum for all oil price assumptions; bars represent ranges on Reference Case oil prices; vertical line within bar is average for Reference Case oil prices.

**Figure 2-21.** Impact of Time Horizon on Fuel-Vehicle System Shares in 2050

## SUMMARY OF FINDINGS

- There are opportunities to dramatically improve the fuel economy of light-duty vehicles.
- All of the fuel-vehicle systems demonstrate the potential to achieve wide-scale commercialization by 2050.
- CNGVs are the strongest economic competitor to liquid ICE vehicles.
- Internal combustion engines will likely remain a dominant propulsion technology.
- Reducing PEV and FCEV systems cost can have a large impact on share.
- Fuel diversification is increased relative to today.
- Petroleum and alternative fuels price assumptions have a material impact on the cost of driving and alternative fuel-vehicle system share.
- The economic value of alternative fuel-vehicle systems may be substantial.
- Lowering the cost of non-powertrain efficiency technologies provides benefits for all fuel-vehicle systems.
- Vehicle efficiency evaluated over a longer time horizon has a positive impact on fuel economy, cost of driving, and wide-scale commercialization of alternative fuel-vehicle systems.



APPENDIX 2A:

**RANGE OF PRIMARY INPUT VALUES  
FOR FUEL-VEHICLE SYSTEMS**

Fuel-Vehicle System	Primary Inputs	2015 Input Range	2050 Inputs Range
<b>Liquid ICES – Gasoline, HEV, Diesel, and Biofuels</b>	Technology price ranges (\$/increase in fuel economy) Non-powertrain fuel efficiency technology (e.g., aerodynamics and lightweighting) Powertrain efficiency technology (e.g., turbocharging and hybridization)  <i>FE = fuel economy</i>	Gasoline Small Car: \$600-1,200 for 20% FE improvement over 2008 Gasoline Small Car  Diesel Small Car: \$1,400-2,800 for 20% FE improvement over 2008 Gasoline Small Car  HEV Small Car: \$1,400-2,500 for 40% FE improvement over 2008 Gasoline Small Car	Gasoline Small Car: \$1,100-2,300 for 50% FE improvement over 2008 Gasoline Small Car  Diesel Small Car: \$3,300-7,700 for 70% FE improvement over 2008 Gasoline Small Car  HEV Small Car: \$2,900-5,600 for 100% FE improvement over 2008 Gasoline Small Car
	Biofuel supply	10 billion gallons gasoline equivalent (gge)	10–63 billion gge
<b>Natural Gas (ICEs)</b>	Technology price ranges Non-powertrain fuel efficiency technology Powertrain efficiency technology NGV System (\$/vehicle)	Non-powertrain and powertrain: same as Gasoline above  NGV system: \$2,400-3,800 for Small Car for engine modification and CNG component assembly	Non-powertrain and powertrain: same as Gasoline above  NGV system: \$220-1,200 for Small Car for engine modification and CNG component assembly
	Natural Gas Storage System	\$340 + \$180/gge for steel storage  \$680 + \$330/gge for carbon fiber storage	\$215 + \$140/gge for steel storage  \$215 + \$120/gge for carbon fiber storage
<b>Electricity PEV</b>	Technology Price Ranges Non-powertrain fuel efficiency technology (same as conventional ICE above) Battery price (\$/kWh usable, including adjustment for secondary mass due to mass compounding)	Non-powertrain – Small Car: \$190-840 for 10% FE improvement over 2008  BEV battery price: \$680-1,100/kWh  PHEV battery price: \$850-1,370/kWh	Non-powertrain – Small Car: \$120-590 for 10% FE improvement over 2008  BEV battery price: \$290-480/kWh  PHEV battery price: \$330-550/kWh
	PHEV electric miles (% electric miles) <i>R = residential only charging</i> <i>U = ubiquitous charging</i>	PHEV10 27% (R) / 50% (U)  PHEV40 65% (R) / 80% (U)	PHEV10 27% (R) / 50% (U)  PHEV40 65% (R) / 80% (U)
<b>Hydrogen FCEV</b>	Technology price ranges Non-powertrain fuel efficiency technology Fuel cell system price (\$/kW)	Non-powertrain – Small Car: \$190-840 for 10% FE improvement over 2008  Fuel cell system price: \$52-74/kW	Non-powertrain – Small Car: \$120-590 for 10% FE improvement over 2008  Fuel cell system price: \$34-48/kW
	Hydrogen storage system	Storage system: (\$1,200 + \$900/kg) to (\$2,300 + \$1,780/kg)	Storage system: (\$470 + \$370/kg) to (\$920 + \$720/kg)