EXECUTIVE SUMMARY

SUMMARY OF FINDINGS AND RECOMMENDATIONS

OVERVIEW

Transportation in the United States is undergoing dramatic changes. These changes could evolve at an accelerated rate dependent on the speed of technology advancements and the economic viability of alternative fuels and vehicles. Vehicles powered by petroleum and internal combustion engines (ICEs)—the foundation of travel for over a century—continue to become more efficient and cleaner. They now run on petroleum blended with biofuels, some of their engines are assisted by electric motors, and they are being joined on the nation's roadways by vehicles running on natural gas, electricity, and hydrogen.

For example, natural gas is used in urban buses and refuse vehicles and is being introduced in trucks; biofuels comprise 10% of U.S. gasoline; a growing number of plug-in hybrid electric vehicles (PHEVs) and all-electric vehicles are becoming available to consumers; and, shortly, hydrogen fuel cell passenger vehicles will enter the market.

If the technology and infrastructure hurdles identified by this study can be overcome, plug-in hybrid, fuel cell, battery electric, and natural gas powered passenger vehicles, and natural gas heavy-duty (HD) vehicles could come into widespread national use over the coming decades. The scale of this effort will be enormous. Even with sustained investment in technology and infrastructure, these fuel and vehicle advances are not assured. They will be driven by the combined effects of economics, technology, environmental and other policies, and consumer demand—yielding incremental and cumulative gains for the United States.

Profound changes are possible with disruptive, yet highly uncertain, innovations such as ultra-light-weight vehicle materials that could further improve fuel efficiency; new battery technologies that significantly increase electric vehicle driving range; low-cost, low-pressure storage for natural gas or hydrogen, which could allow those systems to become cost competitive; or breakthroughs yielding lower-cost, low-carbon transportation fuel.

This report is the National Petroleum Council's response to the Secretary of Energy's request for advice on accelerating U.S. alternative fuel-vehicle prospects through 2050 for passenger and freight transport, while examining ways to economically reduce the U.S. transportation sector's 2050 life-cycle greenhouse gas (GHG) emissions. In order to examine acceleration, this study assumes that aggressive improvements in alternative fuels and vehicles can be achieved and substantial transition hurdles can be overcome. This optimistic approach provides insights about the transportation possibilities associated with the potential for significant advances. The study does not provide perspective as to the likelihood, cost, or timing for this transition.

Based on two years of review and analysis, involving more than 300 participants, this study concludes that:

- As cost competitiveness improves, existing technologies can be applied to substantially increase vehicle fuel economy.
- Overcoming twelve identified Priority Technology hurdles is essential to the commercialization of advanced fuels and vehicles.

- Implementing mitigation strategies can help overcome the substantial fuel-related infrastructure challenges.
- Continued investment in multiple combinations of advanced fuels and vehicles could yield solutions that benefit American consumers and significantly reduce GHG emissions.
- Achieving 50% GHG emission reductions in the transportation sector by 2050, relative to 2005, will require additional strategies beyond technology and infrastructure advances.
- Increasing the diversity of economically competitive fuels and vehicles will bolster the nation's energy security.

STUDY APPROACH

The following perspectives and assumptions are central to interpretation of the study's findings:[1]

- **Focus on 2050 –** Many of the technology advances described in the report are not broadly deployed today. However, the Council was asked to consider accelerating the commercialization of alternative fuel-vehicle systems. It is important to recognize that there is significant uncertainty in considering such a long-term horizon.
- **Aggressive Improvement Assumptions –** This study assumes that aggressive but not disruptive improvements in advanced fuel-vehicle systems are achieved and substantial transition hurdles are overcome. Further, the study did not consider the impact of changes in projected supply and demand on fuel prices. The NPC adopted this optimistic approach because it provides insights about the potential impact of these technology and infrastructure advances. The ranges of technology cost and performance are drawn from publicly available literature.
- **Reference Case and Modeling Tools[2] –** The NPC chose the Energy Information Administration's (EIA) Annual Energy Outlook 2010 (AEO2010) as a reference point from which to consider accelerating commercialization of alternative fuels and vehicles. The study participants chose to use the Vehicle Attribute, Vehicle Choice, TRUCK, and VISION modeling tools to consider ranges of potential outcomes. The Council recognizes the uncertainty in considering possible outcomes in 2050. Therefore, by using a credible and well-documented reference point and modeling tools, others may adjust selected inputs should their assumptions differ from those used in the analysis.
- **Cost, Timing, and Likelihood of Advances –** The NPC does not forecast cost, timing, or likelihood of advances. Some technologies are being deployed today, while others may take several decades and significant investment to overcome technology, cost, and infrastructure hurdles to commercialization.
- **Comparative Analysis on Vehicle and Fuel Costs –** The relative competitiveness of the fuel-vehicle systems are assessed on the basis of their fuel and vehicle costs. The NPC did not consider other attributes of consumer preferences in the quantitative analysis.

FINDINGS

There are competing priorities in the pursuit of new fuel and vehicle technologies that are at once reliable, affordable, and environmentally responsible. Striking a balance that meets individual and societal goals is the challenge at hand for both industry and government. This study attempts to address these priorities and strike a balance; the study provides the following findings and recommendations.

Increasing Vehicle Fuel Economy

Finding: **Fuel economy can be dramatically improved in the light-duty and heavy-duty sectors through the advancement and application of existing and new technology. Internal combustion engine technologies are likely to be the dominant propulsion systems for decades to come, with liquid fuel blends continuing to play a significant, but reduced role.**

Technology advances such as vehicle light-weighting, improved aerodynamics, and drivetrain

1 Additional assumptions can be found in the "Integrated Results" section of this Executive Summary.

2 The U.S. Energy Information Administration is the statistical and analytical agency within the U.S. Department of Energy. Models and accompanying documentation are available at www.npc.org.

electrification are already being deployed in the marketplace and have considerable potential to boost vehicle-fleet efficiency. Relative to 2010 levels, fuel economy could improve 60–90% by 2050 for a light-duty (LD) fleet of liquid ICE vehicles, primarily due to hybridization and incremental improvements.

Building on the improved light-duty liquid ICE vehicles, increased market penetration by plug-in electric vehicles (PEVs) and fuel cell electric vehicles (FCEVs) can lead to even more dramatic increases in LD fleet fuel economy, with portfolios containing large shares of hybrid vehicles, PEVs, and FCEVs increasing fleet fuel economy by up to 140%.

And—unless a Disruptive Innovation results in a more compelling alternative—internal combustion engines will remain dominant because of their lower cost and use in a diverse set of vehicle platforms: conventional gasoline and diesel liquid ICEs, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles, and compressed natural gas vehicles (CNGVs). In the LD segment, liquid fuels will continue to play a significant role, as they will be used in declining numbers of conventional ICE vehicles and increasing numbers of HEVs and PHEVs. Under the aggressive assumptions used in this study, all of the fuel-vehicle systems examined have the potential to be competitive in terms of combined fuel and vehicle costs. If the lower cost of natural gas (relative to petroleum) persists, and if fueling infrastructure is available and fully utilized, CNGVs are most competitive with conventional liquid ICE for LD vehicles under a broad range of conditions, primarily because fuel costs and vehicle technology hurdles are both relatively low. Advanced biofuels in liquid-fueled vehicles could gain significant share in LD vehicles, but will need to overcome technology, cost, and scale challenges.

The study also considered medium-duty (MD) and HD ICE vehicles (including non-plug-in hybrids) using liquid hydrocarbons, biofuels, and natural gas. With a cumulative impact of incremental advances in HD engine and vehicle designs, the fuel economy of new HD vehicles could improve up to 100% by 2050, relative to 2010 levels, thereby reducing the cost of freight transportation. Assuming fueling infrastructure is available, liquefied natural gas (LNG) and compressed natural gas (CNG) could become cost-competitive options, for HD and MD respectively, although diesel will remain the primary HD fuel. Biofuels could also play a role in MD and HD. Without Disruptive Innovations, alternative fuel options such as electricity and hydrogen are not likely to have a material impact on MD/HD fleets, but may still find use in niche applications.

Considering the potential impact of oil prices, the NPC found that their rise would prompt increased adoption of fuel economy technologies and alternative-fuel vehicles, while the adoption of new technology and alternative fuels is not economically attractive at low oil prices.

Overcoming Technology Hurdles

***Finding:* Priority Technology hurdles were identified that must be overcome for wide-scale commercialization of advanced fuel-vehicle systems by 2050. A broad portfolio of technology options provides the opportunity to benefit from potential Disruptive Innovations.**

The cornerstone of the study's technical analysis was the identification of technology hurdles for each fuel-vehicle system. More than 250 hurdles were identified to help define the challenges, requirements, or barriers that hinder alternative fuels and vehicles from reaching wide-scale commercialization. Rigorous evaluation reduced the 250 hurdles to twelve Priority Technology hurdles (see Table ES-1) that, if overcome, would improve the functionality, cost, and scalability of the fuel-vehicle systems. Leading scientists, economists, and industry experts conducted robust analyses of the scope, process, and results of these evaluations. Consistent and sustained effort is needed to overcome the Priority Technology hurdles. But because it is too early to determine which of these efforts could succeed, or when, a broad portfolio of technology options should be pursued.

The report also describes examples of possible but more uncertain Disruptive Innovations, which offer potential opportunities to transform the transportation sector. For example, discovering new battery chemistry could improve electric vehicle performance and reduce costs. Advanced-storage technologies for natural gas and hydrogen could reduce storage and compression costs. Genetic engineering

Fuel-Vehicle System	Technology Hurdle
Light-Duty Engines and Vehicles	• Low-cost lightweighting (up to 30% mass replacement)
Biofuels	• Hydrolysis • Fermentation of C5 and C6 sugars • Lignocellulose logistics/densification • Production of higher-quality pyrolysis oil • Biotechnology to increase food and biomass
Light-Duty Compressed Natural Gas	• Leverage liquid ICE fuel economy technology
Light-Duty Electric	• Lithium-ion battery energy density • Lithium-ion battery degradation and longevity
Light-Duty Hydrogen	• Compression and storage for dispensing • Fuel cell degradation and durability
Medium-/Heavy-Duty Engines and Vehicles	• Combustion optimization

Table ES-1. *Twelve Priority Technology Hurdles*

could boost feedstock yields and cut costs for biofuels. Low-cost ultra-lightweighting (i.e., reduction of vehicle mass by 50 to 70%) could improve the fuel efficiency for all LD vehicles. Research and development in Disruptive Innovations has historically been an area in which the federal government plays a significant role.

Addressing Infrastructure Challenges

Finding: **Infrastructure challenges must be overcome for wide-scale commercialization of advanced fuel-vehicle systems. Options exist to facilitate concurrent development of alternative-fuel vehicles and infrastructure, such as building on existing infrastructure, corridor-deployment, and multi-fuel vehicles.**

New fuel infrastructures require significant investment. While these costs are unlikely to be a significant portion of the cost of driving once the fuel infrastructure achieves high utilization, early fueling infrastructure is likely to be underutilized and therefore uneconomical, discouraging investment in both vehicles and fueling infrastructure. It is difficult but essential, therefore, that vehicles and the associated fueling infrastructure be deployed concurrently.

There are strategies that can help mitigate this issue, each with different costs and benefits. For example, natural gas technology can be deployed first in HD vehicles that travel highway freight corridors, enabling more targeted fueling station deployment. Plug-in hybrid electric vehicles can be refueled using the existing electricity supply system, and can also use gasoline if a charging station is not within range. Flexible/bi-fuel vehicles, such as gasoline/ethanol flexible fuel vehicles or gasoline/CNG bi-fuel vehicles, allow the use of gasoline and varying amounts of alternative fuels while infrastructure is being installed and not yet widely available.

Reducing GHG Emissions

Finding: **If technology hurdles and infrastructure challenges can be overcome, economically competitive low-carbon fuels and improvements in fuel economy will result in substantial reductions in GHG emissions. Additional strategies will be required to**

achieve a 50% reduction in GHG emissions relative to 2005 in the transportation sector by 2050.

Based upon the assumption that the twelve Priority Technology hurdles and the infrastructure challenges are overcome, all individual 2050 LD, MD, and HD fuel-vehicle systems analyzed could achieve greater than 40% calculated GHG emission reductions per mile, relative to 2005 levels. However, LD/MD/HD vehicle miles traveled (VMT) is projected to increase by 60 to 80% by 2050, relative to 2005, which counteracts per-mile GHG reduction gains. After considering projected demand growth alongside LD/MD/HD fuel-vehicle system GHG reduction improvements, the study identified a very limited set of portfolios and unique conditions that could achieve a 50% GHG reduction in the LD fleet.

For MD/HD vehicles, average fuel economy could almost double by 2050. However, on a fleet basis, demand growth mitigates the GHG impact of fuel economy improvements and total MD/HD GHG emissions remain similar to 2005 levels. The study participants did not identify a set of MD/HD vehicle portfolios that could achieve 50% reduction on a fleet-wide basis when accounting for VMT growth.

In response to the Secretary's specific question on ways to achieve 50% GHG reductions in the total transportation sector, if Disruptive Innovations do not occur, then additional strategies—such as reducing electric generation GHG emissions, reducing transportation demand (VMT), improving transportation system operating efficiencies, and other actions—need to be considered along with expanded use of low-carbon fuels and more efficient vehicles.

Enhancing Energy Security

Finding: **In the years ahead, the U.S. transportation sector could have access to a broad array of economically competitive fuel-vehicle system options, the diversity of which can contribute to our nation's energy security.**

Energy and national security are closely linked. Energy is essential to prosperity and disruptions to the energy supply can trigger adverse impacts throughout the economy. Historically, security concerns are usually heightened when geopolitical events threaten reliable energy supply. There are reasons, however, to be optimistic about North American energy sources and technologies, which are abundant, accessible, reliable, affordable, efficient, and clean. Increasing the diversity of economically competitive fuels and vehicles will bolster the nation's energy security.

RECOMMENDATIONS

The study makes the following recommendations:

- Government should promote sustained funding and other resources—either by itself or in combination with industry—in pre-competitive aspects of the twelve Priority Technology areas identified, as well as in areas that could lead to Disruptive Innovations.

- There is a great deal of uncertainty regarding which individual fuel-vehicle systems will overcome technology hurdles to become economically and environmentally attractive by 2050. Therefore, government policies should be technology neutral while market dynamics drive commercialization.

- The federal government should take a leadership role in convening state, local, private sector, and public interest groups to design and advocate measures to streamline the permitting and regulatory processes in order to accelerate deployment of infrastructure.

- When evaluating GHG emission reduction options, the government should consider full life-cycle environmental impact and cost effectiveness across all sectors. It should also continue to advance the science behind the assessment methodologies and integrate life-cycle uncertainty into policy frameworks.

- Fuel, vehicle, and technology providers should consider existing or new voluntary forums that include federal and state governments and other stakeholders, to address concurrent development of vehicles and infrastructure.

BACKGROUND

The Executive Summary continues with a description of the nation's transportation system today and looks forward at the projected demand for transportation services through 2050. The primary advantages and disadvantages of the various fuel-vehicle systems considered in this study are provided to give a high-level overview of how this future transportation demand could be met. Information about the technology and infrastructure challenges that would need to be overcome to enable future fuel-vehicle options is then provided. Following this information, the potential future fuel and vehicle systems are discussed. Implications to future GHG emissions from transportation and possible fleets of vehicles are then considered along with strategies for emissions reduction and energy security benefits that could result. Finally, the Executive Summary sets out recommendations in response to the Secretary of Energy's request, and ends with concluding remarks.

TRANSPORTATION INDUSTRY TODAY

The vehicle manufacturing and petroleum industries are mature, wide-scale, and very effective at providing transportation service across the nation. Over the past 100 years, these industries have evolved continually in response to customer demand, commercial pressures, and government regulations. In the coming decades, the transition to new vehicle technologies and fuels will require significant and fundamental changes to both the vehicle and fuels industries as plants, supply chains, logistics, refineries, and extraction operations evolve. Significant changes in the skill sets of the workforce will also be needed as industry adapts to changes in the transportation system. For example, worker training will need to expand from mechanical to electrical disciplines and from component to systems thinking.

Vehicle Manufacturers

The motor vehicle industry today is global and producing increasingly efficient and reliable vehicles. In 2010, there were approximately 75 million new light- and heavy-duty vehicles sold around the world; approximately 12 million of these vehicles were sold in the United States. The global LD vehicle on-road fleet is approximately 830 million, with the U.S. fleet accounting for approximately 28% of that total (230 million vehicles). The longevity of vehicles in a country's operating vehicle inventory varies. Based on recent LD sales rates and longevity levels, it would take 17 years to replace the entire U.S. vehicle fleet.

The cost-effective, high-volume production of LD vehicles relies on maximizing the use of globally common components, systems, designs, and processes. For mass-market original equipment manufacturers (OEMs), multiple vehicle brands and body-style derivatives are produced from common vehicle and powertrain platforms that ideally have annual production volumes in the many hundreds of thousands. These platforms are typically built in plants around the world to align 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, life cycle, and longevity are similar across auto manufacturers worldwide. It takes two to four years to conceptualize and develop a vehicle. Mild updating and refreshing takes the least amount of lead time, while new platforms and vehicle models take the most time. Powertrain development lead times are typically longer than those for new vehicle models. While the definition and execution of a vehicle platform varies among manufacturers, it is often expected that core platforms will be 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. Auto manufacturers typically manage their product portfolios with a 5- to 10-year horizon, timing the development and launch of vehicles to address their best assessment of market demand and balancing workload, engineering expense, capital investment, and showroom freshness.

The auto industry today is producing vehicles that continue to become more efficient and cleaner. Many vehicles can run on petroleum blended with biofuels or have engines that are assisted by electric motors. New generations of vehicles joining the fleet are powered by natural gas, electricity, and hydrogen.

Buses and trucks that run on natural gas are being introduced, and although there are far fewer heavy-duty vehicles than cars on the road, they are a significant factor in overall transportation-energy consumption. MD and HD trucks, defined as Class 3-8 on-road vehicles,[3] consume over 20% of the fuel used in transportation in the United States. That share is expected to grow to almost 30% by 2050 based on extrapolations of the AEO2010. According to the American Trucking Association, there are over 8 million Class 3-8 trucks on the road, with 96% of fleets operating fewer than 20 trucks. HD vehicles often are purchased as capital goods for the purpose of helping a company or government entity conduct business and/or perform a specific, dedicated task. Six companies produce over 98% of the U.S. market for Class 8 trucks. Many of the same players compete in the Class 3-6 truck and bus markets. Advancements are being made to MD and HD vehicles through modifications to truck designs and powertrains that increase fuel economy and reduce emissions.

Petroleum Industry and Liquid Hydrocarbons for Internal Combustion Engine Vehicles

The petroleum supply chain touches every corner of the country and links to a global supply chain providing efficiency and flexibility. It takes approximately 14 million barrels of oil per day to meet U.S. transportation demand. To satisfy transportation demand, the petroleum industry has a domestic refining capacity (as of 2010) of approximately 17.5 million barrels per day, 168,000 miles of crude oil and products pipeline, 1,400 petroleum product terminals, and 100,000 tanker trucks delivering to over 160,000 service stations.

In recent years, the crude oil supply outlook for the United States and Canada has improved significantly. U.S. oil production has reversed a long-term declining trend, while Canadian production continues to increase. This positive trend is expected to continue due to the increasing role of unconventional sources such as tight oil, heavy oil, and oil sands. U.S. oil imports have decreased since 2005 and are forecast to continue to decline slowly to 2035. Significant further reductions in imports are possible with improved vehicle efficiency or further increases in U.S. oil production facilitated by greater access to resources.

Hydrocarbon liquids have unique properties that make them well suited as transportation fuels including high energy density, liquid form with easy transport, adjustable combustion characteristics for use in a wide range of engines, and consumer familiarity and risk acceptance. For these reasons, they are expected to continue to play a key role in the future U.S. transportation system. Going forward, hydrocarbon liquids will increasingly facilitate the use of biofuels and other new liquid fuels through blended products and shared dispensing infrastructure.

TRANSPORTATION DEMAND

Transportation Services Demand Projections

Transportation services demand is a pivotal factor for evaluating the impact of new vehicle and fuel technologies on energy consumption, GHG emissions, and energy security. This study uses AEO2010[4] projections of travel and freight transportation services through 2035. For 2036 to 2050, it uses Argonne National Laboratory's extrapolations in VISION[5] where available and, where not, extends the AEO2010 growth rate from 2030 to 2035 out to 2050.

The AEO2011 and 2012 updates were not available when this study began. They have been reviewed as released and found to not include data that significantly affect the findings. They do,

3 The Department of Transportation categorizes vehicles by Gross Vehicle Weight Rating. Commercial trucks are typically categorized as Classes 3 through 8. Chapter Three, Heavy-Duty Vehicles, describes these classes.

4 *Annual Energy Outlook* is published by the U.S. Department of Energy, Energy Information Administration. Most recent and prior editions are accessible at www.eia.gov.

5 The VISION modeling tool was developed by Argonne National Laboratory to provide estimates of the potential energy use, oil use, and carbon emission impacts of advanced light- and heavy-duty vehicle technologies and alternative fuels through the year 2050 (www.transportation.anl.gov/modeling_simulation/VISION/).

however, project lower transportation demand in 2035, which has a material impact on total energy use and GHG emissions in 2035 and 2050. Therefore, this report comments on those differences where relevant, but did not redefine the Study Reference Case since more recent projections do not significantly alter the relative performance of alternative vehicle and fuel systems in our analysis.

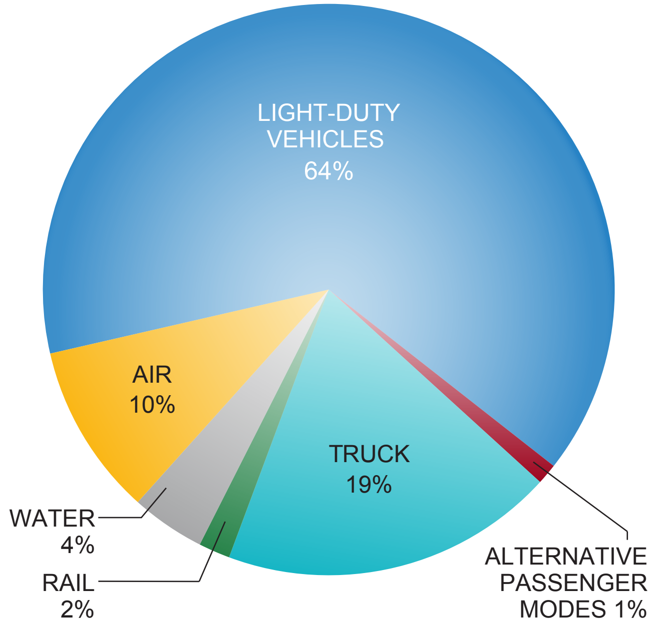
The modal distribution for 2010 transportation energy consumption is presented in Figure ES-1. The LD vehicle segment was the largest energy consumer, at 64%, followed by MD and HD trucks, accounting for 19%. The study focuses more heavily on these on-road categories.

The demand for transportation services is typically expressed in terms of vehicle miles traveled, ton miles, or passenger seat miles depending on the mode of transit. Figure ES-2 shows the growth in transportation services by mode from 2010 to 2050. The blocks indicate the average annual growth rate in the Study Reference Case. The first three variables are the growth rates of the key macro indicators—GDP, population, and the value of industrial shipments.

As can be seen in Figure ES-2, all transportation modes are projected to grow. Note that the range of uncertainty in economic activity translates into a comparable range of uncertainty in the demand for services. The growth of the different modes aligns more closely with particular indicators. The growth range in LD vehicle and air passenger miles corresponds more closely to population growth, while the growth range of freight trucks corresponds more closely to GDP and industrial shipments.

While the demand for transportation services is largely determined by macro indicators, energy demand is determined by both the services demand and vehicle energy efficiency. Energy efficiency relates to how much energy is consumed per unit of service—such as miles traveled per gallon for on-road vehicles. Energy demand will increase through time if demand for services increases at a faster rate than efficiency improves.

The price of energy relative to the cost of new vehicle fuel efficiency technology through time determines the rate of fuel efficiency improvement. Generally, more vehicle technology is adopted to improve efficiency as the cost of energy increases.



Note: Pie chart includes commercial light-duty trucks under "Truck," and excludes transportation sectors of recreational boats, lubricants, pipeline, and military use.

Source: AEO2010.

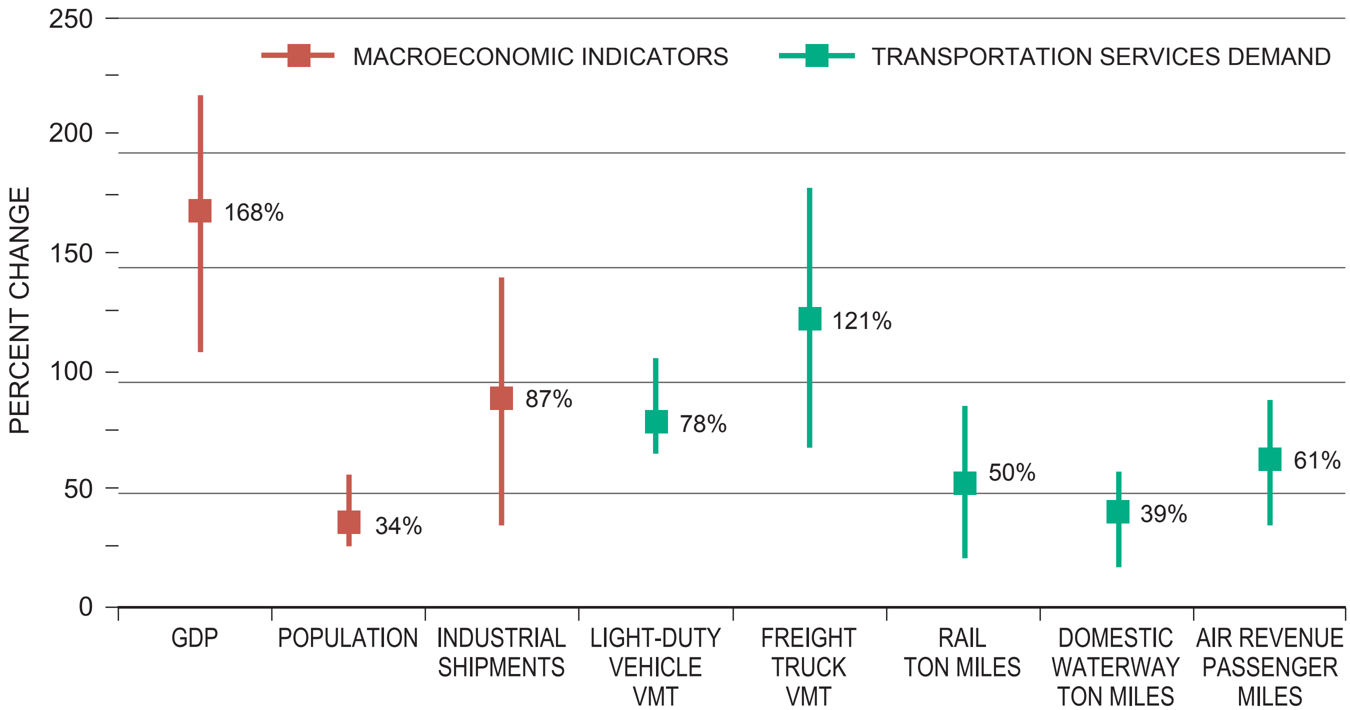
Figure ES-1. *Transportation Energy Consumption, Modal Distribution in 2010*

The fuel savings compensate for the increased cost of the vehicle fuel economy technology. This premise underlies the AEO2010 and the analysis of this study. In general, therefore, transportation energy consumption is more sensitive to energy prices than transportation services.

Light-Duty Vehicles

LD vehicle VMT was 2.7 trillion miles in 2010 and is projected to reach nearly 5 trillion miles by 2050 in the Study Reference Case. Consistent with the recent historical trend, the rate of VMT growth is projected to slow over the study period. This is attributed to changing demographics and a weakening relationship between household VMT and income. The AEO 2012 Early Release projects a 15% lower LD vehicle VMT in 2035 as compared to the Study Reference Case, highlighting the uncertainty in projecting future VMT.

In general, LD vehicle energy demand is more sensitive to sustained price increases than VMT because consumers adopt more fuel-efficient



Note: The maximum and minimum points of the vertical line are the growth rates in the AEO2010 high and low economic growth cases, respectively.

Figure ES-2. *Modal Growth, 2010–2050*

vehicles to limit the impact on their total transportation expense. The report does not evaluate the opportunities for passengers switching to alternative modes; rather its focus is on comparing alternative LD fuel-vehicle systems.

Freight Transportation Services – Truck, Rail, Water

Freight transportation services by MD (Class 3-6) and HD (Class 7&8) truck, rail, and water accounted for 25% of total transportation energy consumed in 2010. Trucking alone accounted for 19%. Growth in HD truck VMT aligns with growth in manufacturing and natural resource industries. MD vehicle VMT growth is slightly stronger, reflecting ties to deliveries in the service sectors. Trucking VMT is relatively insensitive to fuel prices. However, the industry is highly competitive, so sustained higher fuel prices drive service providers to adopt new fuel saving technology when it is cost effective. The study investigates and evaluates the impact new vehicle and fuel technologies in trucking can have on energy consumption and GHG emissions. However, worsening road congestion could offset the benefits.

The rail industry continues to invest in more fuel-efficient equipment and improve the operational efficiency of freight services. Trucking, rail, and water compete for some freight, but the study does not evaluate modal shifts from changes in fuel and vehicle technologies. Continued investment in both rail and water equipment and infrastructure will be necessary to carry the freight they take off the roads.

Air Transportation

Air transportation accounted for approximately 10% of transportation energy demand in 2010. The Study Reference Case projects passenger seat miles could increase 61% between 2010 and 2050, or about 1.4% average annual growth. This is less than the 3.9% growth experienced between 1978 and 2009. Current industry projections range between 2.9% and 3.9%. Projections that indicate a slowing from historical growth, like the AEO2010, may be influenced by expected capacity constraints or other limiting factors on air infrastructure development.

FUEL AND VEHICLE SYSTEMS

The following subsections describe the various fuel and vehicle systems considered in this study—light-duty liquid fueled internal combustion engine vehicles; biofuels for light-, medium-, and heavy-duty ICE and plug-in electric hybrid vehicles; electric vehicles; natural gas fuel and vehicle systems; hydrogen fuel cell electric vehicles; and heavy-duty vehicles. Summaries of the primary advantages and challenges of each system are provided.

Light-Duty Liquid Fueled Internal Combustion Engine Vehicles

This study examines technologies (and their related costs) to reduce the 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 in LD Vehicles

The primary advantages of conventional liquid fueled ICE vehicles include the maturity and scale of the technologies involved, with high-volume, low-cost supply chains and manufacturing capability and a liquid fuels supply chain that is also mature, large-scale, and well developed. Manufacturers are currently introducing more efficient vehicles and have additional fuel economy improvements in the pipeline that will benefit consumers in the near term and beyond.

Many of the vehicle and propulsion system technologies considered for liquid ICE fuel-vehicle system fuel economy improvement are applicable to other fuel-vehicle systems as well. Advances in vehicle-level technologies such as improved aerodynamics, reduced rolling resistance, and lightweighting (up to 30% of vehicle mass) apply to all fuel-vehicle systems. Advances in ICE propulsion system technologies are applicable to both liquid and gaseous fueled engines. The most significant fuel economy improvements come from hybridization (up to 90% relative to 2010 conventional vehicle) and mass reduction (up to 20% improvement from 30% mass reduction).

Primary Challenges to the Use of Liquid Fueled ICEs in LD Vehicles

The primary challenge to significant fuel economy improvement in the ICE fuel-vehicle system is achieving cost levels that provide an attractive value proposition to consumers. Increasing fuel economy is strongly correlated to increasing costs related to engineering, materials, and manufacturing. For example, lightweighting of vehicles, which is the replacement of traditional steel in vehicles with much lighter materials, could be leveraged across all vehicle types to improve fuel economy and reduce greenhouse gas emissions. However, one of the primary technology challenges recognized in this study is the accomplishment of lightweighting at low cost. Additionally, to achieve the maximum fuel economy benefit, multiple technologies must be developed and deployed as systems. These systems can take many years to develop and deploy in sufficient volume to impact the total LD fleet.

Alternative Hydrocarbon Liquids

Long-term commercial development of alternative hydrocarbon liquids—gas-to-liquid (GTL), coal-to-liquid (CTL), and oil shale—will require higher oil prices than are currently forecast, unless capital costs are reduced significantly. However, these alternative hydrocarbon liquids represent a large potential resource that could augment petroleum supply. Commercial production of methanol from natural gas is established, but unlike GTL and other liquids, significant investment would be needed in fueling and vehicle infrastructure.

Liquid ICE Vehicle Insights

- Many technologies in varying stages of development can provide up to 90% fuel economy improvement in liquid ICE light-duty vehicles relative to 2010 vehicles.
- The primary obstacle to high-volume application of these technologies is cost.
- Multiple technologies need to be developed and deployed as systems to maximize fuel economy, which can take many years.

- ICE technology will likely be a dominant technology as it is applied to plug-in hybrid-electric vehicles and compressed natural gas vehicles over time.

Biofuels for Light-, Medium-, and Heavy-Duty ICE and Plug-In Hybrid Electric Vehicles

Primary Advantages to the Use of Biofuels in LD Vehicles

Conventional biofuels are commercial today and can provide a GHG benefit over fossil fuels. The United States has current annual production capacity of approximately 14 billion gallons (910,000 barrels/day) of ethanol derived from corn starch. In addition, the United States is producing about 2 billion gallons per year of biodiesel. The potential exists for significant expansion of first generation biofuels as improvements in yields continue to increase; specifically, corn yields are predicted to double by 2030.

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 expanding the feedstock supply and providing greater GHG reduction than conventional liquid transportation fuels.[6] There are significant quantities of biomass available, which if converted to biofuels, could increase the volume of available biofuels several fold from today's levels. Several demonstration plants are under construction to demonstrate the technology for producing advanced biofuels. Biofuels can also provide a significant opportunity to leverage existing vehicle and fueling infrastructure—for example, flexible fuel vehicles and fueling stations.

Primary Challenges to the Use of Biofuels in LD Vehicles

There are no major technological hurdles preventing expansion of today's corn-based biofuels because feedstock logistics and fuel production technologies are well established. Increasing production volume, however, will require the support of additional fuel and vehicle infrastructure. Continued expansion of biomass feedstock supply depends upon crop yields, arable land availability, and co-product utilization. As yields continue to increase, soil, water, and other sustainability criteria must be taken into consideration.

There are material challenges to the development of cellulosic biofuels. Significant research efforts are underway to increase the yields of cellulosic energy crops such as switch grass and miscanthus. Infrastructure development to collect, store, transport, and process biomass is critical to the wide-scale adoption of biofuels. 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 chemical products.

There are two major technology platforms for cellulosic conversion, biological and thermochemical. Each technology platform has several separate pathways under development that could allow for the commercial deployment of cellulosic biofuels in the form of ethanol, isobutanol, and other "drop-in" biofuels. However, according to a recent study,[7] there are technological and economic challenges for advanced biofuels, and uncertainty about biofuel greenhouse gas benefits.

Biofuel Insights

- Advanced ethanol, biodiesel, and cellulosic-based biofuels each represent a significant potential opportunity to reduce GHG emissions.
- Lignocellulosic biofuels have the potential to be economically competitive with petroleum-based fuels if key technology hurdles are overcome in the conversion of lignocellulosic biomass to biofuels.
- Increasing corn supply and continued improvements in yield and environmental performance could enable corn-based ethanol and vegetable oil based biofuels to be

6 Study analysis did not include biofuel GHG emissions associated with indirect land use change (ILUC) because of considerable current and future ILUC emission uncertainties. Chapter Six, Greenhouse Gases and Other Environmental Considerations, provides additional background on ILUC as well as GHG emissions uncertainty ranges, including ILUC, for individual fuel-vehicle systems.

7 National Research Council of The National Academies, *Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy,* 2011.

produced at volumes beyond those currently produced.

- While the volume of lignocellulosic biomass could be available, logistics are not well suited to feeding large centralized plants. Development of smaller more intensified technologies or local economical densification technologies will be necessary.
- The biofuels industry will be challenged to meet targets of the Renewable Fuel Standard 2 (RFS2).

Natural Gas Vehicles

The availability of long-term, low-cost domestic sources of natural gas, driven by significant new sources of shale gas, may present an opportunity to increase the role of natural gas as a transportation fuel. Natural gas fueled vehicles could play a significant role in both LD and HD fleets if the cost differential between natural gas and oil persists and natural gas vehicle (NGV) costs significantly decrease through increased production scale.

Primary Advantages to the Use of Natural Gas for Transportation in LD and HD Vehicles

Natural gas vehicles benefit from nearly identical powertrains and vehicle structure to the liquid ICE vehicles. Technology improvements needed to advance the fuel economy potential of both LD and HD compressed natural gas and liquefied natural gas vehicles have been identified. Economic drivers could have a significant impact on accelerating the scaling of natural gas use in transportation if refueling infrastructure is expanded. Natural gas has already made successful penetration in three U.S. HD market segments: transit systems; school buses; and refuse trucks. Early adoption into heavier duty Class 7&8 freight trucks has begun.

Primary Challenges to the Use of Natural Gas for Transportation in LD and HD Vehicles

The main challenges to market expansion are vehicle price premiums and infrastructure availability. Creating sufficient demand to quickly migrate to fully OEM-produced vehicles will result in substantial cost improvements from today's low-volume vehicle-modifier approach. Primary LD market technical and commercial challenges that need to be addressed and overcome are: limited make-model availability; limited refueling infrastructure; and minimal inclusion of CNG in the OEM's current long-term product architecture plans regarding powertrain and chassis.

Infrastructure to provide natural gas to LD or HD vehicle users is a challenge, although to different degrees. HD natural gas demand for Class 7&8 trucks could be met more quickly and easily along heavily traveled freight corridors than MD trucks or LD vehicles, which require more widespread refueling infrastructure.

Natural Gas Insights

- The potential for a long-term and low-cost domestic supply of natural gas, driven by economically recoverable shale gas resources may provide an economic driver for the increased use of natural gas for transportation.
- There is an opportunity for LD and HD natural gas vehicles to become attractive to both retail and fleet consumers. The economic competitiveness of these vehicles is contingent on sustained price spread between the lower cost of natural gas vs. gasoline/diesel as a transportation fuel.
- There are few technological barriers to market entry and expansion for either LD or HD natural gas vehicles. Technology developments can be used to extend the performance and economics of natural gas vehicles through improved fuel economy and lower cost.
- Enhancements in ICEs can generally be translated to natural gas engines.
- Build out of infrastructure is critical to support the increased use of natural gas. Infrastructure build out for HD vehicles is more cost effective than the development of wide-scale retail infrastructure for LD vehicles.

Electric Vehicles

Primary Advantages to the Use of Electricity for Transportation in LD Vehicles

Because electric motors are highly efficient, plug-in electric vehicles can be two-to-three times more efficient than a comparable gasoline vehicle on a tank-to-wheels basis. Additionally, electric vehicles can be economically competitive because 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. Compared to conventional gasoline vehicles, these vehicles also reduce well-to-wheels GHG emissions, and there is opportunity to reduce GHG emissions even further by using electricity generated from low carbon sources, the additional cost of which has not been considered. Over 60% of all housing in the United States has an attached garage or carport to facilitate recharging, and adding a dedicated circuit for a 110 volt outlet to charge a vehicle has minimal cost. In terms of electricity supply, even if a large percentage of the vehicle fleet were "electrified," and new electricity generation capacity were needed, the increase in electricity demand could be met through capacity additions already planned for in the existing long-term asset planning processes of electric supply entities.

Primary Challenges to the Use of Electricity for Transportation in LD Vehicles

The challenges at the vehicle level are centered on the battery, and include cost, energy density, degradation, and longevity. As stated above, plug-in electric vehicles, which include both battery electric vehicles (BEVs) and PHEVs, provide an operating cost savings, but the cost of the battery leads to substantially higher upfront vehicle price when compared to a conventional vehicle. This cost must be reduced for more wide-scale adoption.

The lower energy density of batteries, which affects the range of the vehicle relative to liquid fuels, is somewhat compensated for by the high efficiency of electric motors. For PHEVs, the limited electric range is augmented by the addition of a gasoline engine, but for BEVs, the lower energy density leads to a limitation in vehicle range.

There are two factors 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 factor of longevity is the degradation of power and energy storage capacity that occurs over time.

For vehicle charging, while PHEVs can easily recharge the battery overnight using a standard 110-volt outlet, drivers of BEVs will most likely need to charge at a higher power level (240 volts). This requires the purchase and installation of a separate charging unit, which could be a barrier to vehicle purchase if the expense is high.

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

Electric Vehicle Insights

- Battery cost, energy density, degradation, and longevity are the highest R&D investment priorities.
  - A breakthrough beyond those expected for lithium-ion batteries is necessary to increase the driving range of a battery electric vehicle so that it can be a substitute for a conventional vehicle.
  - By 2020, battery costs will likely be in the range of $200 to $500 per kilowatt hour, which is above the Department of Energy targets for commercialization.
- The highest priority for charging infrastructure is to enable convenient and affordable home charging.
- Electricity generation and transmission for a large grid-connected vehicle population is not a constraint, as potential capacity additions can be included in existing long-term asset planning processes.

Hydrogen Fuel Cell Electric Vehicles

The current hydrogen fuel cell electric vehicle has full electric drive and is powered by a fuel cell system that converts gaseous hydrogen fuel stored onboard at pressures of 70 megapascals (10,150 pounds per square inch) to electricity. For the 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 Fuel Cell Electric Vehicles

The FCEV emits no tailpipe emission other than water and 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 ICE. This increased efficiency is the enabler for competitive driving range and fuel operating cost per mile. Hydrogen produced from natural gas and used in an FCEV reduces per-mile GHG emissions by approximately 50% compared to a conventional gasoline vehicle. Further reductions in GHG emissions are possible using hydrogen produced from lower carbon sources, the additional cost of which has not been considered.

Primary Challenges to the Use of Hydrogen Fuel Cell Electric Vehicles

FCEV propulsion technology development has progressed significantly over the past several decades, but two remaining challenges are fuel cell durability and cost. Demonstrated on-road durability is less than 100,000 miles and needs to increase by a factor of two to meet vehicle lifetime expectations. Several vehicle model updates, along with increases in the scale of production, will be required to bring FCEV prices down to a competitive level.

While hydrogen production is already a large-scale and mature industry, the distribution and dispensing of hydrogen for use by consumers as a vehicle fuel is relatively new and limited. The key challenge in this pathway is the significant capital requirement for equipment and its physical footprint (including setback distances) at refueling stations. 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.

Hydrogen Fuel Cell Electric Vehicle Insights

- Fuel cell durability (life) improvements by a factor of two are needed to be comparable to today's conventional vehicles. Commercial durability targets have been demonstrated in laboratory environments and these improvements need to be incorporated into next generation vehicles.
- Upon commercial introduction, fuel cell electric vehicles are expected to have a price premium. Ongoing effort will be needed to lower the cost of subsequent generations of vehicles to make them cost competitive with gasoline vehicles.
- The economic viability for hydrogen fueling infrastructure is significantly dependent on the scale and utilization of installed fueling capacity (i.e., leveraging economies of scale).
- Technology advancements in compression and storage at stations are necessary to provide reductions in capital costs, operating costs, and land requirements, and to increase fueling capacity.

Heavy-Duty Vehicles

Diesel engines will remain the powertrain of choice for HD vehicles for decades to come because of their power and efficiency. There are, however, opportunities to improve the technology. Significant fuel economy improvements in diesel powered trucks are possible. Indeed, the fuel economy (miles per gallon) for new Class 7&8 HD vehicles, which consume more than 70% of the fuel in the trucking fleet, could be doubled.

There is also the possibility of increased use of alternative fuels in HD vehicles. CNG and LNG have the greatest opportunity for accelerated adoption into the HD fleet, assuming that the current price spread between diesel and natural gas persists over time. Because of the high annual fuel use and fleet base, as well as the regional nature of a large element of the freight industry, HD vehicles are well positioned to take advantage of natural gas. There are challenges to overcome, however. The infrastructure transition to supply this fuel demand represents one of the largest obstacles to alternative fuels entering the HD market. The characteristics of initial customers for natural gas MD and HD trucks, such as inter-urban fleets, regional fleets, and freight corridors connecting regions, may provide pathways to expanding the vehicle market.

Heavy-Duty Vehicle Insights

- There is a potential for significant HD fuel economy improvement.
- There is potential for natural gas trucks to gain significant market share.
- Gasoline engines need improved durability and fuel economy to compete with diesel engines.
- An integrated approach to tractor-trailer aerodynamics requires a coordinating mechanism between tractor and trailer manufacturers to maximize benefit.

TECHNOLOGY AND INFRASTRUCTURE

TECHNOLOGY AND INFRASTRUCTURE OPPORTUNITIES AND CHALLENGES TO COMMERCIALIZATION

This section addresses the technology hurdles and infrastructure challenges that need to be overcome to achieve wide-scale commercialization of advanced fuel-vehicle systems.

Finding: **Priority Technology hurdles were identified that must be overcome for wide-scale commercialization of advanced fuel-vehicle systems by 2050. A broad portfolio of technology options provides the opportunity to benefit from potential Disruptive Innovations.**

Technology Evaluation Criteria
• Technology improvements needed to realize performance (primarily energy density and efficiency)
• Technology improvements required to attain acceptable cost
• Technology improvements that would accelerate deployment
• Technology to support fuel-dispensing infrastructure development
• Technologies that enable scaling to material volumes
Technology Analysis Approach
• Critical Path Analysis (evaluate the sequencing and dependencies among hurdles) – if the initial hurdle is not overcome, efforts on subsequent hurdles would not be warranted
• Light-Duty Go/No-Go Analysis – if this hurdle is not overcome, the technology cannot achieve wide-scale material volumes
• Cost/Benefit Analysis (available for MD/HD only) – assigned higher priority to hurdles that are more attractive from a cost/benefit perspective

Table ES-2. *Technology Evaluation Criteria and Approach*

Technology

Overview

Technology development is essential for the wide-scale commercialization of the fuel-vehicle systems under review in this study. More than 250 fuel-vehicle system technology hurdles were evaluated. From the 250 hurdles, twelve Priority Technology hurdles were selected using the evaluation criteria and approach shown in Table ES-2. An expert

Light-Duty Engines and Vehicles	
Low-cost lightweighting (up to 30% mass replacement)	Low-cost lightweighting is the replacement of traditional steel in vehicles with much lighter materials in a way that is fully integrated into the OEM operating models. Resolving this hurdle would mean wide-scale availability of vehicles that are 20–30% lighter than comparable vehicles today. Low-cost lightweighting can be leveraged by all vehicle types: internal combustion engines (ICEs), battery electric vehicles, plug-in hybrid electric vehicles, fuel cell electric vehicles, and compressed natural gas vehicles.
Biofuels	
Hydrolysis	Reduce the volume of enzymes required or advancement of chemical hydrolysis to break down pretreated lignocellulosic materials into component sugars.
Fermentation of C5 and C6 sugars	Develop microbes that can simultaneously ferment C5 and C6 sugars. Yeasts commonly used in corn ethanol production are able to ferment 6 carbon sugars, but fermenting 5 carbon sugars is critical to the economic viability of cellulosic ethanol.
Lignocellulose logistics/ densification	Improve economics of transportation and long-term storage of localized biomass to increase scale of biomass conversion plants
Production of higher-quality pyrolysis oil	Improve bio-oil quality and stability. Raw bio-oil contains potential impurities such as alkali metal, chlorine, nitrogen, and sulfur that could poison hydrotreating catalysts and limit long-term activity, stability, and lifetime of the catalyst.
Biotechnology to increase food and biomass	Continue to increase yield and productivity of land to enable both food and fuel needs to be met.
Light-Duty Compressed Natural Gas	
Leverage liquid ICE fuel economy technology	Incorporate gasoline powertrain and platform technology in CNG light-duty vehicles for enhanced fuel economy. To date, no purpose-built CNG vehicle has been developed. If this hurdle is overcome, the vehicle premium of CNG vehicles over ICE vehicles could be reduced through improved fuel economy and reduction in fuel storage requirements.
Light-Duty Electric	
Lithium-ion battery energy density	Increase the amount of stored energy per unit mass and/or volume. The energy density of lithium-ion chemistries (in today's newest mass-market models, they deliver a range of less than 100 miles) is still much lower than liquid fuels (which can travel more than 300 miles on a full tank for a similar type vehicle). Improvements in energy density could be used to reduce the cost of the vehicle and/or increase the driving range.
Lithium-ion battery degradation and longevity	Increase both the calendar life (life of the vehicle) and cycle life (how many times the battery can be charged and discharged). Resolving this technology hurdle means that the degradation that will occur in the battery will not impact the customer for the life of the vehicle, regardless of charging cycle.
Light-Duty Hydrogen	
Compression and storage for dispensing	Reduce land, maintenance, and capital requirements for compression and storage of hydrogen at a fueling station, so that dispensing capability can be added to existing fueling facilities. A typical hydrogen compression and storage system for fueling requires ~600 square feet of land at a fueling station, not including safety setback requirements. The cost of a compression system can range from 20 to 50% of the total cost of hydrogen fueling infrastructure at a fueling location. The cost of storage represents ~25% of the total capital required for a hydrogen fueling site.
Fuel cell degradation and durability	Improve fuel cell to last the life of the vehicle. Fuel cells need to last the life of the vehicle, without degradation impacting the customer.
Medium-/Heavy-Duty Engines and Vehicles	
Combustion optimization	Improve engine combustion efficiency addressing challenges in four key areas: in-cylinder pressure & fuel injection; gas exchange; emerging compression ignition technologies (e.g., low temperature combustion technologies such as homogeneous charge compression ignition, premixed charge compression ignition, and reactivity controlled compression ignition); and friction reduction.

Table ES-3. *Twelve Priority Technologies* review process, which included twelve prominent academic and industry experts, was used to review the technology evaluation criteria, approach, and selection of hurdles.

The twelve Priority Technology hurdles described in Table ES-3 must be overcome to enable each fuel-vehicle system to achieve wide-scale commercialization by 2050. Non-technology hurdles are not included in this table.

The study did not estimate the R&D and implementation cost required to achieve these advancements. However, overcoming these hurdles is expected to have the greatest impact towards removing the technical barriers to wide-scale commercialization of the fuel-vehicle systems under review in this study.

Investment in, and successfully overcoming, the twelve Priority Technology hurdles is important to the advancement of all fuel-vehicle systems considered in this analysis. The level of relative difficulty in overcoming each technology hurdle is shown in Table ES-4.

Results of Overcoming Technology Hurdles

There are circumstances under which all vehicle technology pathways could achieve commercialization. Specifically, sustained R&D investment to resolve the technology hurdles and resolution of the periods of low infrastructure utilization is needed. Should these challenges and other transition hurdles be overcome, Figure ES-3 shows possible ranges of new vehicle and fuel costs for each fuel-vehicle system in 2015 and 2050.

Disruptive Innovation

Although not required for wide-scale commercialization, Disruptive Innovations would provide an advantage to the relevant fuel-vehicle system. Disruptive Innovations have not been considered in the range of cost estimates for 2050 because they depend on inventions that are highly uncertain. It could be decades before they move through basic research, applied research, production engineering, and into production. Examples of some potential Disruptive Innovations are shown in Table ES-5, and discussed in topic papers prepared for the study.

Fuel-Vehicle System	Twelve Priority Technologies
Light-Duty Engines and Vehicles	Low-cost lightweighting (up to 30% mass replacement) [RED]
Biofuels	Hydrolysis [YELLOW]
	Fermentation of C5 and C6 sugars [YELLOW]
	Lignocellulose logistics/densification [YELLOW]
	Production of higher-quality pyrolysis oil [RED]
	Biotechnology to increase food and biomass [BLUE]
Light-Duty Compressed Natural Gas	Leverage liquid ICE fuel economy technology [YELLOW]
Light-Duty Electric	Lithium-ion battery energy density [RED]
	Lithium-ion battery degradation and longevity [RED]
Light-Duty Hydrogen	Compression and storage for dispensing [RED]
	Fuel cell degradation and durability [YELLOW]
Medium-/Heavy-Duty Engines and Vehicles	Combustion optimization [YELLOW]

RED hurdles range from basic research to technology demonstration. These hurdles require invention or have high uncertainty.

YELLOW hurdles range from technology development to demonstration. A pathway for success has been demonstrated and tested but sustained effort is required to achieve wide-scale material volumes.

BLUE hurdles range from systems commissioning to operational. These hurdles have minimal or no barriers to wide-scale material volumes.

Table ES-4. *Comparison of Relative Difficulty for Priority Technologies*

Infrastructure

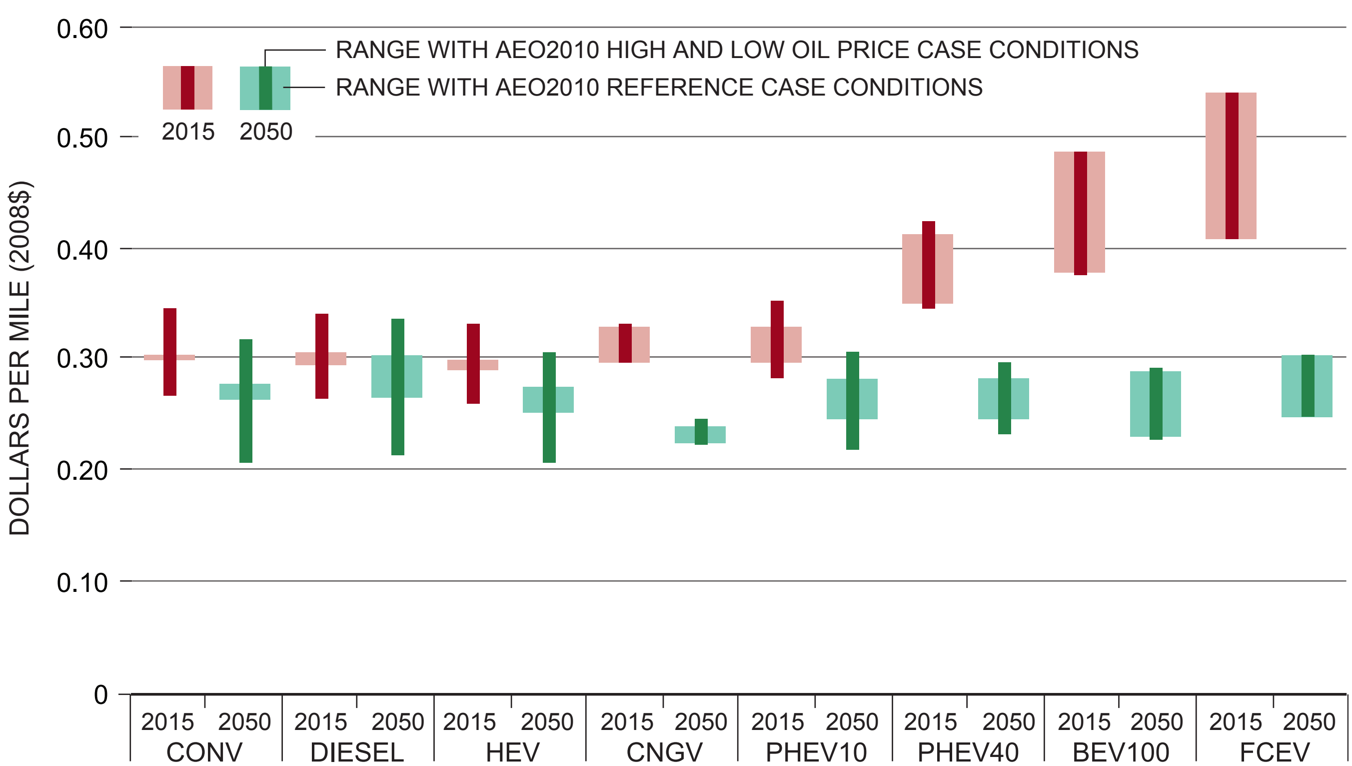
There are infrastructure and other challenges to commercialization by 2050. The development of infrastructure to support new fuel-vehicle systems is critical to wide-scale commercialization. The following section describes the challenges in deploying fuel infrastructure and strategies that can be used to mitigate the challenges.

Infrastructure Challenges

Finding: **Infrastructure challenges must be overcome for wide-scale commercialization of advanced fuel-vehicle systems. Options exist to facilitate concurrent development of alternative fuel vehicles and infrastructure, such as building on existing infrastructure, corridor-deployment, and multi-fuel vehicles.**

Given the scale of the transportation fuel supply and vehicle manufacturing industries, there is a significant lag time from initial deployment to wide-scale commercialization of new technologies. Widespread availability of fuel infrastructure is necessary for adoption of alternative-fuel vehicles. A quantitative analysis of LD and HD infrastructure transition was not possible due to the uncertainty in transition variables such as scale and utilization, and the complexity of the infrastructure required for the various fuels.

Deployment of a new fuel infrastructure is a significant hurdle to the adoption of new fuel-vehicle systems. It could cost tens to hundreds of billions of dollars to provide similar alternative fuel availability as the current gasoline infrastructure and will take decades to fully deploy. Some fuels also require advances in supply-chain infrastructure technology to aid deployment. Specifically, advanced biofuels must overcome technology hurdles related to fuel manufacturing, and hydrogen must overcome technology hurdles related to dispensing infrastructure.



Note: 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.

Figure ES-3. *New Vehicle and Fuel Contribution to the Cost of Driving for Small Cars*

Disruptive Innovation Topic Papers	Description
Advanced Batteries – "Beyond Li-ion"	Chemistries that will have higher energy densities than lithium ion, capacitor technology, and new chemistries such as magnesium ion, metal air, aluminum ion, and sodium ion
Advanced Storage Technologies	Technologies that would allow gaseous fuel storage at higher densities and lower pressures, such as adsorbing onto the material surface, absorbing the material, or storing the fuel as a chemical compound
Genetic Engineering to Add Traits not Natural to the Feedstock	Traits that could deliver yield improvements to both conventional and nonconventional crops, such as frost tolerance and the ability to germinate at colder temperatures, drought and heat tolerances, water and nitrogen efficiency, salt water tolerance, perennially, photosynthetic efficiency, etc.
Non-Precious Metal Catalysts for Oxygen Reduction in PEM Fuels Cells	Catalysts that fully meet the requirements of electrocatalysts for oxygen reduction in proton exchange membrane fuel cells but do not require high-cost precious materials (e.g. platinum) like current catalysts
Ultra-Lightweighting	Reductions of 50–70% of vehicle mass by eliminating components, using new materials and new processing and production methods
Smart Vehicles and Infrastructure	Application of "telematics," or the integration of telecommunication and informatics, has generated the possibility for the vehicle to communicate with the road infrastructure, vehicles to communicate with each other and to obtain information about the traffic environment in which they are operating
Artificial Photosynthesis	Technologies that directly convert solar energy into fuels through a fully integrated system, which apply the principles that govern natural photosynthesis to develop man-made solutions
Microbial Fuel Cells	Fuel cells that are capable of converting chemical energy available in organic substrates into electrical energy using bacteria as a biocatalyst to oxidize the biodegradable substrates
Fatty Acid Biosynthesis	Technologies that use fatty acids as the basis for the production of new fuels such as short-chain alcohols (e.g., ethanol, butanol), branched-chain alcohols (e.g., isobutanol, isopentanol), and long-chain hydrocarbons
Macroalgae	Growing, harvesting, and processing macroalgae (seaweed) for biofuels production at economically competitive costs and scale

Table ES-5. *Potential Disruptive Innovations*

Concurrent Vehicle and Infrastructure Challenge

Successful deployment of alternative fuel-vehicle systems in the market requires the concurrent deployment of fuel and vehicle infrastructure. However, simultaneous introduction is difficult to achieve on a nationwide basis due to the cost, time, and low early-phase utilization. Limited availability of fueling infrastructure increases consumer inconvenience and hinders adoption of alternative-fuel vehicles. At the same time, low vehicle penetration can result in low utilization of fueling infrastructure, which increases fuel-dispensing cost and is a disincentive for investment.

Mitigation Strategies

Transition-phase strategies can play an important role in mitigating the challenges discussed above. Leveraging existing infrastructure can reduce initial investments and facilitate a faster transition. Localized, corridor, or niche-application deployment can improve dispensing infrastructure utilization during the transition. Flex-fuel vehicles, bi-fuel vehicles, and PHEVs also facilitate transition by allowing vehicle deployment while alternative fuel supply is not readily available; however, these options have cost and performance drawbacks compared to single-fuel vehicles.

Each alternative fuel has unique advantages and disadvantages in leveraging these strategies. Electricity and biofuels are able to leverage existing grid and liquid fuel infrastructure and can be used in PHEVs and flex-fuel vehicles. Natural gas has the option to leverage HD freight corridors for dispensing infrastructure deployment. Based on assumptions for the initial investment required for dispensing infrastructure only, biofuels and electricity are likely to be the least sensitive to low utilization during the transition phase followed by natural gas and then hydrogen.

While there are challenges to building new infrastructure, once an alternative fuel has achieved commercial scale and infrastructure utilization is high, infrastructure costs are not likely to be a significant portion of the cost of driving (defined as vehicle plus fuel costs). Dispensing infrastructure, which is critical for consumer uptake, makes up 1–8% of the cost of driving when fully utilized.

Home refueling can be convenient for the consumer and might reduce transition challenges. Equipment additions and upgrades can be made to existing homes to enable home fueling with electricity and natural gas. This study considers home fueling costs for electricity but not for natural gas.

INTEGRATED ANALYSIS

FUEL-VEHICLE INTEGRATED ANALYSIS METHODOLOGY

This section provides a summary of the methodology used in the LD and HD analyses. Inputs from the individual fuel-vehicle system chapters were used as inputs to the modeling. Output ranges of vehicle fleet characteristics were compared to determine directional trends and draw insights.

Basic Principles and Methodology

The study analysis considered relevant combinations of vehicle platforms and fuel types in the following categories:

Light-Duty Vehicles

- Four vehicle platforms: liquid fuel ICE including hybrids, CNGVs, PEVs, and FCEVs
- Six fuel types: gasoline, diesel, biofuels, natural gas, electricity, and hydrogen

Medium- and Heavy-Duty Vehicles

- ICE vehicles, including hybrids
- Four fuel types: gasoline, diesel, biofuels, and natural gas

The analysis used ranges of inputs from the individual fuel-vehicle system chapters of this report, and assumes all necessary technical and transition hurdles are overcome. Significant effort was made to ensure consistency of the inputs and analysis. Individual fuel-vehicle system information was integrated using the tools/models identified in Figure ES-4.

All fuel-vehicle systems were compared on an economic basis (vehicle price plus fuel costs over a given time horizon) while inputs such as fuel and technology costs were varied. New vehicle shares were calculated and the resulting fleet[8] was assessed. The characteristics of the fleet (e.g., vehicle and fuel expenditures, GHG emissions, and fuel demand) were then calculated and analyzed for similarities and trends.

The Fuels and Infrastructure Model was used to generate normalized dispensed fuel cost ranges. The Vehicle Attribute Model was used to design vehicles and calculate vehicle price and fuel economy ranges. The ranges of outputs from the Fuels and Infrastructure and Vehicle Attribute Models were used as inputs to the Vehicle Choice Model, or the TRUCK Model for M0D/HD vehicles, to compare combinations of fuel-vehicle systems based on economics and calculate ranges of new vehicle shares over time. 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.

8 Fleet refers to the total sum of vehicles in operation in any given year.

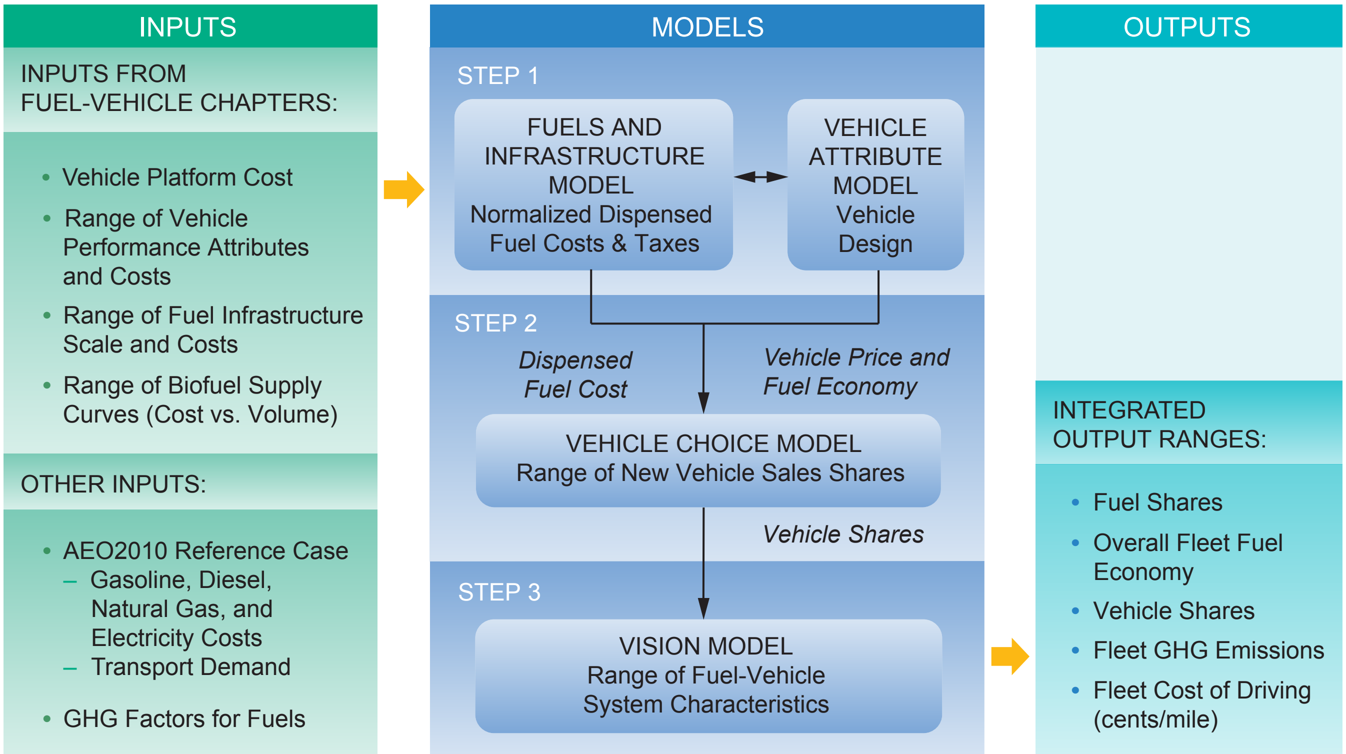


Figure ES-4. *Overview of Models*

The results of this analysis describe a wide array of possible outcomes, not forecasts, from which insights on the potential impact of fuel-vehicle systems are drawn. The ranges represent highest and lowest outcomes that are produced from simulations for a particular modeling scenario as the model selects high and low values of input variables. Several "dashboard" calculators that allow readers to select and model scenarios of their own choosing are available at www.npc.org.

Assumptions and Resulting Bias

To conduct this analysis, several foundational assumptions were made that had a major impact on findings reached in this analysis. The real world accomplishment of these assumptions may prove very difficult. The analysis assumes that:

1. Priority Technology hurdles[9] for each fuel-vehicle system are overcome.
2. Fuel-dispensing infrastructure is available, fully utilized, and all expenditures (including capital) are reflected in fuel cost.
3. Consumer purchase decisions are based only on economics.
4. Vehicles are designed to minimize the new vehicle price plus fuel costs over a given time horizon, three or seventeen years.[10]
5. Vehicle fuel economy from the AEO2010 was used as a minimum.
6. Each fuel-vehicle system benefits from sustained investment and development.

Assumptions about technology advancements, infrastructure availability/utilization, and impact of demand on fuel prices were made, which generally favor the alternative fuel-vehicle systems. The models do not include supply/demand feedback mechanisms on fuel prices. The model results are not predictions or forecasts.

9 The Priority Technology hurdles for each fuel-vehicle system are discussed in Chapter Four, Priorities for Technology Investment.

10 Three years is a widely used time span for analyzing consumer purchase decisions. Seventeen years is used as a typical vehicle life span and, for example, is used by the EPA to develop Corporate Average Fuel Economy (CAFE) standards.

ACCELERATING ALTERNATIVE FUEL-VEHICLE SYSTEM COMMERCIALIZATION BY 2050

This section summarizes the key findings of the LD, MD, and HD analyses. Characteristics of the fleet in 2050 are described, including fuel economy and fuel-vehicle shares.

Finding: **Fuel economy can be dramatically improved in the light- and heavy-duty sectors through the advancement and application of existing and new technology. Internal combustion engine technologies are likely to be the dominant propulsion systems for decades to come, with liquid fuel blends continuing to play a significant, but reduced role.**

Light-Duty Vehicles

Technology advances can provide a wide range of fuel economy improvement. Advancements such as improved aerodynamics and reduced rolling resistance in LD vehicles have relatively low costs and wide applicability to improve fuel economy of all vehicle platforms. Relative to a 2010 LD conventional ICE baseline vehicle, improved fuel economy—measured as miles per gallon equivalent—ranges from 10 to 50% based on lightweighting, downsized engines, with turbo-charging and improved transmissions. The cost of fuel economy may be relatively low for initial improvements, but rises as the improvements become greater. At higher cost for improved fuel economy, HEVs, FCEVs, and BEVs offer more significant opportunities to raise fuel economy through powertrain hybridization and electrification. Relative to the 2010 light-duty ICE baseline vehicle, improvements in mile-per-gallon equivalent range from 100 to 400%.

Figure ES-5 shows the fleet fuel economy from the LD integrated analysis.[11] All fleet portfolios in 2050 have a significantly higher fuel economy than

11 The ranges shown in this figure were achieved under Reference, High, and Low Oil Price conditions, with vehicles designed to achieve the lowest cost of driving given 3-year economics.

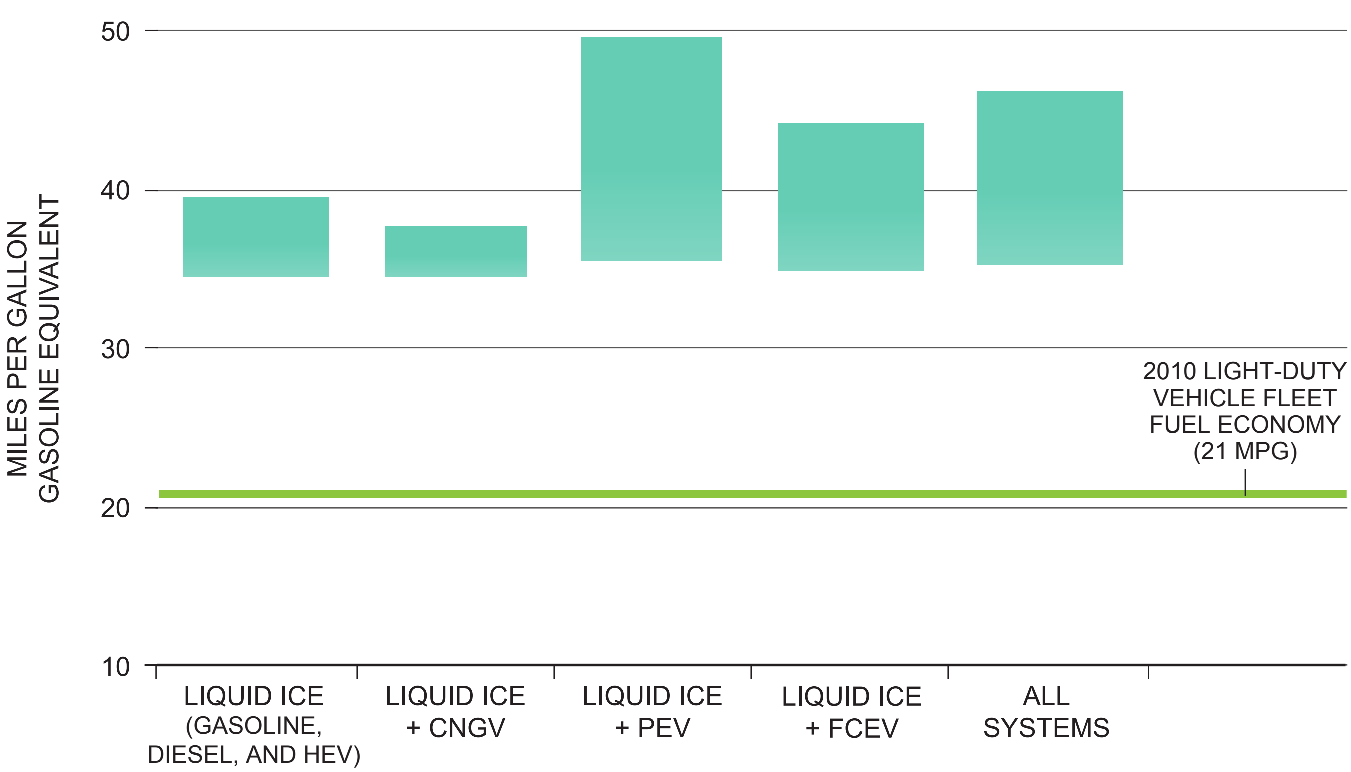


Figure ES-5. *Range of Light-Duty Vehicle On-Road Fleet Fuel Economy in 2050 (3-Year, All Oil Prices)*

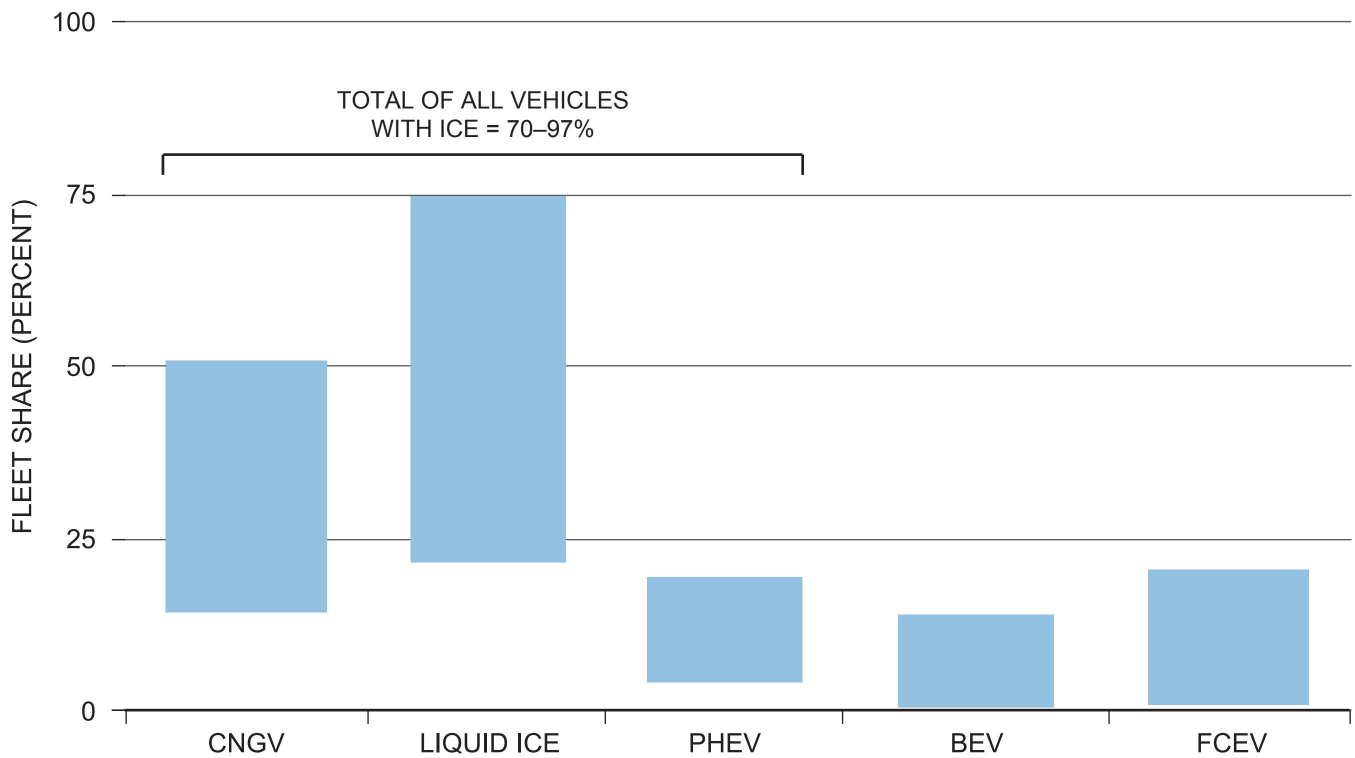


Figure ES-6. *Range of Light-Duty Vehicle Fleet Shares in 2050 (3-Year, All Oil Prices, All-In Combination)*

the average 2010 baseline fleet fuel economy of 21 miles per gallon (mpg). For liquid ICE vehicles, 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. 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 to 90%, relative to 2010. Increased penetration of PEVs and FCEVs increases the overall fleet fuel economy up to a maximum of 140%. In contrast, penetration of CNGVs does not increase the fleet fuel economy. Persistent low-cost CNG is a disincentive to the adoption of high fuel economy technologies.

All of the vehicle systems could achieve wide-scale commercialization by 2050 under certain conditions. As shown in Figure ES-6, ICEs will remain dominant because of their lower vehicle and fuel costs, and their use in a diverse set of vehicle platforms: conventional liquid ICEs, diesel ICEs, HEVs, PHEVs, and CNGVs. The integrated analysis shows that the combined fleet shares in 2050 of ICE containing vehicles ranges from 70 to 97%. Liquid fuel blends will also continue to play a significant, but reduced, role. Biofuels could achieve a significant share in LD vehicles, but will need to overcome technology, cost and scale challenges. Petroleum-biofuel blends accounted for 30–80% of LD energy use in the integrated results. If the lower cost of natural gas relative to petroleum persists, CNGVs are more competitive with conventional liquid ICEs under a broad range of conditions. PEVs and FCEVs have higher tank-to-wheels fuel efficiency, but have higher vehicle costs. PEVs and FCEVs also have the potential to be competitive under scenarios where sustained fuel cost savings can offset the impact of higher vehicle price, but generally achieve smaller share than CNGVs.

Medium- and Heavy-Duty Vehicles

The integrated analysis of this study found that if technology costs reduce over time, there could be up to 100% improvement in the fuel economy for new HD trucks primarily due to multiple incremental advances in engine and vehicle design. The ranges of potential fleet fuel economy improvements for MD and HD are shown in Figure ES-7.

Natural gas engines for MD and HD vehicles are derivatives of gasoline or diesel ICEs. In the long-term, the increased fleet share of NGVs depends on incorporating powertrain and vehicle advancements from gasoline and diesel vehicles for fuel economy improvements, and increasing the manufacturing scale to reduce costs. Figure ES-8 shows ranges for potential MD and HD fleet shares in 2050.

In MD, gasoline trucks are primary competitors to diesel trucks due to lower vehicle costs. Natural gas vehicles are also economically competitive to conventional ICE vehicles in MD and HD, primarily because of low fuel cost and low technology hurdles. As shown in Figure ES-9, when the price spread[12] between diesel and natural gas increases, the fleet share of NGVs increases. LNG and CNG

12 Price spread is the average difference in dispensed fuel cost of diesel versus liquefied natural gas for the period 2015–2050, based on AEO2010 projections and infrastructure analysis (see Chapter Five, Infrastructure, for details).

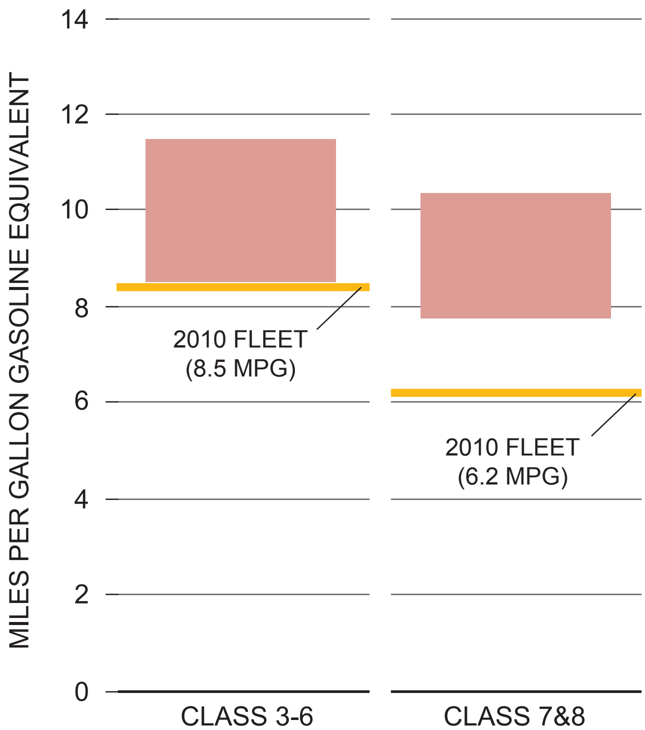


Figure ES-7. *Range of Medium- and Heavy-Duty Vehicle On-Road Fleet Fuel Economy in 2050 (All Oil Prices)*

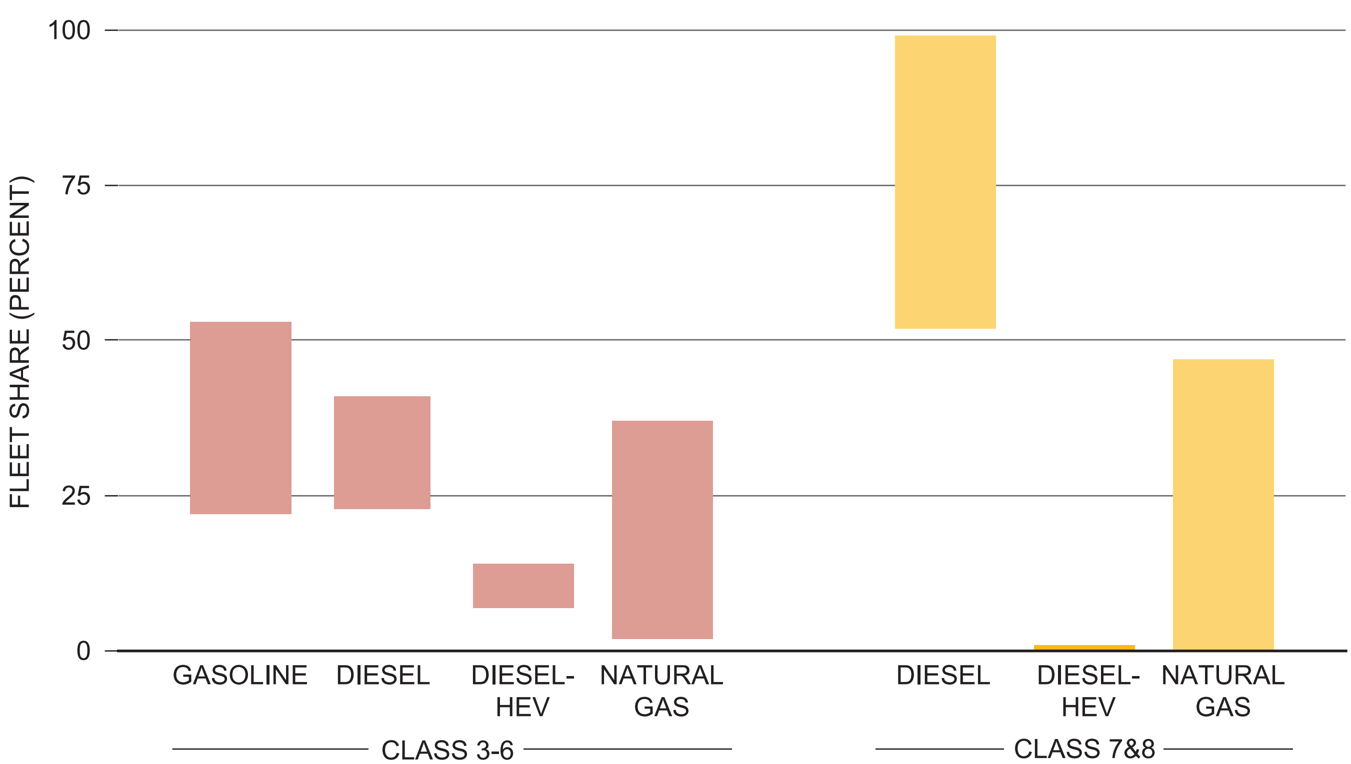


Figure ES-8. *Range of Medium- and Heavy-Duty Vehicle Fleet Shares in 2050 (All Oil Prices)*

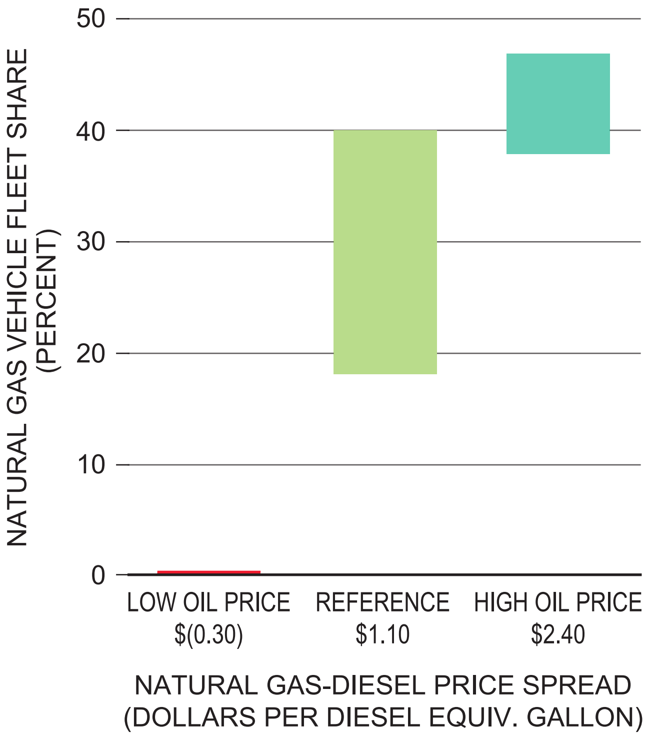


Figure ES-9. *Impact of Natural Gas-Diesel Price Spread on Natural Gas Fleet Share in the Heavy-Duty Vehicle Sector in 2050*

are cost-competitive options, although diesel will remain the primary fuel for HD vehicles.

Biofuels will also play a role in MD and HD, but are likely to be supply-limited. Alternative fuel options including electricity and hydrogen are not likely to have a material impact on the MD/HD fleet. However, these systems may excel in niche applications.

LD, MD, and HD Fuel Demand

The study analysis suggests a wide range of future petroleum demand, with most scenarios having lower petroleum demand than today, due to increased vehicle efficiency and use of alternative fuels. Projected efficiency gains can potentially offset all of the growth in LD demand and most of the growth in MD and HD demand, so the range in 2050 highway vehicle energy use overlaps with today's levels. Alternative fuel-vehicle systems, if competitive, could contribute significantly to meeting future demand. In the integrated analysis, alternative fuels accounted for 20 to 90% of LD plus MD/HD energy demand in 2050. In most cases, natural gas is the largest contributor to alternative energy demand, followed by biofuels, as shown in Figure ES-10. Higher shares of alternative fuel-vehicle systems were benefited by low alternative vehicle costs, and sustained fuel price differentials. The integrated analysis did not include any supply and demand feedback, which if included, could re-balance supply and demand and likely lead to a narrowing of any price differential between alternate fuels over time and a reducing of their fleet shares.

GHG EMISSIONS

GHG Emissions in the Transportation Sector

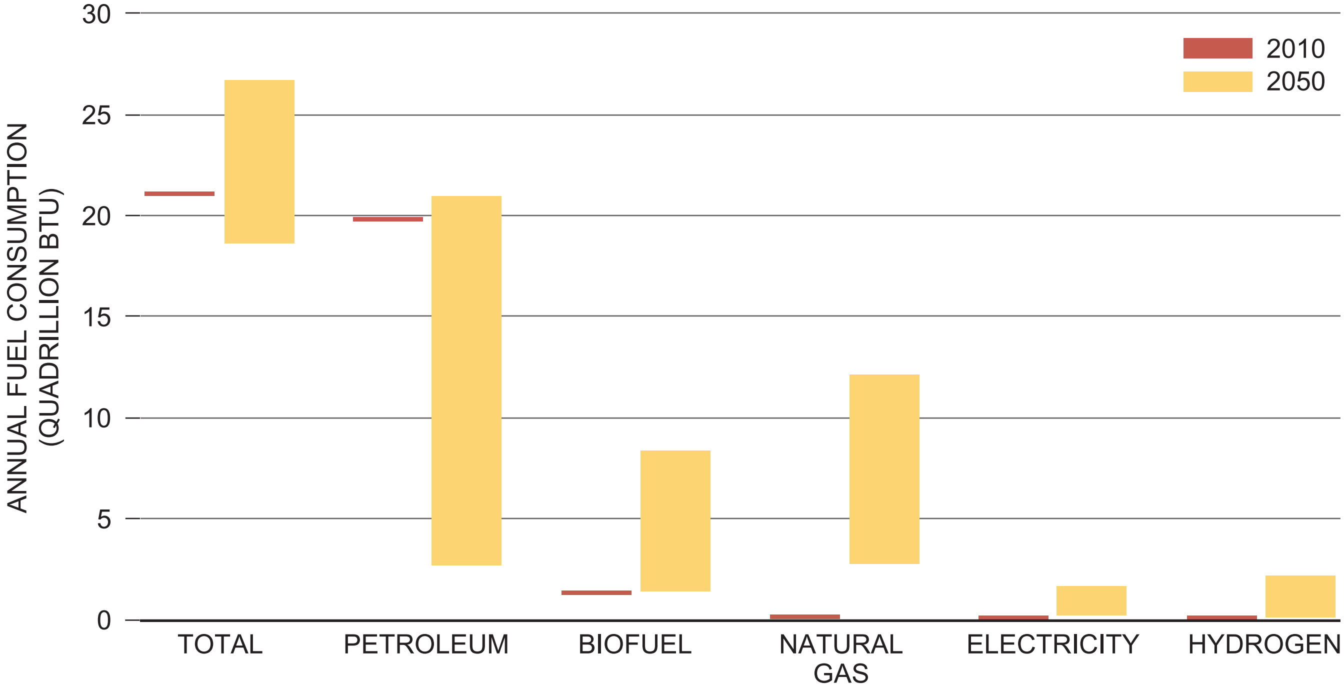
GHG emissions in the transportation sector result from the interaction of four major factors: vehicle fuel economy, transportation fuel carbon content, travel demand, and travel efficiency.[13]

In 2010, the U.S. transportation sector accounted for 33% of total U.S. GHG emissions and represented the second largest emission source by economic sector. On-road transportation was the focus of this study and represents ~80% of U.S. transportation sector GHG emissions. The study did not perform a quantitative GHG analysis on marine, rail, and air segments, which make up ~20% of total transportation GHG emissions.

A well-to-wheels (WTW) emissions measurement was used to calculate total GHG emissions from vehicle use. Several vehicle systems, such as BEVs and FCEVs, do not have tailpipe GHG emissions, but their use contributes to GHG emissions through the production of electricity and hydrogen, which is included in WTW emissions accounting. This study did not consider emissions from vehicle manufacturing or recycling because they are significantly smaller than emissions from the production and use of transportation fuels.

The WTW GHG emissions model used for the study was the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed at Argonne National Laboratory. GREET was selected due to its integrated use with other DOE models used in this study as well as for its transparent treatment of assumptions used in

13 Objectives and examples of travel efficiency and travel demand are provided in the section entitled "Additional GHG Reduction Strategies."



Notes: On-road includes light-, medium-, and heavy-duty sectors.
Figure does not include additional energy consumption associated with fuel production.
At equivalent fuel consumption (by energy), alternatives such as hydrogen fuel cell electric vehicles and other electric vehicles can support two to three times the miles due to their higher fuel economy.

Figure ES-10. *Range of 2050 On-Road Fuel Consumption, Assuming All Alternatives are Successfully Commercialized*

the model. Future GHG emissions per mile were estimated by combining the future carbon intensity of fuels from GREET with the 2050 future fuel economy range calculations from the light- and heavy-duty vehicle integrated analysis, described earlier.

Policy decisions and other factors, such as Corporate Average Fuel Economy (CAFE), will impact future energy efficiency and GHG emissions. For the 2011 model year, the industry target for fuel economy for both domestic and imported cars was 30.2 mpg; for light-duty trucks it was 24.1 mpg. More recently, fuel economy standards were set by the Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) for model year 2012 to 2016 vehicles. These programs require an industry-wide target standard of 250 grams of carbon dioxide (CO_2) per mile and 34.1 mpg by model year 2016. The EPA and NHTSA have proposed to extend the CAFE from 2017 through 2025. As of the writing of this report, the final ruling had not been issued, thus this report does not reflect the proposal.

Uncertainty

Given the long time frame of the study analysis, a number of uncertainties in the calculation of GHG emissions arise. Following are some examples:

- *GHG measurement variability.* Publicly available and recognized U.S., Canadian, and European Union GHG models and data sets provided alternate WTW GHG values to GREET for similar fuel-vehicle systems. These alternate GHG data sets were used to represent GHG emissions variability in the GHG study analysis.

- *Transportation demand.* Light- and heavy-duty VMT projected to 2050 and based on AEO2012 Early Release are ~10% and ~15% lower, respectively, than the 2050 VMT projections based on the AEO2010 Reference Case. This uncertainty was used to calculate approximate ranges of GHG emissions per mile necessary to achieve a 50% GHG reduction in LD and MD/HD fleet segments by 2050.

- *Indirect land use change (ILUC).*[14] Calculations from this study do not include biofuel GHG emissions associated with ILUC due to significant ILUC variability in recognized GHG models and data sets. When ILUC is excluded, there is a directional bias towards lower calculated GHG emissions per mile from biofuels than if ILUC is included. Also, it is unknown how ILUC will change over time with advances in technology and agricultural practices. For example, improved biomass yields could help mitigate ILUC impacts over time.

- *GHG emissions intensity of electricity generation.* The future fuel mix for electricity generation and resulting GHG emission characteristics are uncertain and can be affected by regulations, natural gas displacement of coal, the amount of nuclear and renewables, and many other factors. The AEO2012 Early Release projects a 7% lower electric generation carbon intensity for 2035 relative to the AEO 2010 due to recent changes in the electric generation mix, such as displacement of coal by natural gas power generation.

Calculated GHG Emissions from the Transportation Sector

Finding: **If technology hurdles and infrastructure challenges can be overcome, economically competitive low-carbon fuels and improvements in fuel economy will result in substantial reductions in GHG emissions. Additional strategies will be required to achieve a 50% reduction in GHG emissions relative to 2005 in the transportation sector by 2050.**

Significant GHG emission reductions are possible as fuel-vehicle systems advance. In 2005, the LD and MD/HD vehicle fleets averaged approximately 550 and 2,000 grams of CO_2 equivalent (CO_2e) per mile respectively. All 2050 LD, MD, and HD fuel-vehicle systems analyzed could potentially achieve at least a 40% GHG emission reduction on a per-mile basis, compared to average 2005 vehicle emissions.

14 ILUC refers to the regional and global market-driven conversion of land for agricultural purposes to produce crops that previously were raised on land that is now being used to produce biomass for fuel.

Light-Duty Fleet Emissions

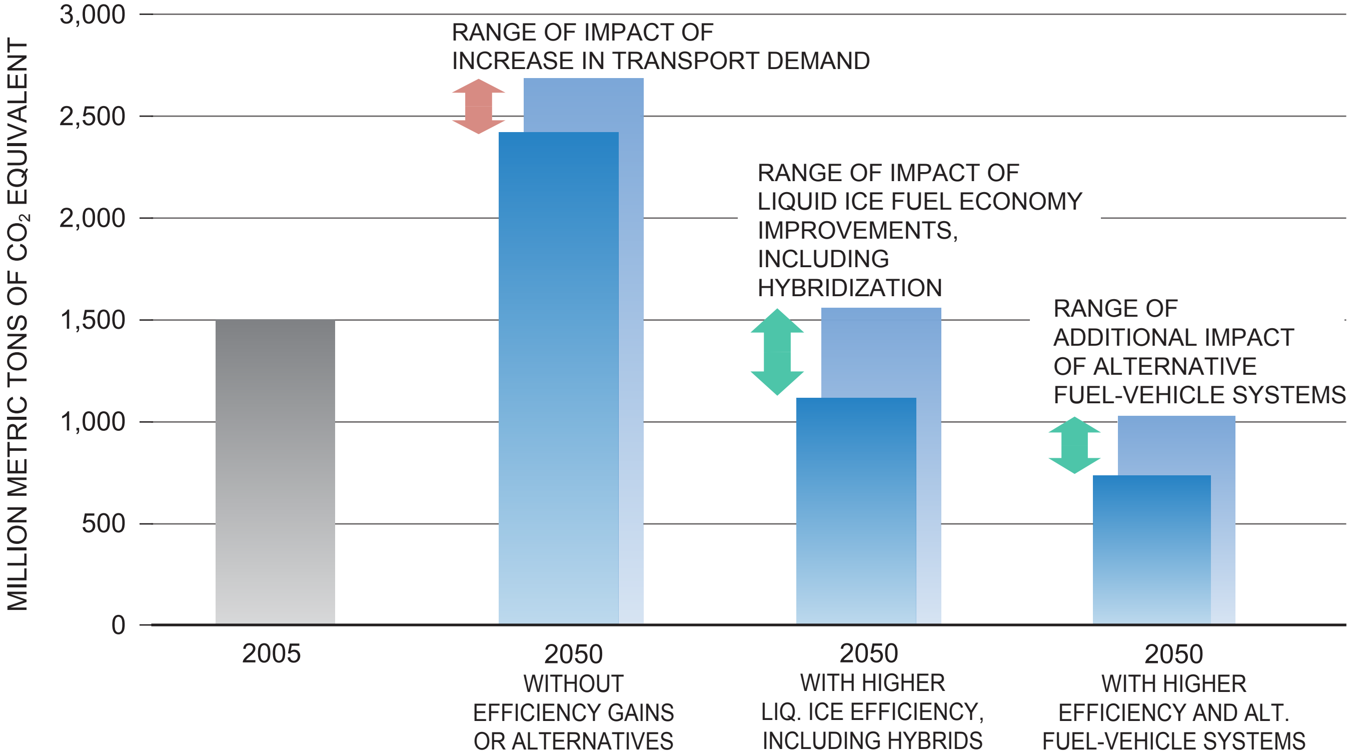
Figure ES-11 shows the potential 2050 GHG emissions impact from LD VMT growth and changing LD fuel-vehicle system portfolios. The ranges represent the difference in emissions from fuel economy variation when vehicles are designed to achieve the lowest cost of driving with 3-year economics versus 17-year economics. The total LD vehicle fleet GHG emissions in 2005 were ~1,500 million metric tons of CO_2e. VMT growth through 2050 alone would increase total LD fleet emissions to ~2,400–2,700 million metric tons (MMT) of CO_2e. Liquid ICE fuel economy improvements (from a 2050 fleet of ICE and hybrid ICE vehicles) would drop total LD fleet GHG emissions back to near 2005 levels (~1,200–1,600 MMT CO_2e) offsetting increased VMT. If all fuel-vehicle systems evaluated in this study advance and are commercialized, total LD fleet GHG emissions would decrease to ~700–1,000 MMT CO_2e. Reductions in electricity generation emissions could further reduce PEV GHG emissions.

Reducing GHG emissions in the LD fleet to 50% of 2005 LD vehicle segment levels requires limiting LD vehicle GHG emissions to $\leq$750 MMT CO_2e. Only a very limited number (<3%) of study analysis portfolios achieved $\leq$750 MMT CO_2e and a combination of factors was required: high fuel economy, low VMT, and significant economic volumes of cellulosic biofuels (not considering the impact of indirect land use changes). In the study model, this was achieved under Reference and High Oil Price Cases with vehicles designed to minimize fuel and vehicle costs over a 17-year period. Additionally, portfolios that achieved these low GHG emissions were characterized by significant shares of FCEVs and very limited numbers of CNGVs.

Heavy-Duty Fleet Emissions

Figure ES-12 shows the potential 2050 impact of MD/HD VMT growth and changing MD/HD fuel-vehicle system portfolios. The total MD/HD vehicle fleet GHG emissions in 2005 were ~500 MMT CO_2e. VMT growth alone would increase total MD/HD fleet emissions to ~900–1,000 MMT CO_2e. If all MD/HD fuel-vehicle systems evaluated in this study advance and are commercialized, total HD fleet GHG emissions would fall to ~350–500 MMT CO_2e.

Because of the significant increases in VMT, MD/HD fuel-vehicle systems improvements are not



Assumptions:

- Based on AEO2010 Reference Case conditions with 3-year and 17-year fuel expenditure considerations.
- VMT range based on AEO2010 Reference Case and AEO2012 Early Release, extrapolated to 2050.
- Carbon intensity (grams CO_2e/megajoule) values for fuels are from GREET in 2020.
- For cases including alternative fuel-vehicle systems, technology and transition hurdles are assumed overcome.
- Biofuels, where included, do not consider the impact of indirect land use change.

Figure ES-11. *Projected Range of Impact of Demand, Fuel Efficiency Improvements, and Alternative Fuel-Vehicle Systems on 2050 Light-Duty Fleet GHG Emissions*

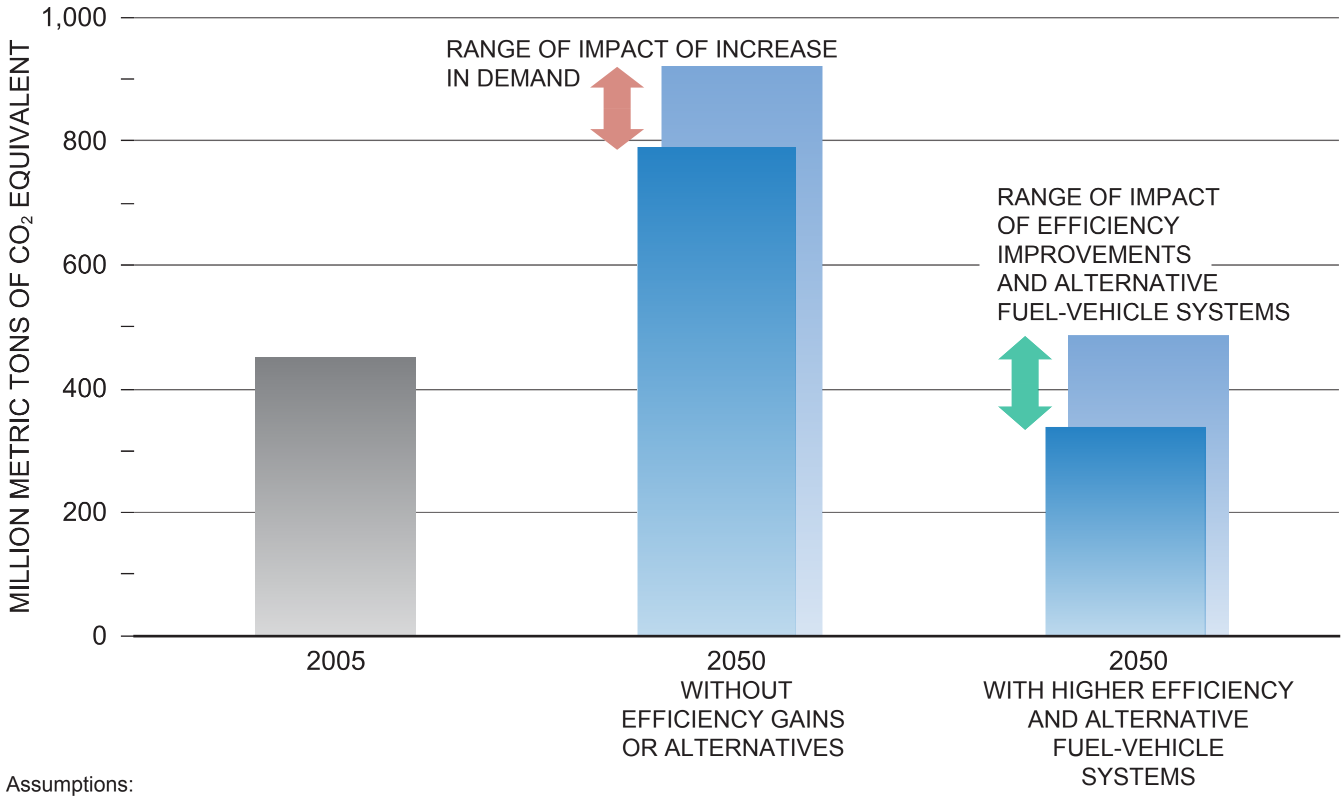
expected to achieve a 50% GHG emissions reduction from 2005 levels (~250 MMT CO_2e). Further GHG emissions reductions beyond those calculated in this analysis are possible through supplemental efforts such as the use of bio-based diesel, advanced biofuels, renewable natural gas (RNG), and/or improved freight efficiency, but will likely have higher costs associated with them.

The following conditions are necessary to achieve the lower end of the range presented in the 2050 "Higher Efficiency and Alt. Fuel-Vehicle Systems" case in Figure ES-12: nearly twofold fuel economy improvement for Class 7&8, significant penetration of natural gas into Class 7&8 vehicles, availability of advanced biofuels for Class 3-6 (not considering the impact of ILUC), and VMT projections lower than those in the AEO2010 (e.g., AEO2012).

Additional GHG Reduction Strategies

In addition to efficient vehicles and low-carbon fuels, additional strategies could enable deeper GHG emissions reduction in the transportation sector than those based on the assumptions in this study. While numerous strategies could be considered, the study selected five GHG emission reduction strategies that can supplement GHG reductions beyond those achieved through advances in fuel-vehicle systems. The costs of these strategies were not considered.

- **Electricity Generation Carbon Intensity Reduction –** Increased use of low GHG-emission power generation sources, such as natural gas, nuclear, wind, solar, and hydroelectric power, will further reduce WTW GHG



Assumptions:

- Based on AEO2010 Reference Case conditions with 3-year and 17-year fuel expenditure considerations.
- VMT range based on AEO2010 Reference Case and AEO2012 Early Release, extrapolated to 2050.
- Carbon intensity (grams CO_2e/megajoule) values for fuels are from GREET in 2020.
- For cases including alternative fuel-vehicle systems, technology and transition hurdles are assumed overcome.
- Biofuels, where included, do not consider the impact of indirect land use change.

Figure ES-12. *Projected Range of Impact of Demand, Fuel Efficiency Improvements, and Alternative Fuel-Vehicle Systems on 2050 Medium- and Heavy-Duty Fleet GHG Emissions*

emissions per mile for plug-in electric vehicles. Carbon capture and storage technology applied to coal and natural gas power generation will also reduce plug-in vehicle GHG emissions per mile.

- **Reduced Travel Activity –** Reducing travel demand, shifting travel to more efficient modes, or other actions can reduce GHG emissions associated with personal travel. Reduction strategies can include: pricing strategies to increase the cost per mile of driving, improvements to transit, non-motorized and intermodal travel to increase the energy efficiency of travel per person-mile traveled, and commuter and worksite trip reduction programs as alternatives to single-person transport.

- **Improved Operational Efficiency of Travel –** Travel efficiency strategies optimize the use of the transportation network by improving the efficiency of transportation operations through reduced vehicle travel time, improved traffic flow, decreased idling, and other operational efficiency improvements. Debottlenecking highly congested roads and inter-connections is an important means of gaining operational efficiency. Improvements in transportation systems offer GHG reduction opportunities in all transport modes. Examples of travel efficiency strategies include: intelligent traffic systems for highway operations, harmonizing laws to permit higher weights and longer trailers for heavy-duty truck operations, and transforming our nation's ground and airspace program (e.g., Federal Aviation Administration's NextGen program).

- **Renewable Natural Gas –** RNG can be produced from a variety of biomass and/or biogas sources including landfill gas, solid waste, municipal wastewater, and agricultural manure via purpose-built anaerobic digesters. It can also be produced from lignocellulosic sources such as forestry and agricultural waste through the process of thermal gasification. The use of RNG leverages the existing natural gas network to distribute or deliver a renewable fuel. RNG can offer significant GHG reductions when compared to diesel, gasoline, and fossil natural gas. However, overall GHG reduction potential of RNG in transport will depend on cost, feedstock availability, and competing uses (e.g., RNG use in power generation).

- **Ultra-Lightweighting of Light-Duty Vehicles –** Ultra-lightweighting is generally considered to be a 50–70% reduction in the weight of a vehicle, which leads to fuel economy improvements and thereby GHG emissions reductions. Some lightweighting materials, such as carbon fiber composites and magnesium, require more energy to produce than materials currently used for many light-duty vehicle components. Additional studies are needed to understand life-cycle GHG emissions from ultra-lightweighting.

Criteria Air Pollutants and Water Use

The study also analyzed additional environmental impacts to understand well-to-wheels criteria air pollutant emissions and water consumption for alternative fuel-vehicle systems when compared to gasoline and diesel ICEs. Other environmental issues such as biodiversity and land impacts were beyond the scope of this study.

When compared to conventional gasoline and diesel vehicles, all alternative fuel and vehicle options analyzed provide comparable or improved criteria air pollutant emissions on a vehicle-miles basis. For water consumption, all alternative fuel and vehicle systems analyzed generally have similar or improved water consumption performance on a per-mile basis, except for irrigated biomass used for biofuels.

ENERGY SECURITY

Finding: **In the years ahead, the U.S. transportation sector could have access to a broad array of economically competitive fuel-vehicle system options, the diversity of which can contribute to our nation's energy security.**

Energy and national security are closely linked. The study approached the multi-faceted issue of energy security by identifying a set of characteristics describing the important attributes that fuels and vehicle systems should exhibit in order to contribute to energy security. The characteristics are abundant and accessible, reliable, diversified, affordable, energy efficient, and clean.

Abundant and Accessible Resources

Recent increases in North American natural gas and oil resources enable more abundant and accessible production of conventional fuels for use in transportation and other energy sectors. Additionally, increased supplies of biomass represent a large potential source of energy. However, there are significant technological, economic, commercial, and logistical hurdles to overcome to sustainably produce and deliver biofuels on a wide scale for transport use.

Reliability

The U.S. liquid petroleum, natural gas, and electricity transmission and distribution systems are highly reliable. American consumers are supplied with fuels through a complex and efficient system that produces, refines, and delivers fuels and power from the source to the point of use.

In the United States, power outages or fuel supply disruptions are relatively infrequent and short in duration mainly due to the reliable and well-maintained infrastructure. Diversity of supply sources helps maintain the high level of reliability of the power and fuel supply systems.

Energy Diversity

Increased diversity creates the resiliency of the supply system by offering more optionality, which can come from having more suppliers, more supply types, different supply chains, or methods to migrate demand. This flexibility, however, typically comes at a higher cost. Given the scale of the infrastructure in the United States, supply chain redundancies for the sole purpose of increased supply security are not cost effective. The current U.S. fuel supply chain is even more robust from participation in the global energy marketplace where multiple supply sources are available.

The option of producing multiple fuels from a single feedstock, or a single fuel from multiple feedstocks, may provide increased resiliency. For example, natural gas can be used for electricity generation, CNG, LNG, and hydrogen production. Hydrogen can be made from a wide variety of domestic and readily available energy sources such as natural gas, coal resources, and low-carbon feedstocks such as wind power and nuclear. Electricity can be generated from renewables, oil, gas, coal, or nuclear. While multiple supply chains could provide increased resiliency, ultimately the infrastructure costs for a wide variety of options would impact the utilization and cost effectiveness of the supply chains.

Flexibility in transportation fuel choices can contribute to energy security. Over the coming decades, technological and non-technological advancements could enable each of the alternative fuel-vehicle systems to compete for market share. Flexible-fuel, bi-fuel, and PHEVs could be deployed while widespread fuel-dispensing supply and infrastructure is installed.

The combination of increased North American oil and gas production, increased fuel efficiency, and diversity of fuel types should more than meet the demand from increases in VMT, and result in future domestic production meeting a larger portion of transportation fuels demand.

RECOMMENDATIONS

While there are likely to be significant technical and other advances that enable the wide-scale commercialization of one or more alternative fuel-vehicle systems, it is uncertain if and when advances will occur. For this reason, it is premature to predict which fuel-vehicle systems will be the most economically and environmentally attractive by 2050. The study offers the following recommendations:

- Government should promote sustained funding and other resources—either by itself or in combination with industry—in pre-competitive aspects of the twelve Priority Technology areas identified, as well as in areas that could lead to Disruptive Innovations.
- There is a great deal of uncertainty regarding which individual fuel-vehicle systems will overcome technology hurdles to become economically and environmentally attractive by 2050. Therefore, government policies should be technology neutral while market dynamics drive commercialization.
- The federal government should take a leadership role in convening state, local, private sector, and public interest groups to design and advocate measures to streamline the permitting and regulatory processes in order to accelerate deployment of infrastructure.
- When evaluating GHG emission reduction options, the government should consider full life-cycle environmental impact and cost effectiveness across all sectors. It should also continue to advance the science behind the assessment methodologies and integrate life-cycle uncertainty into policy frameworks.
- Fuel, vehicle, and technology providers should consider existing or new voluntary forums that include federal and state governments and other stakeholders, to address concurrent development of vehicles and infrastructure.

CONCLUDING REMARKS

In response to a request from the Secretary of Energy, the NPC convened over 300 subject matter experts from its membership and across diverse stakeholder groups. These experts met to address the opportunities and challenges of deploying alternative fuel and vehicle systems to meet transportation needs in 2050, achieve significant GHG emissions reductions, and enhance energy security.

The NPC reiterates the important findings of this study:

- Fuel economy can be dramatically improved in the light- and heavy-duty sectors through the advancement and application of existing and new technology. Internal combustion engine technologies are likely to be the dominant propulsion systems for decades to come, with liquid fuel blends continuing to play a significant, but reduced role.

- Priority Technology hurdles were identified that must be overcome for wide-scale commercialization of advanced fuel-vehicle systems by 2050. A broad portfolio of technology options provides the opportunity to benefit from potential Disruptive Innovations.
- Infrastructure challenges must be overcome for wide-scale commercialization of advanced fuel-vehicle systems. Options exist to facilitate concurrent development of alternative fuel vehicles and infrastructure, such as building on existing infrastructure, corridor-deployment, and multi-fuel vehicles.
- If technology hurdles and infrastructure challenges can be overcome, economically competitive low-carbon fuels and improvements in fuel economy will result in substantial reductions in GHG emissions. Additional strategies will be required to achieve a 50% reduction in GHG emissions relative to 2005 in the transportation sector by 2050.
- In the years ahead, the U.S. transportation sector could have access to a broad array of economically competitive fuel-vehicle system options, the diversity of which can contribute to our nation's energy security.

In conclusion, through successfully overcoming technology, infrastructure, and other hurdles, widespread commercialization of advanced fuel-vehicle systems could occur and benefit America's economy, environment, and security.