

Potential of Electric Propulsion Systems to Reduce Petroleum Use and Greenhouse Gas Emissions in the U.S. Light-Duty Vehicle Fleet

by

Michael Khusid

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Signature of Author.....
Michael Khusid
System Design and Management Program

Certified by
John P. Heywood
Professor of Mechanical Engineering
Sun Jae Professor, Emeritus
Thesis Supervisor

Accepted by
Patrick Hale
Director
System Design and Management Program

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Abstract

In the summer of 2008, the United States of America experienced an oil shock, first of a kind since 1970s. The American public became sensitized to the concerns about foreign oil supply and climate change and global warming, and to the role of transportation in emissions of carbon dioxide and other greenhouse gases (GHG). Several proposed federal policies impose stringent limits on the transportation sector, in terms of fuel consumption and GHG emissions. Within transportation sector, light duty vehicles (LDVs) - cars, light trucks and SUVs - currently emit the most GHGs.

Hybrid technology emerged as a promising option to address several of these challenges. A modern hybrid electric vehicle (HEV) offers significantly better fuel economy together with lower levels of pollutant and CO₂ emissions. HEVs are currently categorized as *Advanced Technology* Partial Zero Emission Vehicles (AT-PZEV) by California Air Resource Board. Recently, a new generation of vehicles, plug-in hybrid electric vehicles (PHEV), has been announced in the immediate future by major auto manufacturers. While HEVs have a relatively small battery that is recharged by the engine or by regenerative braking, a larger battery of a PHEV and a charger allows a vehicle owner to recharge the battery from the electric grid. The plug-in technology further increases fuel economy and reduces emissions from the tailpipe. For example, a Chevrolet Volt PHEV is expected to be launched as 2011 model with 40 mile all-electric travel with no tailpipe emissions.

However, there are multiple challenges associated with the new technology. HEVs and PHEVs incur higher costs due to additional components, such as electric motors and motor controllers, and a battery. Today's batteries provide energy storage density hundred times lower than that of gasoline. Electricity consumed by hybrids is generated by coal and other fossil fuel power plants that emit harmful chemicals and greenhouse gases. The infrastructure for electric cars is at the infancy stage. Some government policies designed to introduce all-electric cars, such as the California ZEV mandate of the late 1990s, failed to introduce a sustained number of electric vehicles to the market.

To provide an integrated approach to the causes and effects of electrified powertrains, two plausible scenarios of advanced vehicle market penetration were developed. Federal policies and consumer preferences were considered as primary drivers. Biofuels were considered alongside fossil fuels as primary energy sources for transportation. Rapid adoption of PHEVs was found to cause a perceptible, but not a significant increase in electric power demand. The scenarios demonstrated ability to achieve fuel economy milestones and quantified the challenge of achieving 80% reduction in greenhouse gas emissions by 2050.

Thesis Supervisor: John B. Heywood.

Title: Professor of Mechanical Engineering, Sun Jae Professor, Emeritus.

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1 Motivation

In 1908, Ford introduced the Model T(1). It was a simple gasoline vehicle optimized for cost and for ease of maintenance. The Model T emerged as the dominant design and defined the world automotive market for the next 100 years. Even though the Model T could utilize multiple fuels, gasoline emerged as the primary fuel with the discovery of oil in Texas. For the next ninety years, the U.S. relied on gasoline as the primary fuel. The fuel was abundant and cheap. Extensive infrastructure of refueling stations was built to distribute and to retail fuel all over the country. Over 100,000 gas stations are in operation today.

In 1970s, the U.S. experienced the first oil shock. With the shortage of oil, the gasoline prices rose sharply and the availability of fuel was drastically reduced. As a response, the United States government introduced policies targeted to reduce U.S. dependence on oil. One of the policies resulted in a significant public attention to fuel economy of the U.S. Light Duty Vehicles (LDVs). However, as the shock subsided, the country reverted to the old ways.

In 2008, the second oil shock occurred. Price of oil jumped to \$147 per barrel, and gasoline price rose to the highest levels in history. The public became keenly aware of fuel dependence on the foreign supplies. In particular, oil imports from the foreign countries provided the significantly larger share of the U.S. oil consumption, potentially subjecting the country to the political instabilities. At the same time, the environmental concern has been high on the public agenda. These concerns include both climate change and environmental consequences of expanding oil extraction, such as the Gulf of Mexico disaster of 2010. This time, the following concerns amplified each other – fossil fuel scarcity, shortage of U.S.-produced petroleum, a chance of environmental disaster and climate change due to emissions of CO₂.

Since the 1990s, multiple advancements to automotive technologies were introduced, such as wide adoption of automatic transmission, improved materials, and safety features such as advanced airbags and electronic stability controls. For this study, the most important one is the advancement in vehicle propulsion technology, namely the hybridization of the vehicle powertrain. The most popular and best recognized hybrid electric vehicle on the market today is Toyota Prius (2), followed by other hybrids from Toyota, Ford and Honda.

In the automotive fuel arena, biofuels, in particular corn ethanol, were introduced and mandated by federal and state policies (3). Currently, biofuels are produced in low billions barrels per year, and they comprise only 4% of total U.S. fuel supply.

Among the several possibilities of the future automotive technology development, one can consider the challenges associated with the evolving technology tree as well as its associated infrastructure. The rates of technological changes will be discussed in the further chapters. The changes to the infrastructure are often more subtle. The primary infrastructure for automobiles is associated with roads and refueling stations. We will not consider roads in this study since all proposed vehicular technologies use the roads in a similar manner to how the Ford Model T did when it defined the dominant vehicle design: four wheels with front wheel steering. In this study, we will focus on the potential changes in the refueling infrastructure. One must observe that there has *never* been a significant change in the refueling infrastructure since the introduction of the automobile.

Emerging Automotive Propulsion Technology	Significant changes in vehicular technology required?	Significant infrastructure change required?
Advanced conventional vehicles (direct injection, diesel, turbocharging) using gasoline and/or ethanol	No	No
Hybrid electric and plug-in hybrid electric vehicles	Some	No
Non-conventional fuel (compressed natural gas, hydrogen ¹) vehicles	Some	Yes
Battery Electric Vehicles	Yes	Yes

Table 1. Emerging Automotive Propulsion Technologies and Associates Challenges.

The table above illustrates several main possibilities among the automotive propulsion technology and the associated relevant infrastructure. In this study, we will limit ourselves to the technologies which do not require a significant and rapid change in the infrastructure. Current refueling infrastructure consists of approximately 150,000 gasoline refueling stations which provide fuel, often blended gasoline and ethanol, for nearly 250 million of gasoline vehicles. Any change in such infrastructure is expected to take significant amount of times and require large expenditures. Nevertheless, recent history shows a very significant change in the infrastructure for the internet and for the cellular phones (4). However, we observe mobile phones and some computers are “small devices” and are not considered durable goods, as opposed to the automobiles which last for years. In addition, the communication technologies of the past decade have few or no substitute goods, thus justifying the high rate of infrastructure change and new technology adoption. At the same time, the analyzed automotive technologies

¹ Hydrogen is grouped with compressed natural gas since today’s most efficient strategy for hydrogen production relies on natural gas steam reforming.

are close substitutes to the conventional gasoline vehicles, thus, the cost of a significant change in the infrastructure may not warrant a switch to a different technology. In practical terms, we will examine hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) versus vehicles with incumbent as well as future internal combustion engines.

Previous studies (5) (6) (7) (8) have demonstrated the potential advantages of the hybrid electric and plug-in hybrid electric technologies in addressing the aforementioned public concerns. They have also pointed out limitations of these technologies, especially those related to the rechargeable electrochemical batteries. Therefore, we formulate the fundamental question of this research:

How to achieve the greatest benefit from vehicle powertrain electrification while minimizing the impacts of battery weight and cost.

2 Methodology and Thesis Outline

Our analysis will examine four inter-related aspects of technology and infrastructure development in the automotive and electric power industries. Within each industry, we split the focus on the unit of the technology, such as a car, and the issues related to large groups, such as the vehicle fleet. Each quadrant will be evaluated as a time-dependent entity between now and 2050. A historic prospective will also be examined in several quadrants to analyze trends.

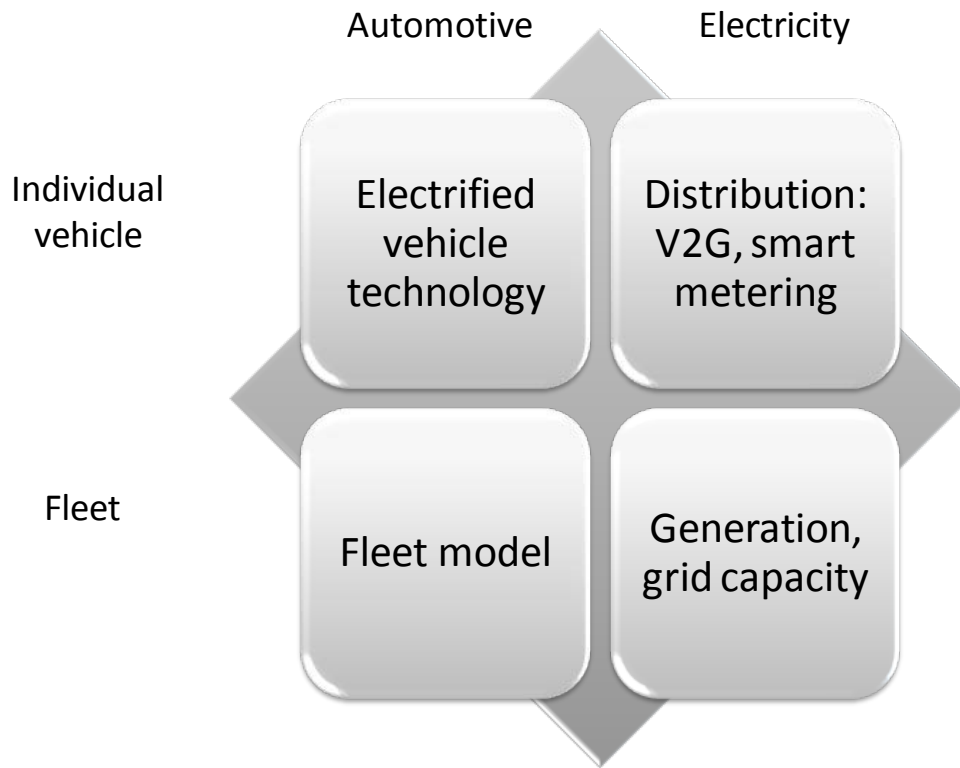


Figure 1. Graphical Illustration of the Analysis Method

In the counter-clockwise fashion, we start at automotive technology. We will examine projections for automotive propulsion technology up to 2050. In Chapter 3, we will examine existing and future internal combustion technology strategies, hybrid and plug-in hybrid electric vehicle strategies and alternatives, and several other potentials.

We will then consider the fleet effects. The U.S. LDVs, or ‘car park’, evolves as the new vehicles are sold and the old vehicles are retired. We will examine the delays associated with this vehicle turnover. We will also assess fleet aggregate vehicle utilization by the consumers and associated energy use and greenhouse gas emissions. In particular, we will examine consumption of the conventional fuels, alternative liquid fuels and electricity.

In chapter 4, we will evaluate power generation required from the power electric grid to provide energy for the vehicle charging. Taking into account the daily cycle, we will estimate the needs for additional electricity generation due to the added vehicle load. We will also assess the corresponding GHG emissions.

Lastly, in chapter 5, we will examine the infrastructure aspect of the vehicle connectivity to the grid. We will examine the emerging requirements for the vehicle-to-grid (V2G) connections. We will also examine infrastructure needed for vehicle charging and the impact of charging behavior, in particular, opportunity charging, on the total energy use.

In chapter 7, we will describe the details of the select scenarios. The results will be presented in chapter 8 and summarized in chapter 9.

3 Automotive Technology

Since the early development of the automobile in the first half of the 19th century, three technologies vied for the main propulsion systems of the automobile. In the early years, steam external combustion engine was placed in the vehicles. The technology was derived from that of the locomotives. However, complexity, expense and the danger of the steam powertrain eliminated this technology from contention in the early 1900s. The two remaining technologies: electricity and gasoline internal combustion are still used in the automobiles today, with some very significant improvements and radical improvements. The “pure” implementations of these propulsion technologies are a battery electric vehicle and an internal combustion engine vehicle, correspondingly. It is possible to hybridize these technologies. These options will be discussed further in this chapter.

3.1 Vehicles propelled by an Internal Combustion Engine (ICE)

An internal combustion engine (ICE) is a type of a reciprocating piston engine widely used in transport, power equipment and stationary applications, such as generators. In the United States, nearly all vehicles sold today have internal combustion engines. A typical vehicle in 2010 is powered by gasoline, gasoline/ethanol mixture, diesel, or compressed natural gas. The ICE technology became to dominate the automotive market since introduction of Model T (1) by Henry Ford and Ford Motor Company in 1908, although the design did not reach popularity until mid-1910s. The benefits of early automobiles were low cost, easy servicing, as well as availability and energy density of fuel. The latter provided much greater range and easy refueling than competing technologies, as it does today.

3.1.1 System Architecture

The essential architecture of an ICE vehicle's propulsion system, shown on Figure 2, remains unchanged since Model T(9). A vehicle has a single engine, which powers the wheels via the transmission. Due to space and weight constraints, vehicle never have multiple engines. A transmission is required to match the torque and rotation speeds of the engine to those of the wheels, primarily due to limited range of the ICE operating conditions. The latter is often further restricted due to fuel efficiency considerations.

The key importance of the architectural innovation introduced by Model T in 1908 is that it was the last fundamental architectural change in the vehicle propulsion systems (10). Since architectural innovation is described to disrupt both technology/production and market/customer, the core definitions of the automotive technology and automotive market remain unchanged

during the last 100 years. The alternative technologies face a formidable challenge disrupting such an incumbent.

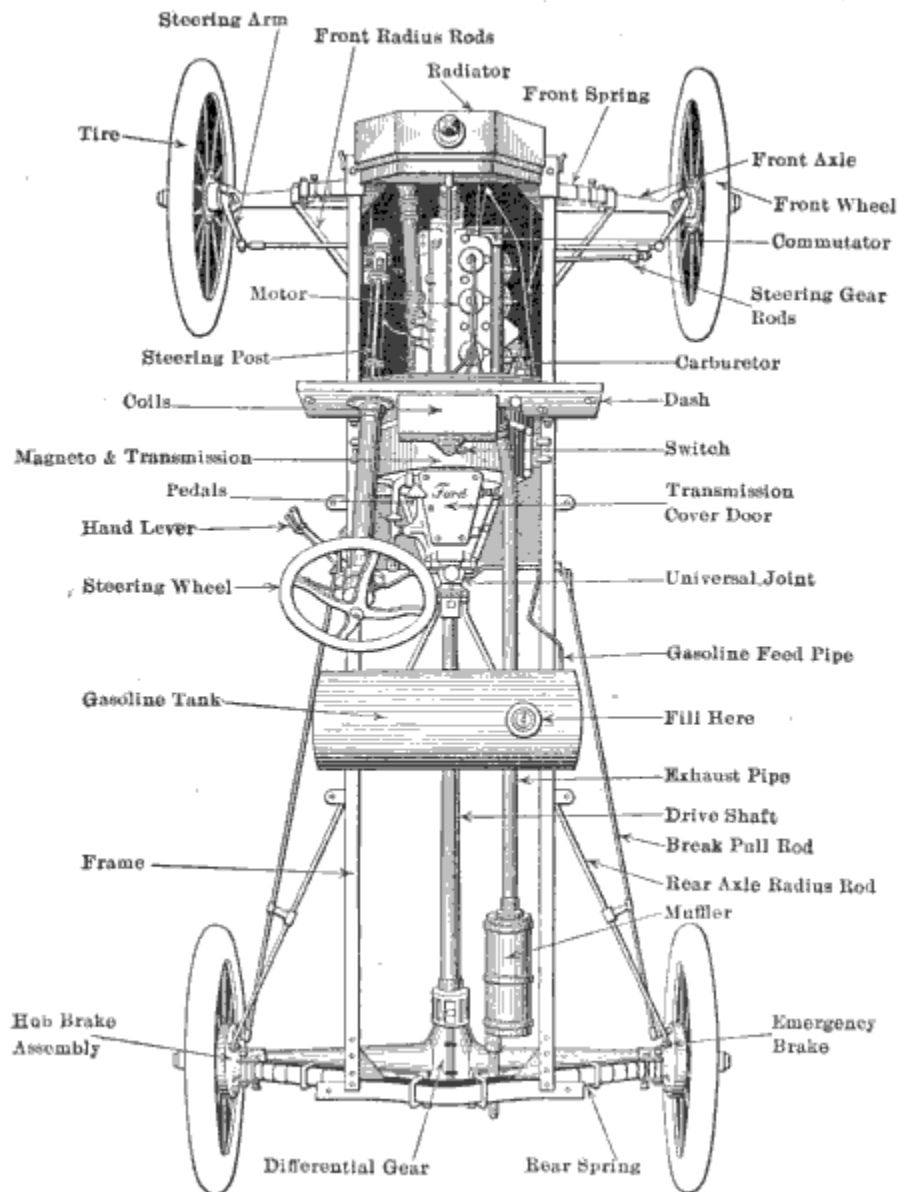


Figure 2. Plan View of the Ford Model T Chassis Showing Relative Location of Important Components,
(9) accessed via Google Books

Very early ICE vehicles did not contain electric motors or batteries. However, the first electric motor in an ICE was introduced by Cadillac in 1912(11), functioning as a starter for the

gasoline engine. Prior to that, ICE vehicles, including Model T, were started by a hand crank, which was difficult and dangerous. For the next 50 years, all light duty vehicles had a starter and a lead acid battery powering the starter, and such architecture nearly exclusively dominated the automotive market.

However, the subsystem of the starter and a battery does not directly contribute to the vehicle propulsion, thus, all such designed as still classified as pure ICE vehicles. In comparison, designs where a similarly placed electric motor provides propulsion, are typically classified as hybrids, and will be discussed later in this chapter.

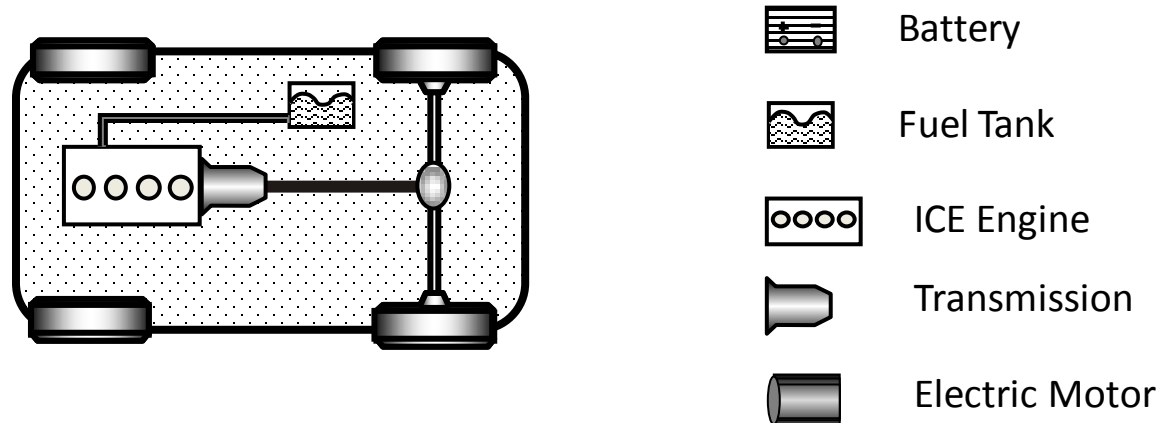


Figure 3. Architecture of a Propulsion System of an Internal Combustion Engine vehicle.

3.1.2 Technology Implementations

Gasoline ICE vehicles currently dominate the United States light duty vehicle market, comprising 97% of the new vehicle sales and 99% of the total vehicle fleet. Currently, the vehicles are powered either by either 100% gasoline or a mix of 90% gasoline and 10% ethanol, depending on the regional mandates. Relatively few vehicles are powered by diesel. Due to the diesel higher energy density, such vehicles usually have lower fuel consumption as measured in liters per 100km, or higher fuel economy measured in miles per gallon. As recently as in 2007,

diesel standards in the United States have adapted to a low-sulfur diesel fuel which permit auto-manufacturers to apply new technologies in order to comply with the emission standards. LDV diesel sales have been increasing [NEED REF] in the past few years, although sufficient data is not yet available to predict long term trends.

About 3% of ICE light-duty vehicles can be powered by a mix of 15% gasoline and 85% ethanol in addition to the standard fuel mix. These vehicles are referred as flex-fuel vehicles (FFVs). The implications of biofuels in the fuel mix will be discussed in Chapter 6.

Relatively few LDVs in the United States are powered by the compressed natural gas (CNG). Natural gas usage is more common in heavy duty vehicles, especially buses and municipal fleets. Although there are subsidy programs that encourage consumers to acquire CNG vehicles, the availability of the latter is limited to a single model by a single manufacturer, a Honda Civic GX, which is not available in all areas. In addition, there are relatively few refueling stations available for the CNG, only approximately 11,000 (12) compared to 121,446 (13) for conventional fuel. As described in Chapter 1, infrastructure challenges remain formidable for this application of technology, and thus, the option is not studied in this work.

3.2 Vehicles with Electric Propulsion

Electric motors have been utilized in the automobiles since 19th century for various purposes. The first electric carriage was built between 1832 and 1839(14). In 1895, the first electric road wagon (Figure 4) appeared featuring four wheels, electric motors and a rechargeable battery(15), essentially introducing the architecture of a modern electric vehicle. Electric car's "golden age" spanned from 1900 to 1912 and culminated with prominent sports cars such as Porsche racing car of 1902 (16).



Figure 4. Morris and Salom electric road wagon of 1896 ('Scientific American') (15)



Figure 5. Riker two-passenger electric tricycle, built by Andrew L. Riker at Stamford, Connecticut, from 1896 to 1898 (17).



Figure 6. Thomas Edison standing by a 1895 Baker Electric Automobile, formerly an industrial machine manufacturer (18)

Prior to 1910s, the automotive industry existed as an extension to several competing industries. Companies specializing in bicycles released electric bicycles and tricycles (Figure 5). Companies specializing in horse carriages or other industrial machines produced sturdy, reliable “horseless carriages” (Figure 6). The majority of electric vehicles were designed for urban areas with heavy horse traffic. Thus, quiet and steady electric propulsion systems gave battery electric vehicles a significant advantage over ICE vehicles. Acceptable cruising speed at the time was 8 to 10 mph within urban limits. Higher speeds were not only technically challenging, but also undesirable due to safety concerns for pedestrians and horses.

3.2.1 System Architecture

A battery electric vehicle propulsion system consists of three primary components: battery, power electronics and a motor (Figure 7). Such architecture remains without significant changes

for over 100 years. The components themselves, however, underwent very significant technological improvements, for example, semiconductor-based power electronics enabled much higher efficiencies and wider range of operations. Compared to the ICE vehicles, a multi-speed transmission is commonly omitted due to much greater operating range of an electric motor compared to an ICE engine. Instead, a fixed gear gearbox is utilized.

Since early 20th century, BEVs were limited by the battery weight, cost and limited energy capacity. Range anxiety (19) has been a subsequent impediment to the market adoption of the BEV technology in addition to higher costs.

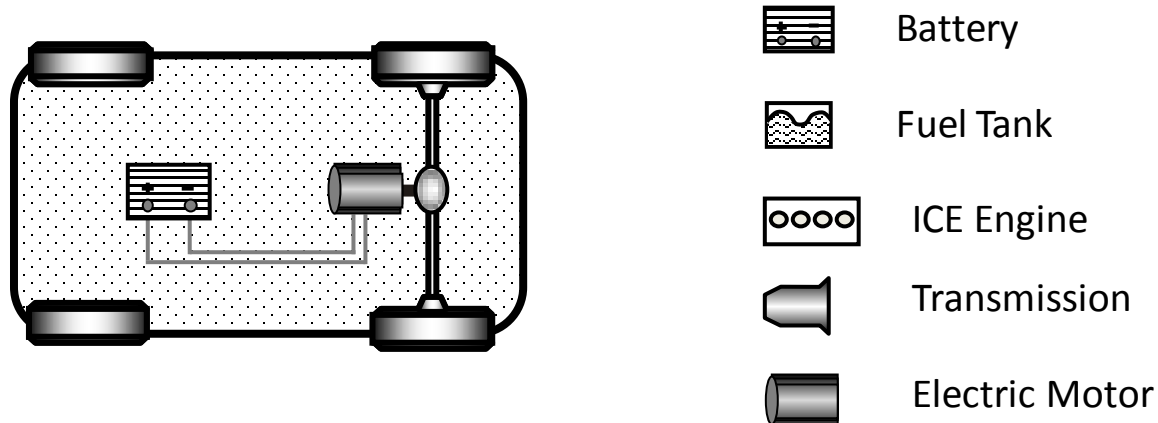


Figure 7. Architecture of a Propulsion System of a Battery Electric Vehicle.

3.2.2 Technology Limitations

A limitation of the battery energy capacity has been long recognized as one of the primary limitations of the BEVs. There are three fundamentally different strategies to solving this challenge.

1. More batteries. Adding more batteries linearly increases energy stored onboard a BEV, however, it does not linearly increase the range, as observed by Kromer in (20) and others. Batteries consume valuable space inside a vehicle and increase weight, thus decreasing vehicle efficiency. Batteries significantly increase cost of the vehicle. In the example illustrated by Kromer, a 200 mile range BEV was analyzed. In fact, 200 mile range is a very modest compared to that of contemporary gasoline vehicles. Therefore, this option has limited appeal.
2. Technical progress. Greater energy capacity of the batteries can be achieved by scientific innovation in the new materials, by providing greater energy density. Lithium-ion battery technology emerged in the consumer electronics sector in the 1990s. It has been successfully applied to the new generation of the vehicles with electric propulsion. Future scientific research is required to further improve battery energy densities.
3. System level changes. The current transportation system in the United States emerged subsequent to the popularity of gasoline vehicles. Even though the average daily commute is 33 miles [REF], the consumers choose to acquire vehicles with much greater range for multiple reasons. So, with the today's pattern of vehicle trips and refueling infrastructure it is unlikely that consumers will accept range limitations of the today's BEVs. However, alternative solutions for the transportation system have been proposed. One such solution relies on Neighborhood Electric Vehicles. This option also required a well developed public transit system. Detailed analysis of the system level changes in the U.S. transportation system to permit range-limited BEVs is beyond the scope of this work.

3.2.3 Technology Implementations

3.2.3.1 Fuel Cell Vehicles

A pure Battery Electric Vehicle stores all onboard energy in rechargeable batteries in an electrochemical form. However, it is possible to store the energy in a more energy dense form, as measured in J per unit volume or J per unit weight, and convert it on board into electric energy. One such example is a fuel-cell vehicle, often powered by hydrogen, but also feasible with methanol, gasoline and other liquid fuels. Using hydrogen as a potentially desired outcome as a hydrogen fuel cell vehicle produces no emissions besides water vapor. At this point of time, costs and technology maturity are significant obstacles in using fuel cells in mainstream vehicles, although pilot vehicles, such as a Honda FCX Clarity or a Ford Focus FCV. For example, Ford does not expect to release fuel cell vehicles (FCVs) until 2020s (21). Besides, the infrastructure challenges for fuels such as hydrogen remain a formidable challenge.

3.2.3.2 Extended Range Electric Vehicles and Series Plug-In Hybrids

Another alternative to a pure BEV includes adding an internal combustion engine to be used as a generator. Since the ICE in such vehicle does not directly contribute to propulsion, we will classify such vehicles in the family of vehicles with electric propulsion. An example of such design is a Chevrolet Volt slated for release in the end of 2010 (22) (23).

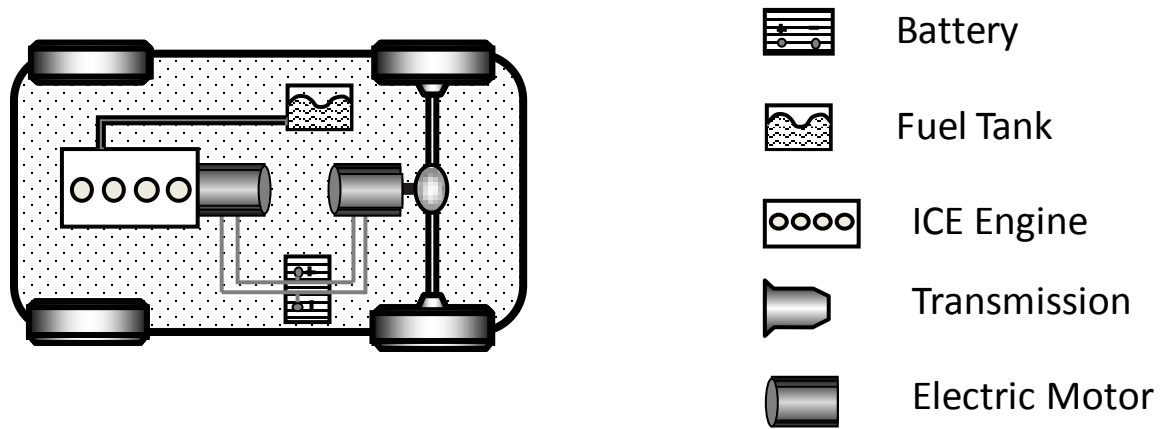


Figure 8. Architecture of a Propulsion System of a Series Plug-in Hybrid Electric Vehicle.

3.3 Vehicles with Hybrid Propulsion

The key assumptions for the hybrid propulsion implementation of this study were based on those described by Kromer in (20). Neither internal gasoline engine nor electric motor are designed to provide maximum power for the vehicle propulsion. Instead, they are expected to complement each other during normal operation of the vehicle. An HEV relies exclusively on a liquid fuel as the energy source. The PHEV operates in the “blended” mode during the “charge-depleting” stage, and afterwards similar to an HEV in the “charge-sustaining” stage (Figure 9).

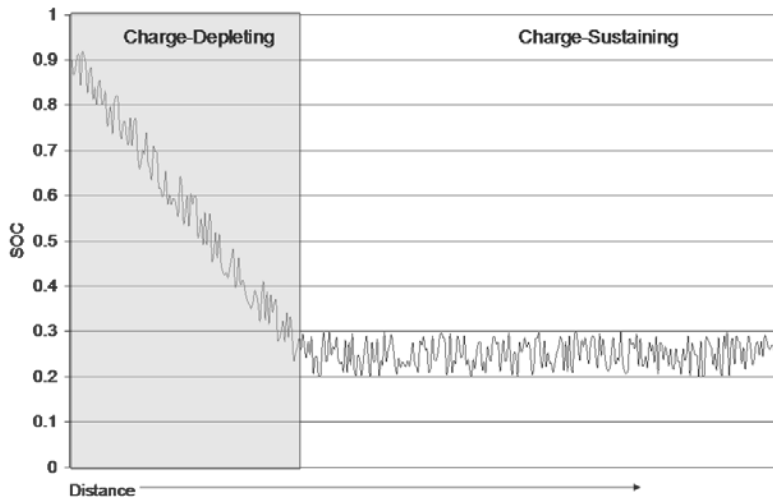


Figure 9. A Typical PHEV Duty Cycle (20).

3.3.1 System Architecture

Just like a conventional vehicle, an HEV or a PHEV is expected to have a single internal combustion motor. This motor contains a mechanical coupling to wheels, usually via a transmission. In some vehicles, the transmission is similar to those of the conventional vehicles, and in some HEVs, the transmission is quite different. The current market leader is the Toyota Hybrid Synergy Drive which uses a patented proprietary technology for the transmission merging it with two electric motors (Figure 10).

For this study, we have taken a simplifying assumption of a single electric motor consistent with Kromer. HEV and PHEV-30 were chosen as illustrative examples of the technology, consistent with the “On the Road in 2035” report.

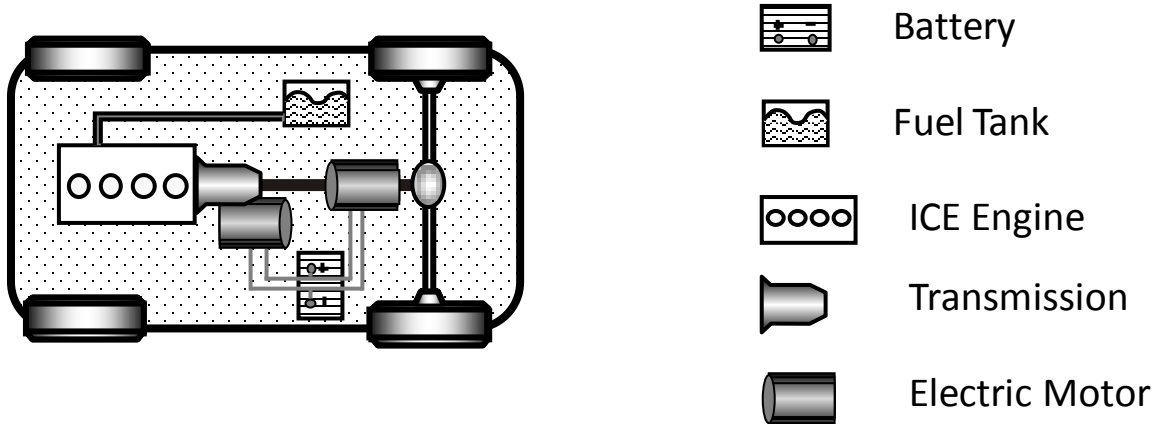


Figure 10. Architecture of a Propulsion System of a Hybrid Electric Vehicle

3.4 Emphasis on Reducing Fuel Consumption

Consistent with the “On the Road to 2035” report, we have utilized a parameter “Emphasis on Reducing Fuel Consumption” (ERFC) to model the utilization of the technology improvements toward reductions of the fuel consumption. The ERFC is defined as:

$$\text{Emphasis on Reducing Fuel Consumption (ERFC)} = \frac{\text{Fuel Consumption Reduction Realized on road}}{\text{Fuel Consumption Reduction Possible with Constant Performance and Size}}$$

or

$$\text{ERFC} = \frac{FC_{\text{current}} - FC_{\text{realized}}}{FC_{\text{current}} - FC_{\text{potential}}}$$

or

$$FC_{\text{realized}} = FC_{\text{current}} - \text{ERFC} * (FC_{\text{current}} - FC_{\text{potential}})$$

In this study, we will assume that the federal and state regulation focus on increasing fuel economy will cause ERFC to be 70% between now and 2035. The 2035 milestone was chosen to coincide with the fuel economy target established by Cheah et al in (24). Such emphasis is optimistic since the ERFC in the past decades in the United States was below 10%. Given the technology and market uncertainties after 25 years, the ERFC is assumed to be 0% between 2035 and 2050. Thus, improvements in reducing fuel consumption and greenhouse gas emissions during the later decades must be derived from other contributions.

4 Electricity Generation

Today, nearly half of the United States electricity generation is derived from coal (25). The second primary energy source by net generation is another fossil fuel, natural gas. Both fuels produce significant levels of CO₂ since the chemical energy of the fuel is released in the process of the combustion. Greenhouse gas emissions and other emissions from these fossil fuels is a significant public concerns. The relative advantage of these fossil fuels compared to petroleum is the national origin of the large portion of these fuels, leading to lesser concerns in regards to the imports.

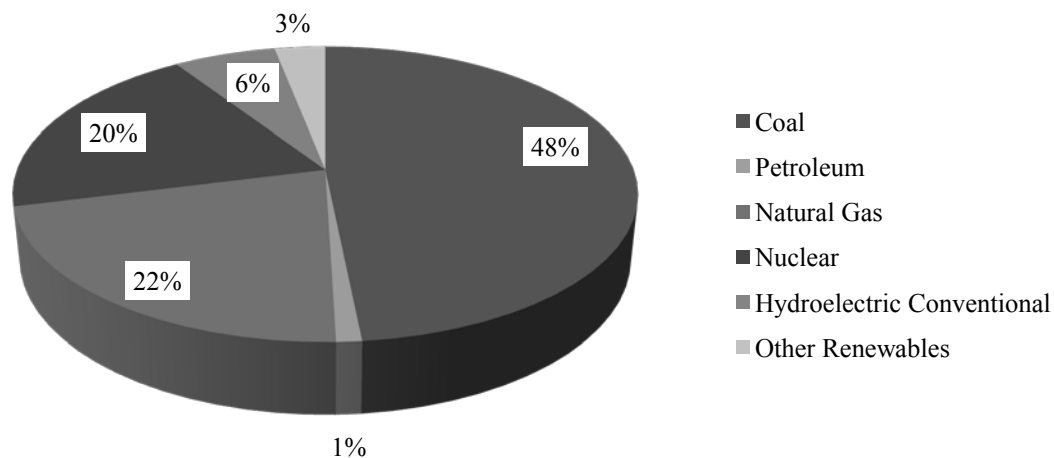


Figure 11. Net Generation by Energy Source in 2008, billion kWh (25)

We included the technological improvements in the electric power generation in our system analysis based on the EPRI study (26). We felt that optimistic “Full Portfolio” was befitting the assumptions taken for the PHEV technology growth. As a result, EPRI model demonstrates a reduction of the annual emissions from the electric power generation by 63% from 2005 to 2050. Figure 12 displays a comparison between this study’s assumptions and the model results from

the EIA Annual Energy Report (27). The Full Portfolio scenario in the EPRI study describes a rapid adoption of renewable technologies and nuclear power. It also projects adoption of the Coal with Carbon Capture and Storage (CCS) beyond 2020. Note that the primary driver for the scenario is an *economy-wide* CO₂ emission cap. There are economic studies which demonstrate that such cap applied to the transportation would not result in comparable decrease of the emissions from the fleet.

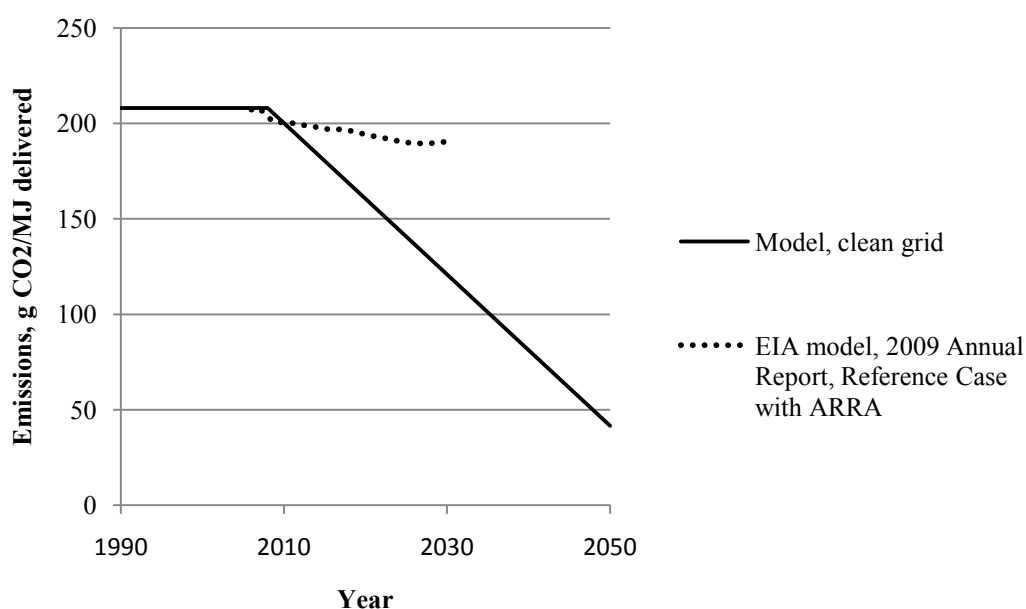


Figure 12. Well-to-Tank Emissions Delivered by Electric Power Grid to a Vehicle

5 Vehicle to Grid interconnection

Since the California ZEV Mandate of the last 1990s, there were several attempts to introduce BEVs to the market and to provide connectivity between the vehicle and the grid. There were multiple approaches, such as inductive charging and conductive charging, that were not compatible to each other. Since then, the J1772 connector has been standardized by the SAE

International. It provides conductive path between the vehicle and the grid. This path can be utilized for both charging and discharging, although we will focus on charging in this study.



Figure 13. J1772 SAE Electric Vehicle Conductive Charge Coupler (28).

Previous studies, including Kromer (20), considered once-a-day charging by the PHEVs. The charging was expected to occur at night. The vehicle is assumed to be parked at the residence where the charging occurs. In the morning, the vehicle is being driven and the battery is discharged in the charge-depleting mode. When the battery charge falls below 20%, the vehicle switches to the charge-sustaining mode.

A study by the National Renewable Energy Laboratory (29) observed a significant reduction in the petroleum consumption if the vehicle is recharging during the day. Since the absolute majority of the U.S. vehicles are parked at either homes or offices during the day, we assume that additional charging opportunities may be available. Since the peak of electricity demand from other consumers occurs in the afternoon during a typical summer day in the United States, we assume a restriction for PHEV charging between noon and 9pm. Therefore, a given vehicle may

charge at night and, usually, one more time after the morning commute. The charging profile across all PHEVs is assumed to be uniform at all times of the day.

In this case, the petroleum consumption of an individual PHEV is further reduced compared to that by Kromer (20). A difference is illustrated on Figure 14 for the PHEV-30 in 2035 considering 100% ERFC. For this study, we have assumed 70% ERFC, therefore, the relevant values for the fuel consumption of liquid fuel and electricity are displayed on Figure 15.

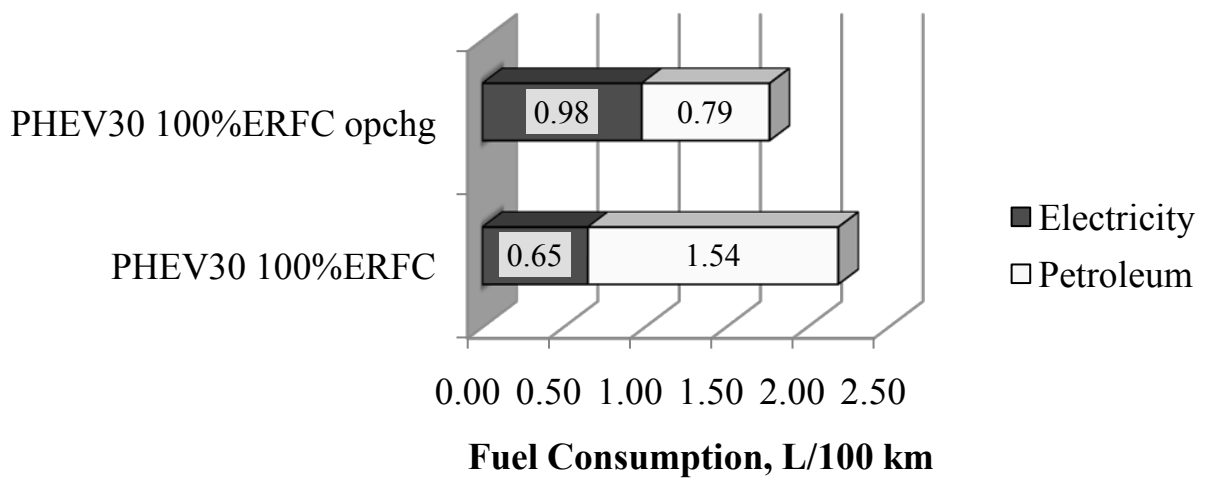


Figure 14. PHEV Fuel Consumption with and without Opportunity Charging (100% ERFC)

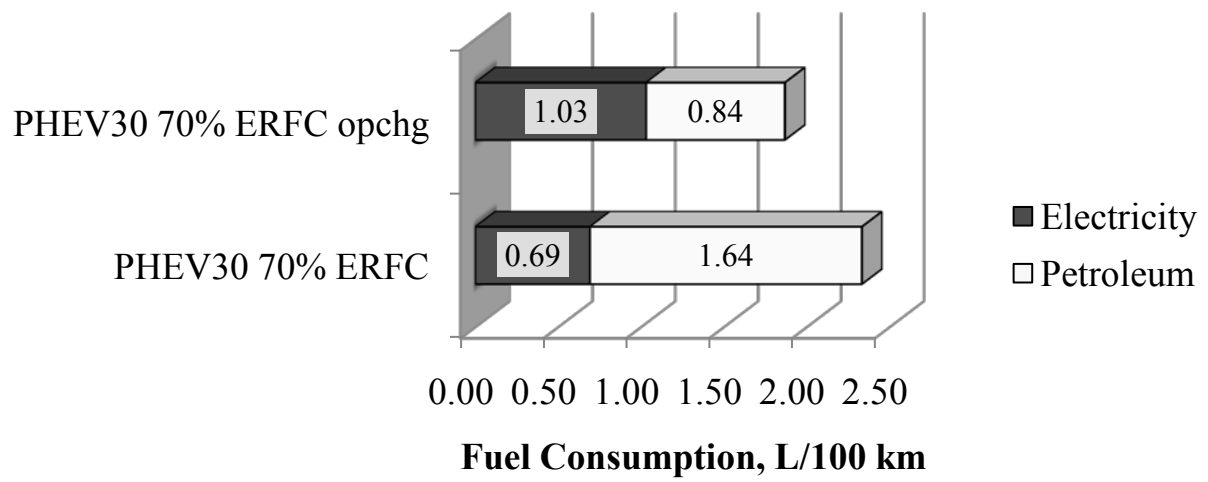


Figure 15. PHEV Fuel Consumption with and without Opportunity Charging (70% ERFC)

6 Biofuels and Conventional Fuels

McAulay (30) outlined a potential for contribution of biofuels to the fuel mix for the LDVs in the United States. In a similar manner, we consider ethanol to be the main type of alternative liquid fuel. McAulay outlined several challenges to widespread adoption of ethanol, most significantly, the so-called “blend wall”. This constraint determines requirements on flex-fuel vehicles (FFV). Furthermore, we observe that widespread HEV and PHEV adoption is likely to further reduce liquid fuel consumption. This effect will likely further increase the percentage of ethanol in the fuel mix assuming the same volume of biofuel production and will exacerbate the FFV concern. In our study we took a simplifying assumption to the FFVs postulating that FFV technology faces lesser challenges than HEV and PHEV technologies. Furthermore, the FFV technology can be readily combined with HEV and PHEV technologies (8).

McAulay proposed three scenarios for biofuel deployment. The Baseline scenario (Figure 16) assumes that corn ethanol capacity will be reached by 2015, primarily based on the ethanol plants currently in operation or under construction. The advanced biofuels such as cellulosic ethanol are not available in any significant quantities.

The “Extended RFS” scenario (Figure 17) builds on of the Baseline scenario consistent with RFS Standard. Given the significant uncertainty beyond the next two decades we assume that considerable biofuel production capacity has been built and remains constant afterwards. This assumption illustrates the potential effect of limited biomass availability.

Lastly, the “Delayed RFS” scenario (Figure 18) recognizes the challenges associated with developing the cellulosic ethanol infrastructure and with the FFV deployment rates. In particular, there is a three-year delay in achieving targets for cellulosic ethanol production compared to the

“Extended RFS” scenario. In the later decades of “Delayed RFS” scenario cellulosic ethanol partially displaces corn ethanol.

It is important to note that the assumed volumes for biofuels range between 50 and 250 billion liters annually beyond 2020. In comparison, the current annual gasoline consumption in the United States exceeds 500 billion liters (27).

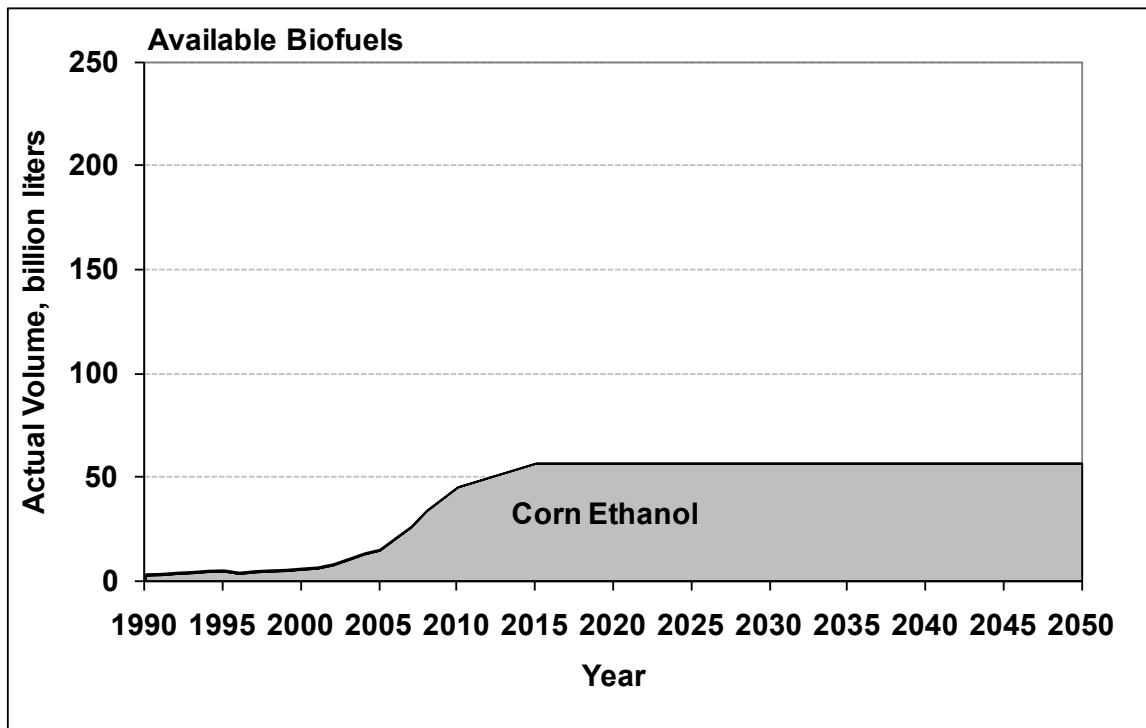


Figure 16. Biofuels Availability in Baseline Scenario (Corn Ethanol only)

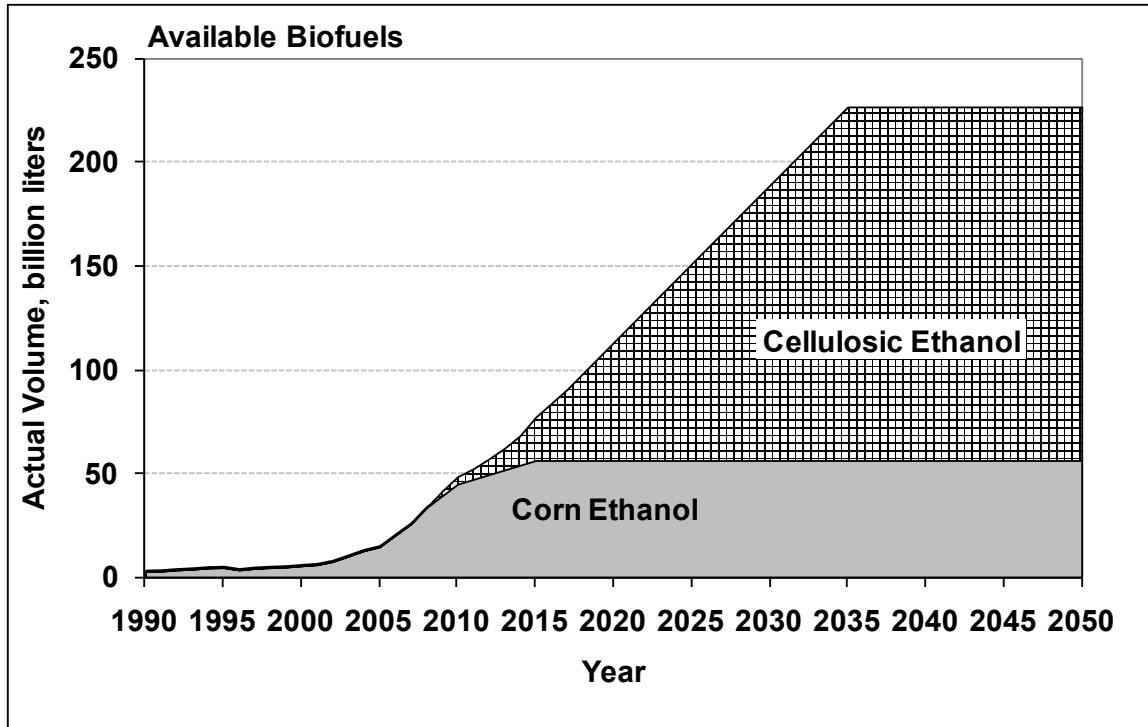


Figure 17. Biofuel Availability in "Extended RFS" Scenario

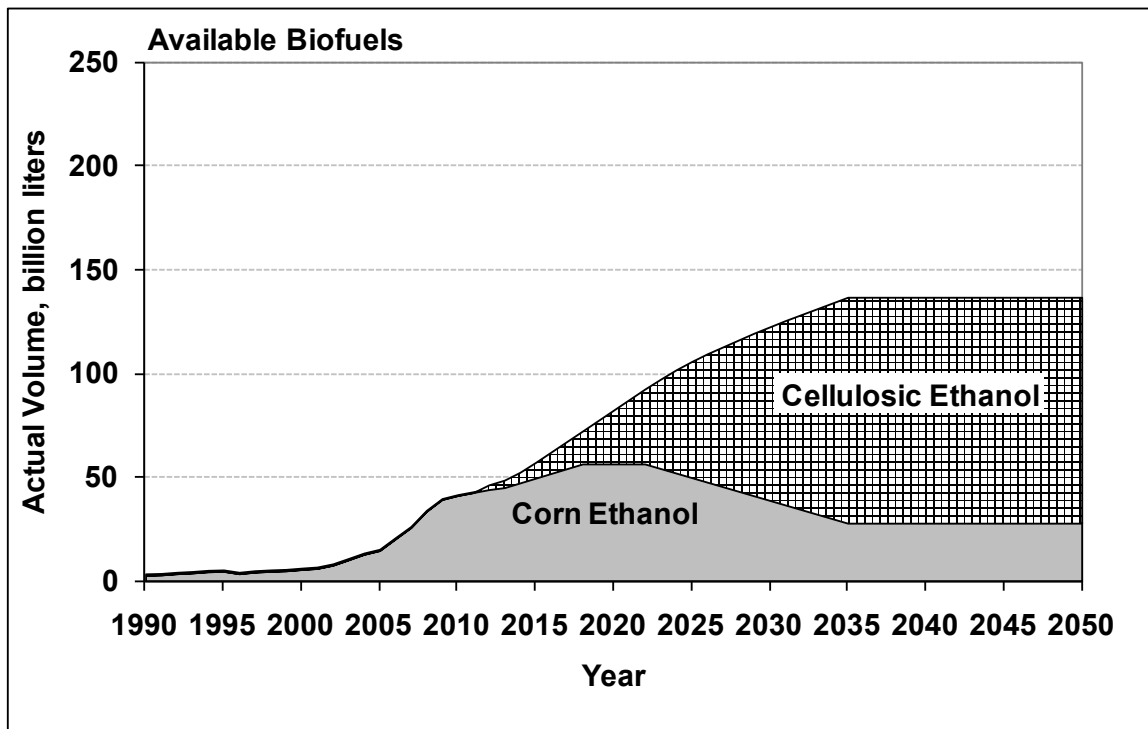


Figure 18. Biofuel Availability in "Delayed RFS" Scenario

7 Vehicle Adoption Scenarios

There is a significant level of uncertainty as to how vehicle manufacturers will utilize technology options available to them. In addition, as described previously, these options are tightly interwoven with development of infrastructure as well as complimentary technologies, such as biofuels. In this section, we will discuss two scenarios for market adoption of HEVs and PHEVs to address the main question of this study. The scenarios were designed to illustrate a potential boundary within the solution space, rather than to forecast or predict future.

The current automotive market is dominated by ICEs which utilize liquid fuels. At present time the majority of LDVs in the U.S. use gasoline while large number of LDVs in Europe and majority of heavy-duty vehicles worldwide use diesel. All gasoline ICEs in the U.S., be it current-generation NASI or newer turbo-charged engines, use spark ignition. Diesel vehicles utilize compression ignition. As described by Bandivadekar in (31), in the immediate future the conventional gasoline technology can progress toward advanced spark-ignited ICEs with a further path toward compression ignition (Figure 19).

Multiple studies explored possibilities of HEV and PHEV penetration (5) (6) (32) into LDV market. Commonly, these technologies are treated as two separate automotive powertrain technologies out of many available to the manufacturers. In this study, however, HEV and PHEV technologies are recognized as being closely related to each other. Therefore, not only market adoption of each of these two technologies is reinforced by adoption of the other, but supply chain constraints for one technology also impact the other technology. For instance, in 2008-2009, the U.S. government helped to fund a number of automotive battery plants in the United States. In the near future, batteries manufactured at these plants can be used in either

HEV or PHEV or both of these types of vehicles. Additionally, given sufficient battery size and advanced power electronics, ability to recharge from the electric grid can become an option for future HEVs, effectively muting the difference between HEV and PHEV technologies. It is also possible to convert an HEV into a PHEV by adding additional batteries and a plug (33). The latter possibility is not considered in this work as our study is focused on new vehicles sold to consumers.

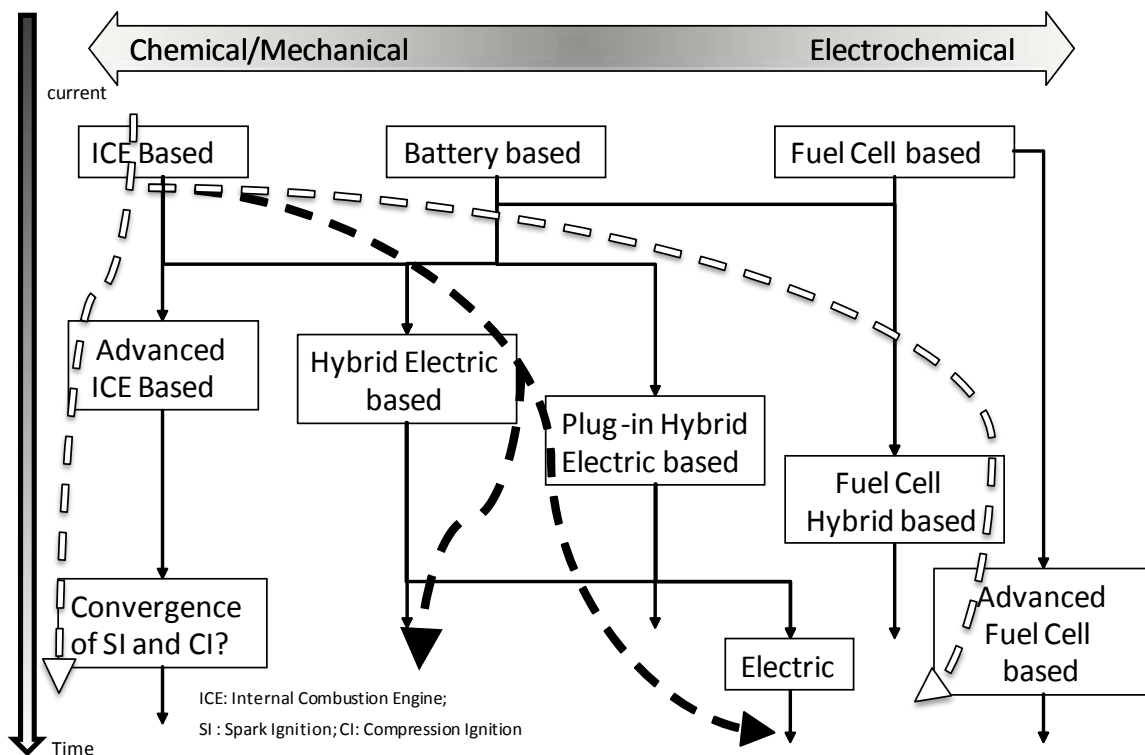


Figure 19. Possible Propulsion Technology Development Scenarios (31)

7.1 Barriers to entry

Several barriers to market penetration of new technologies were discussed in the “On the Road to 2035” report (31). Among HEV and PHEV technologies, battery price is recognized (34) to be the primary barrier to penetration. Barriers related to battery technology are discussed

in more detail below. Other challenges include lack of economies of scale and consumer attitudes.

Batteries represent the main contribution to the higher initial cost of the PHEVs. The premium is estimated to be around 35% compared to conventional ICE technology. Other additional cost drivers are power electronics and propulsion electric motors. HEVs carry lower cost premium than PHEVs since they require fewer batteries. Some of the initial cost can be recouped by savings in fuel consumption over lifetime of the vehicle. However, consumers tend to perceive a high discount rate and limited payback period compared to life of the vehicle.

Range anxiety has been previously identified as a significant barrier to battery electric vehicle adoption. HEVs and PHEVs can compensate for this limitation by carrying liquid fuels in addition to charged batteries. However, this strategy increases vehicle weight and thus reduces efficiency.

Batteries also introduce several safety concerns. These include high voltage which can potentially cause an electrocution during a vehicle accident. An impact can also cause a short circuit resulting in a thermal runaway, which is also possible without an accident. Automotive batteries are required to function in a much larger range of temperatures than consumer electronic batteries, and extremes of the temperature range may cause unforeseen stresses on the battery subsystem. Development of safer batteries is an area of active research.

Consumer attitudes represent a paramount factor in the minds of automotive industry executives considering introduction of HEV and PHEV vehicle lines. Until as recently as 5-6 years ago, hybrid vehicle technology was virtually unknown to the general public. Consumer awareness and adoption of hybrid technologies has grown immensely in recent years, but it is yet

unclear if the surge in popularity will be sustained in a very long term, making it difficult to design a long-term strategy for vehicle manufacturers.

7.2 Hybrid Wedge

We have made a set of aggressive technology and market assumptions to illustrate the effects of significant adoption of HEV and PHEV technologies. In particular, we assume that the battery technology will make sufficient progress in order to resolve previously identified challenges. Several battery technologies such as Lithium Iron Phosphate and Lithium Manganese Spinel show significant promise in safety and temperature range stability. These batteries, coupled with advanced controls, perform well in crash and puncture tests. Battery costs are sensitive to volumes and are expected to go down as volumes increase. There is additional cost mitigation, at least in the early deployment phase, due to government subsidies targeted specifically at the automotive batteries.

We also project that consumer focus on fuel economy will persist over the next decade and beyond. Over the past few years we witnessed an increased public concern about greenhouse gas emissions and carbon footprint of transportation. A recent oil leak off the shores of Louisiana has heightened public awareness of the environmental dangers of oil-derived fuels.

Previous work performed at Future of Transportation Group at Sloan Automotive Laboratory addressed hybrid strong scenario in “On the Road to 2035” (31), Chapter 7.3.3. Our work expands on the previous effort by further exploring the similarities and differences between HEVs and PHEVs (Figure 20). As HEV and PHEV technologies are closely related, they are considered a single technology family. A transition from a mature HEV technology into PHEV technology is feasible by substitution or advances in propulsion subsystem without significant

change of system architecture (32). Consequently, we consider two scenarios: one in which HEV technology dominates and the other in which PHEV technology takes over.

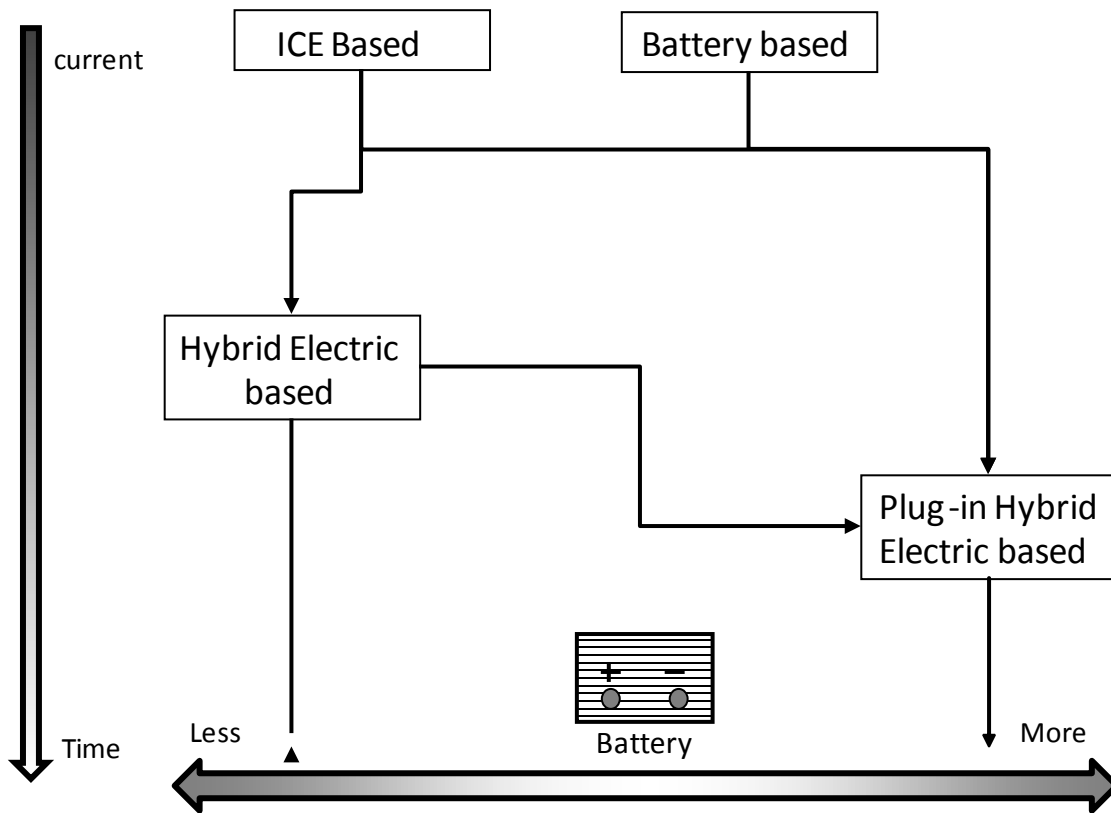


Figure 20. Possible Development of HEV and PHEV Technologies

Hybrid strong scenario in OTR2035 REF assumed continued growth of hybrid electric vehicle market share. PHEVs were treated as a niche product through 2050. Consistent with this scenario, we consider a future dominated by HEVs, subsequently referred to as “HEV scenario”. PHEVs remain a marginal product with a modest market share. The most important distinction from the previous work consists of taking into account the stringent fuel economy standards recently adopted by the federal government. The fuel economy standards are projected to become even more stringent through 2035. Previous study [REF] did not show significant greenhouse gas emission reduction from changes in vehicle fleet. Our current work aims to

investigate whether a set of reasonable, but aggressive assumptions about hybrid technology development and adoption would result in a prediction of significant reduction of greenhouse gas emissions. Thus the key distinction of our HEV scenario from Bandivadekar's Hybrid strong scenario is a much faster adoption rate that starts at 19% per year for the next 10 years compared to 8-11% in Hybrid strong scenario. The adoption rate slows down to about 5-6% per year beyond 2020 as the technology gains mass market adoption.

Our second scenario focuses on the PHEV technology path. We will refer to it as "PHEV scenario". It starts out in a similar fashion to HEV scenario in that hybrids continue to experience strong growth observed between 2000 and 2010. However, further into PHEV scenario plug-in hybrids overtake HEVs and PHEV's market share grows at a much higher rate. Had PHEV technology been considered an independent technology, this high adoption rate would have been an unlikely development. In our scenario, PHEVs simply replace HEVs as the next stage of hybrid electric powertrain evolution, and PHEV market share grows as HEV market share shrinks. Furthermore, we constrain the sum of PHEV and HEV market shares in both scenarios to manufacturer's supply chain constraints, such as the highest possible rate of growth of battery manufacturing capacity. This phenomenon is referred to as Hybrid Wedge (Figure 21). The growth of the market share should be kept in perspective of the total LDV sales growth of 0.8% annually.

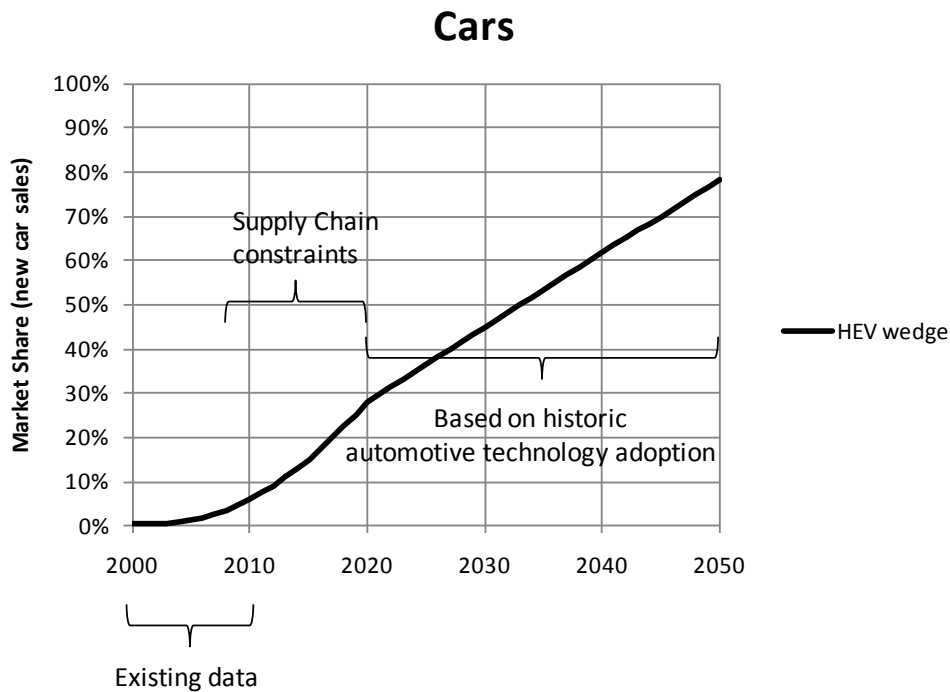


Figure 21. Hybrid Wedge in HEV and PHEV scenarios: a HEV+PHEV Market Share of New Passenger Car Sales

7.3 Similarities and Differences between HEV and PHEV Scenarios

In both HEV and PHEV scenarios, the hybrid electric powertrain is considered an important contributing factor to lower fuel consumption and lower greenhouse gas emissions. In the HEV scenario the only energy source for hybrids is liquid fuel. Given potential constraints in price and availability of gasoline in the next several decades, this scenario is more likely if carbon-neutral biofuels are developed and become widely available in the near future. As such, this scenario is matched with the Extended RFS scenario described in Chapter 6.

Conversely, the PHEV scenario is more likely if electricity becomes a preferred energy carrier due to its wide availability and attractive price thanks to the highly diversified set of primary energy sources for the electricity generation. Geopolitical considerations driving a

desire for greater independence from foreign oil markets are also favorable for this scenario. The battery prices are expected to be much lower than today as well as lower than battery prices in the HEV scenario. A target of \$200/kWh is assumed to have been achieved (35).

Stringent controls on CO₂ emissions recently introduced by EPA (36) will likely favor advanced technologies relevant to both HEVs and PHEVs. CO₂ tax and/or cap and trade regulations may achieve a similar effect. However, details of implementation of the CO₂ regulations might have a varying impact on the balance and attractiveness of HEV versus PHEV scenarios. Given that electricity generation sector is a separate large independent industry, the policies for transportation might not be coordinated with those for electricity generation. For example, current EIA regulations for vehicles do not include upstream emissions from the electricity generation.

Currently, CO₂ and other emissions from the electricity generation are capped in multiple states (37). These constraints consequently limit the total amount of electricity produced, thus making electricity generation for PHEV unfavorable from the electricity generation viewpoint disregarding the total system benefit of charging vehicles from the grid. As such, constraints such as these favor the HEV scenario.

Alternatively, the CO₂ limits from the tailpipe favor PHEV scenario since a PHEV produces no local emissions when powered by electricity. Whether the emissions for the associated electricity generation would be counted in the transportation sector or the electricity sector emissions, is unclear at this time due to challenges in accurately apportioning the emissions and the potential risk of double-counting.

A similar effect may be caused by CO₂ tax imposed on the liquid fuels. The electricity usage by PHEV might be difficult to account for due to their ability to charge from conventional

electric outlets. In addition, the CO₂ footprint of such electricity is region- and time-of-day dependent.

Lastly, fuel taxes are imposed solely on the liquid fuels today. Given the significance of fuel taxes for the development and maintenance of the transportation infrastructure, a substantial decrease in use of liquid fuels will negatively affect this source of revenue. Thus there may be a desire to tax electric vehicles for the purposes of recouping this shortfall (38). The details of the implementation (or lack thereof) of a fuel tax on electricity may favor either HEV or PHEV scenarios respectively.

7.4 HEV Scenario

As described previously, the HEV scenario is characterized by a rapid growth of hybrid-electric powertrain without an ability to recharge from the grid. PHEVs gain only a small share of the market. Our results are markedly similar for cars and light trucks (Figure 22), especially beyond 2015. Figure 23 shows our results in a context of earlier studies.

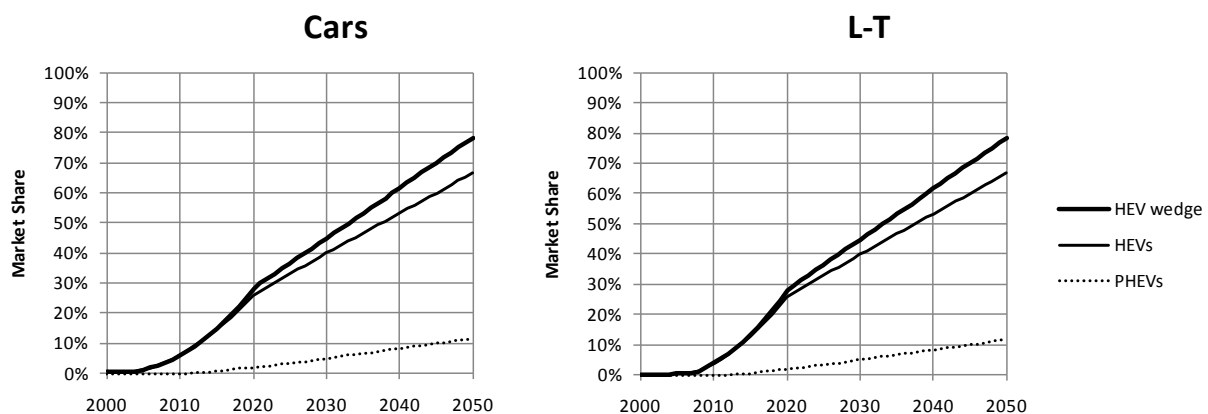


Figure 22. HEV and PHEV New Vehicle Market Share within Passenger Cars and Light Trucks in the HEV Scenario

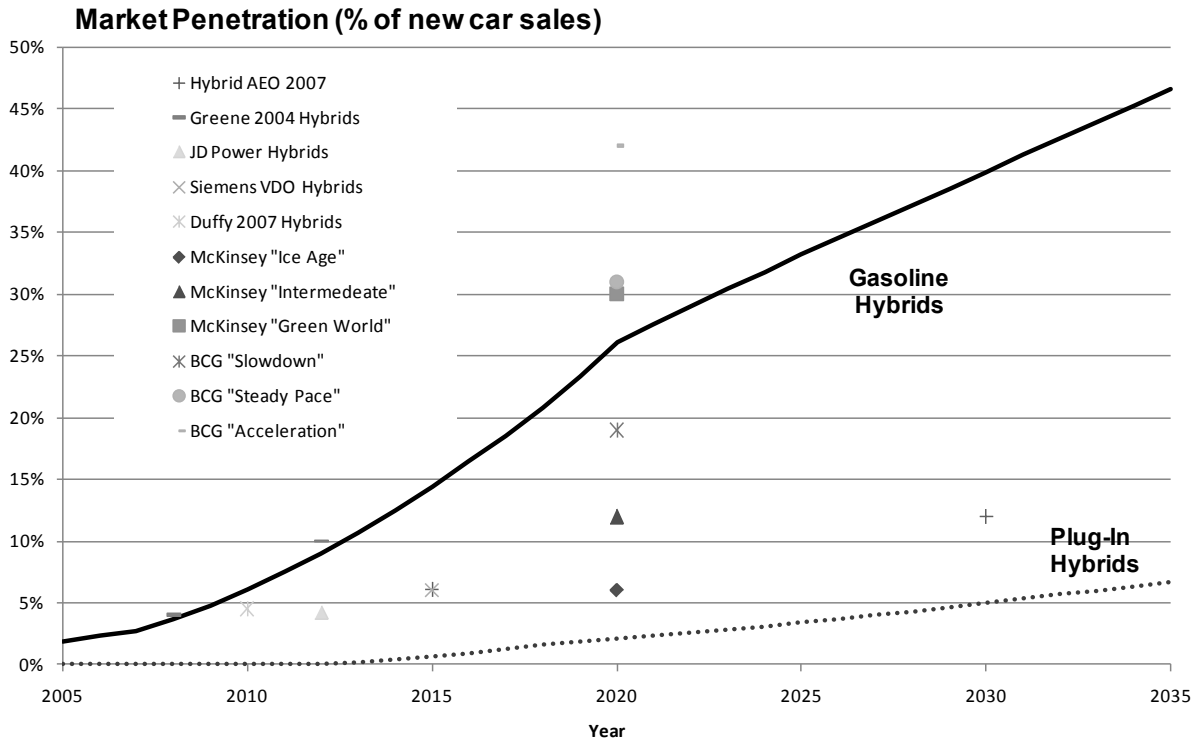


Figure 23. Various Forecasts of U.S. Light-Duty Vehicle Hybrid Market Penetration

7.5 PHEV Scenario

PHEV scenario is similar to HEV scenario between 2000 and 2015 because hybrid technology has been already on the market and PHEV technology is just being introduced to the market in 2010. Although PHEV new vehicle sales grow rapidly between 2010 and 2020, there are still more HEVs than PHEVs sold during this time period. Beyond 2022 PHEV sales continue their rapid growth while HEV sales wane in part because PHEV sales are cannibalizing HEV sales (Figure 24). That is, after 2022, consumers find it more attractive for a vehicle with an electric powertrain to have an ability to charge from the electric grid. Due to this trend, HEVs are relegated to niche markets in the later decades of the 21st century. Examples of such markets

can include vehicles with a high daily mileage, e.g. taxis, or consumers who have no access to electric plugs, e.g. residents of dense urban areas with on-street parking.

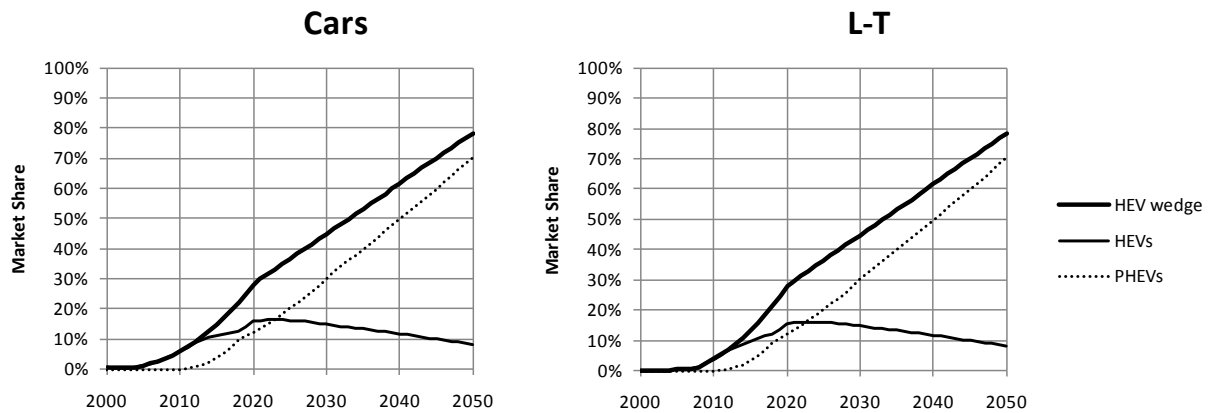


Figure 24. HEV and PHEV Market Share within Passenger Cars and Light Trucks in the PHEV

Scenario

An interesting observation can be made by comparing new vehicle share to fleet share of PHEVs (Figure 25). As discussed in “On the Road in 2035” (31), there is a 15 year delay in adoption of new technologies in the fleet due to vehicle lifetime turnover cycle. This effect is especially significant for plug-in hybrids which are only being introduced to the market this year, in 2010.

Figure 25 illustrates this behavior for passenger cars with (a) showing vehicles in the fleet vs total number of PHEVs, and (b) comparison between the new vehicle share and fleet share. Even though PHEVs constitute 70% of the new vehicles sold in 2050, the total U.S. passenger car fleet comprises slightly over 50% PHEVs in addition to HEVs and advanced conventional ICE vehicles. Sales of light trucks follow a similar trend. The important thresholds are 10 million PHEVs are on the road in 2020, 50 million in 2031 and 100 million in 2039, including passenger cars and light trucks (Figure 25c).

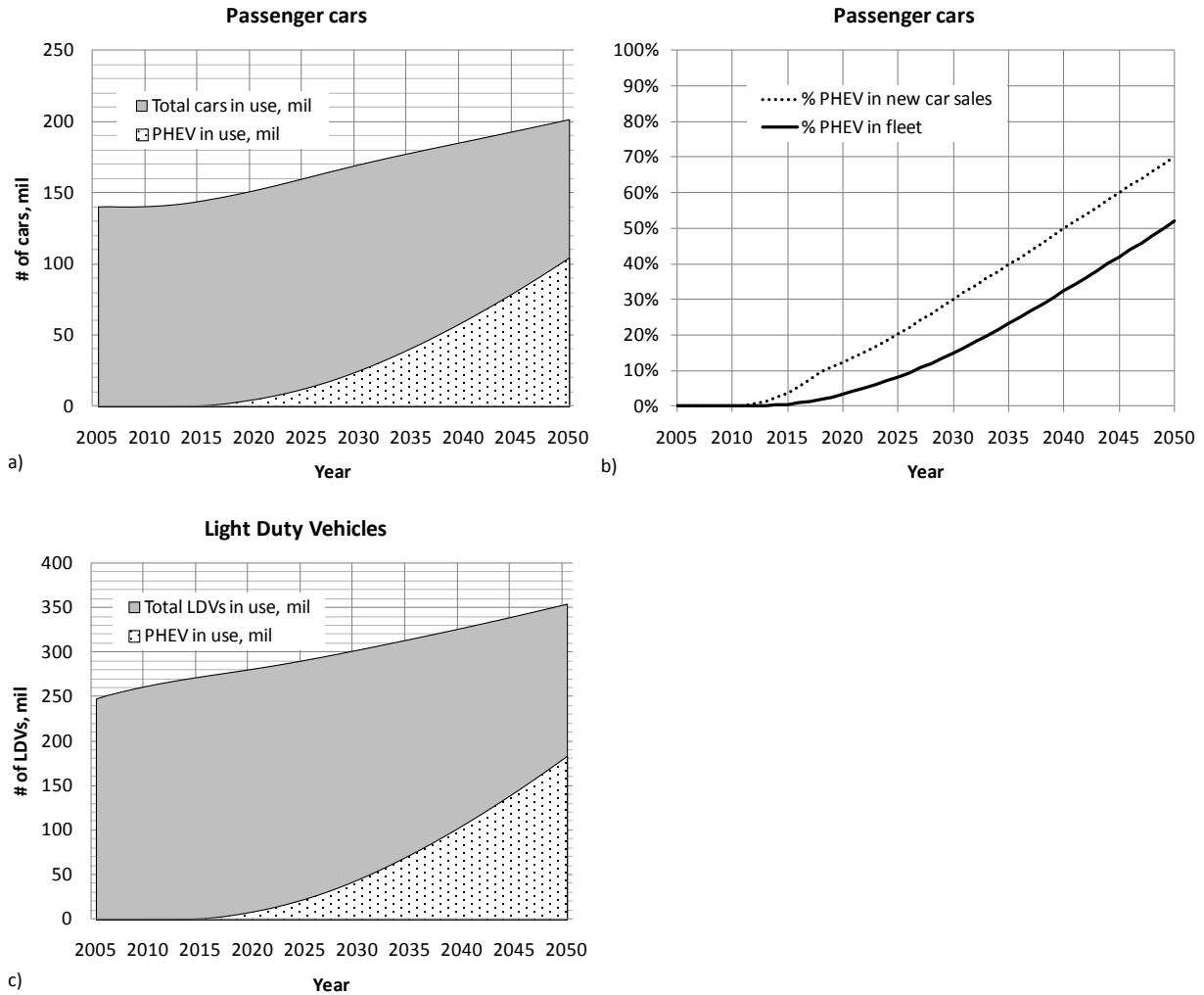


Figure 25. Delay in Fleet Adoption vs New Vehicle Sales Market Share

In addition, we observe that PHEVs reach the mass market penetration as defined by reaching 15%, or early majority, of the total LDV market in 2031 (39). Prior to this date, the purchasers of PHEVs are classified by Rogers as innovators and early adopters. The year 2031 is particularly significant for this study as our assumption for the infrastructure readiness coincides with the mass market adoption of plug-in vehicles. Therefore, we will postulate that opportunity charging of PHEVs becomes available starting in 2031. Note that opportunity

charging is available only in the PHEV scenario and is not available in the HEV scenario since PHEVs never reach the 15% fleet share or even 15% new vehicle share.

7.6 Conventional and Advanced Conventional Technologies

The internal combustion engine technology is expected to continue being improved with incremental innovations during the following decades. The majority of the vehicles sold today are powered by the naturally aspirated spark-ignition engines (NASI). A significant enhancement in the engine technology over the past decade has been the gasoline direct injection (GDI), introduced in mass-market LDVs in 1996 (40). Another important technology innovation is turbo-charging, discussed in details in “On the Road to 2035” report (31), as one of the potential dominating technology scenarios. Recently, these two technology innovations have been combined, and the result is reported to be achieving superior fuel economy while also reaching better performance. An example of this technology on the LDV market is Ford Ecoboost engine (41). We will refer to these enhancements as “advanced conventional engines”. There are potentially other enhancements to the internal combustion engine technology in the upcoming decades, such as compression ignition, which may be powered by either diesel or gasoline. These technologies are not considered separately and are lumped in the “advanced conventional designs” in this study. Such simplifying assumption lets us focus on the HEV and PHEV technology options while still considering the effects of the technology improvements to the incumbent.

We observe that the rate of technology adoption in the next decade is largely impacted by the fuel economy regulations. Having considered the rapid growth of the HEV wedge, we observe that HEVs market share alone is not sufficient to reach the fuel economy goals between 2010 and

2020. As a result, the conventional technology must also be improved rapidly in this time frame; in fact, the advanced conventional technology adoption is expected to provide the greatest benefits. We calculated the resulting market share of the ICE wedge, which demonstrates an unprecedented rapid growth of the advanced conventional share (Figure 26) through 2020. Such rapid growth can be substantiated by the automaker announcements for the very aggressive adoption of such technology, such as Ford announcement of significant expansion of the EcoBoost engines integration in the vehicle models as well as the growth of the advanced engine manufacturing volumes (42). In the following decades, we expect the rate of advanced conventional adoption to slow, since, in our model, the previous growth is solely driven by the regulations.

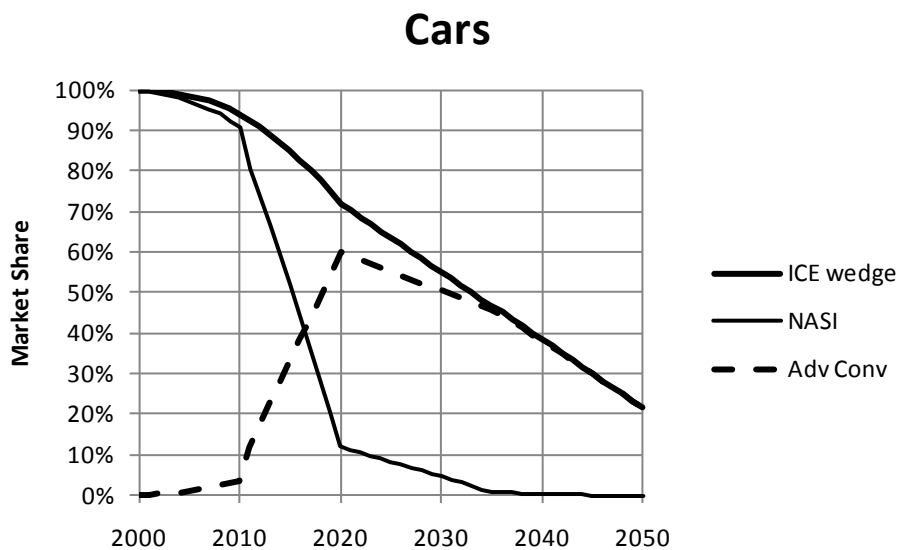


Figure 26. Conventional (NASI) and Advanced Conventional ICE New Vehicle Market Share within Passenger Cars

7.7 2020 Milestone

In the HEV scenario the hybrids continue to gain new vehicle market share and reach 25% of the new vehicles sold across by cars and light truck markets (Figure 27). The average new vehicle fuel economy is 39.2 mpg.

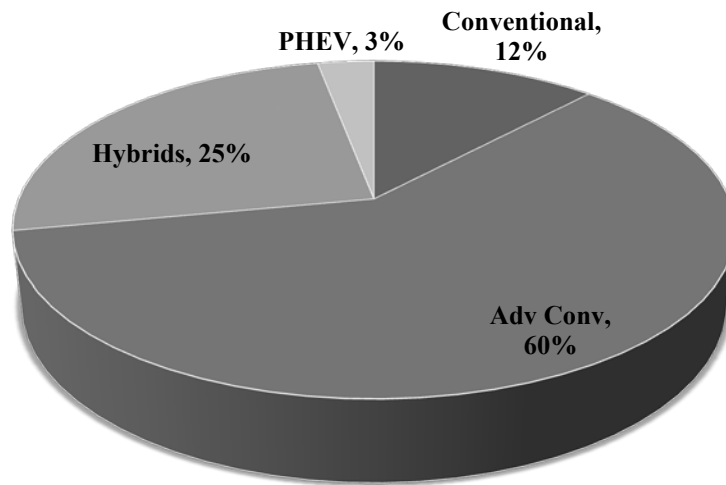


Figure 27. New Market Share in the HEV Scenario in 2020

In the PHEV scenario the immaturity of the PHEV technology limits the number of vehicles sold to 12% of the new vehicles (Figure 28). It is very important to note that, at this milestone, there are more HEVs sold than PHEVs even in the PHEV scenario. The average new vehicle fuel economy is 41.0 mpg.

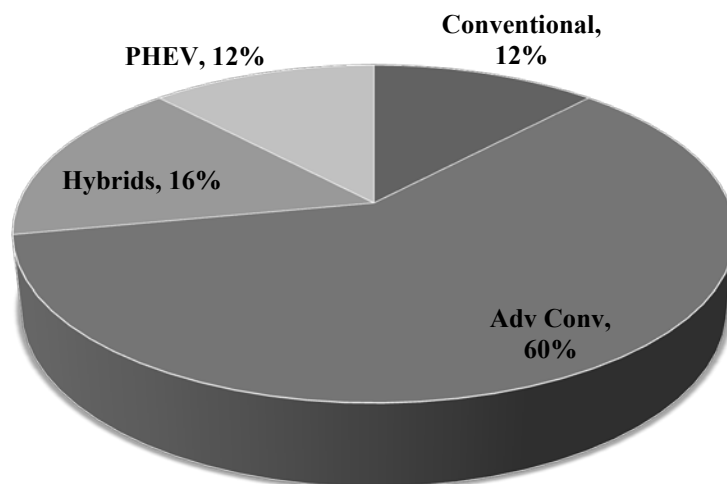


Figure 28. New Market Share in the PHEV Scenario in 2020

7.8 2035 Milestone

In the HEV scenario the hybrids continue to gain new vehicle market share and reach 47% of the new vehicles sold across by cars and light truck markets (Figure 29). The average new vehicle fuel economy is 53.9 mpg.

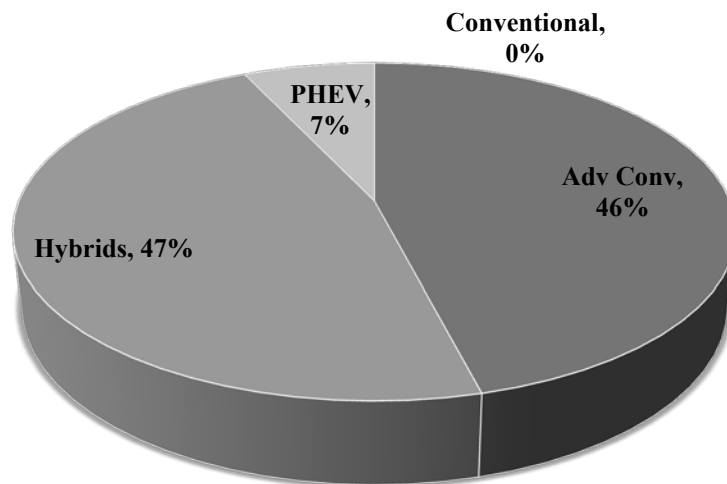


Figure 29. New Market Share in the HEV Scenario in 2035

At this point, PHEV technology matures and the new vehicle market share reaches 40% for PHEVs (Figure 30). The share of HEVs shrinks to 13%. The average new vehicle fuel economy is 60.1 mpg.

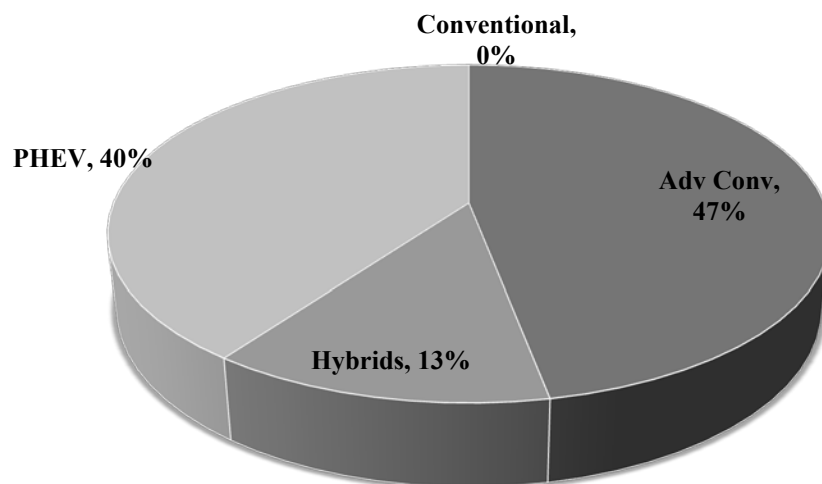


Figure 30. New Market Share in the PHEV Scenario in 2035

7.9 2050 Milestone

In their respective scenarios HEVs and PHEVs continue to grow their new vehicle market share and establish themselves as dominant designs. It is important to observe that ERFC is assumed to be zero leading up to this milestone. That is, the fuel consumption of an individual vehicle type remains unchanged. The new vehicle average fuel economy improvements are achieved only due to a growing share of more efficient vehicles.

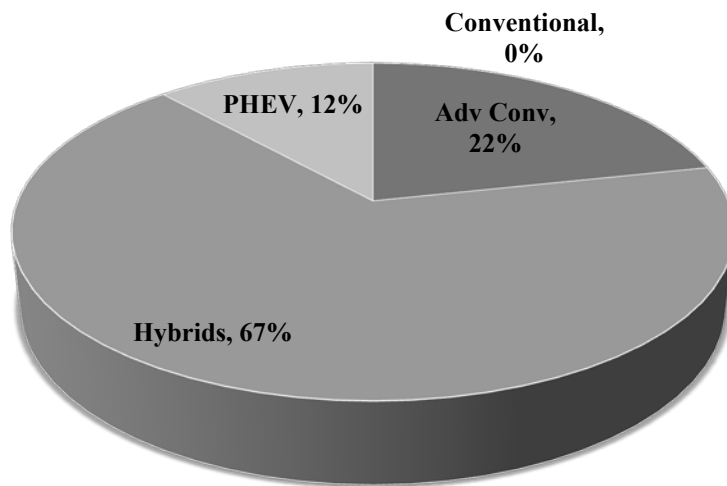


Figure 31. New Market Share in the HEV Scenario in 2050

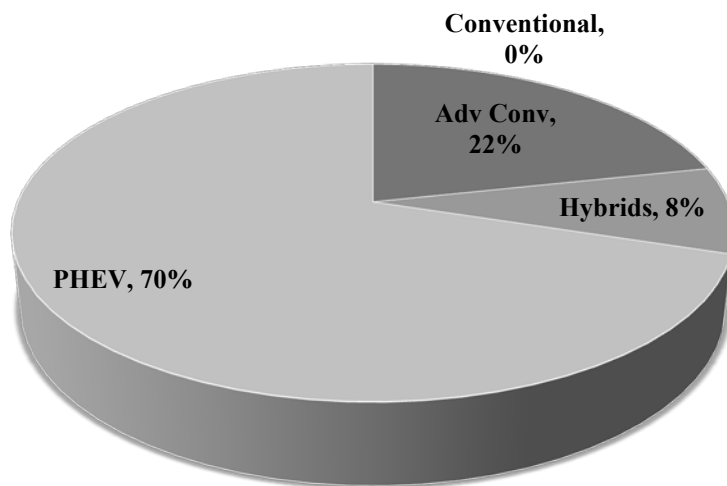


Figure 32. New Market Share in the PHEV Scenario in 2050

8 Results

8.1 Impact of automotive technology

As a baseline case, we will examine the case when the only technology change available is rapid sales growth of vehicles with a hybrid electric powertrain. Without advanced biofuels, the only biofuel included is corn ethanol, as described in the “Baseline” scenario of Chapter 6.

Opportunity charging is assumed to be unavailable in this section.

Fuel use, measured in liters of gasoline equivalent, or essentially in-tank energy content, is reduced significantly from fuel use in 2009 (Figure 33). In fact, the HEV scenario demonstrates a decrease of fuel consumption close to 1990 levels, and the PHEV scenario outperforms the HEV scenario. The main reason is that a PHEV consume electricity in addition to a liquid fuel, thus reducing the total fuel consumption. For this calculation, the electricity energy content is also counted, but it is relatively small due to very high efficiency of the electric powertrain. Nevertheless, if electricity is not counted, the liquid fuel consumption is further reduced by approximately 10% (Figure 33b).

The significant reduction in the fuel consumption between 2010 and 2035 is best explained by the technology change which is forced by the new fuel economy required for 2016 and projected for 2020 and 2035. In fact, the greatest impact between 2010 and 2020 is achieved by the rapid growth of the Advanced Conventional powertrains, rather than Hybrid Electric powertrains. This fact is evident by observing the similarities in results between the HEV and PHEV scenarios. The scenarios diverge beyond 2035 which is justified by the sufficient fleet share of the vehicles with electric powertrain.

On the other side, the significant number of vehicles of advanced conventional vehicles which can consume only liquid fuels and are relatively inefficient compared to HEVs and PHEVs result in fairly significant liquid fuel use between 2035 in 2050. These are the vehicles, sold in 2030s and still in use in 2040s, that consume a large share of the gasoline and other liquid fuels during the last decade of our analysis.

It is important to note that liquid fuel use in the PHEV scenario continues to downward trend beyond 2050 as electricity continues to displace liquid fuels. On the opposite, the HEV scenario demonstrates a rising trend in the liquid fuel use beyond 2050 due to continued increase of the U.S. LDV fleet and the continued growth in the vehicle mileage.

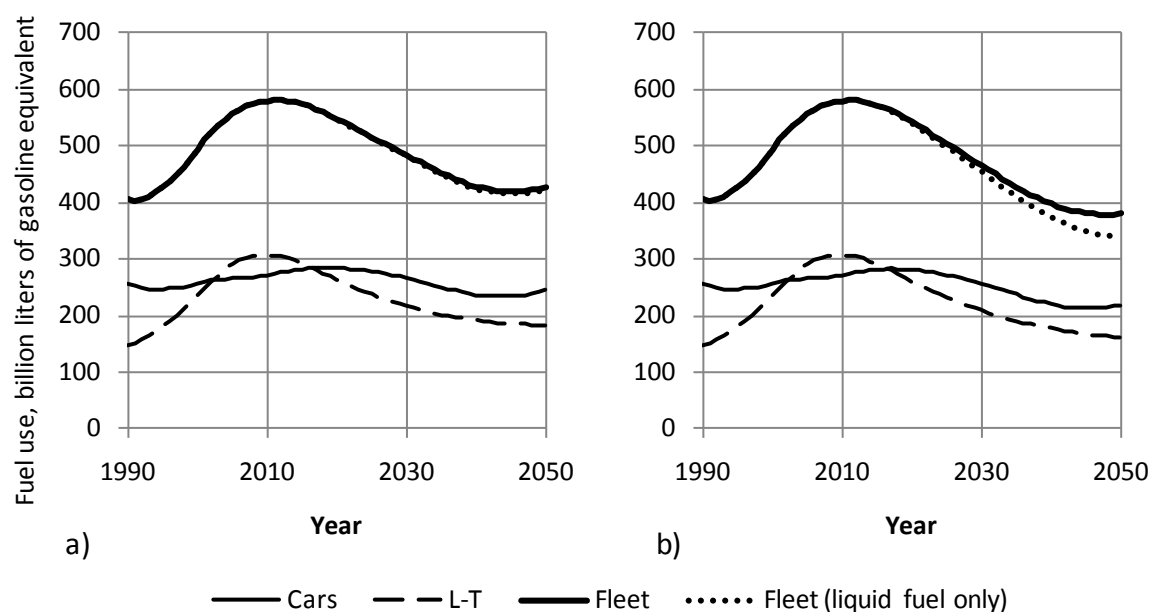


Figure 33. U.S. LDV Fleet Fuel Use Enabled by Automotive Technology Improvements in (a) HEV and (b) PHEV Scenarios

One may also observe that the results significantly differ from the “No change” or “Hybrid Strong” scenarios in the “On the Road to 2035” report (31). The primary cause of the difference of the results in this section to the report results is the assumption of the stringent fuel economy requirements imposed on the new vehicle sales between 2010 and 2035. Therefore, we conclude that the fuel economy standards are an effective tool in reducing fuel consumption and GHG emissions (Figure 34) of LDV fleet in the United States.

Other factors such as advanced biofuels and opportunity charging will be considered in the following sections.

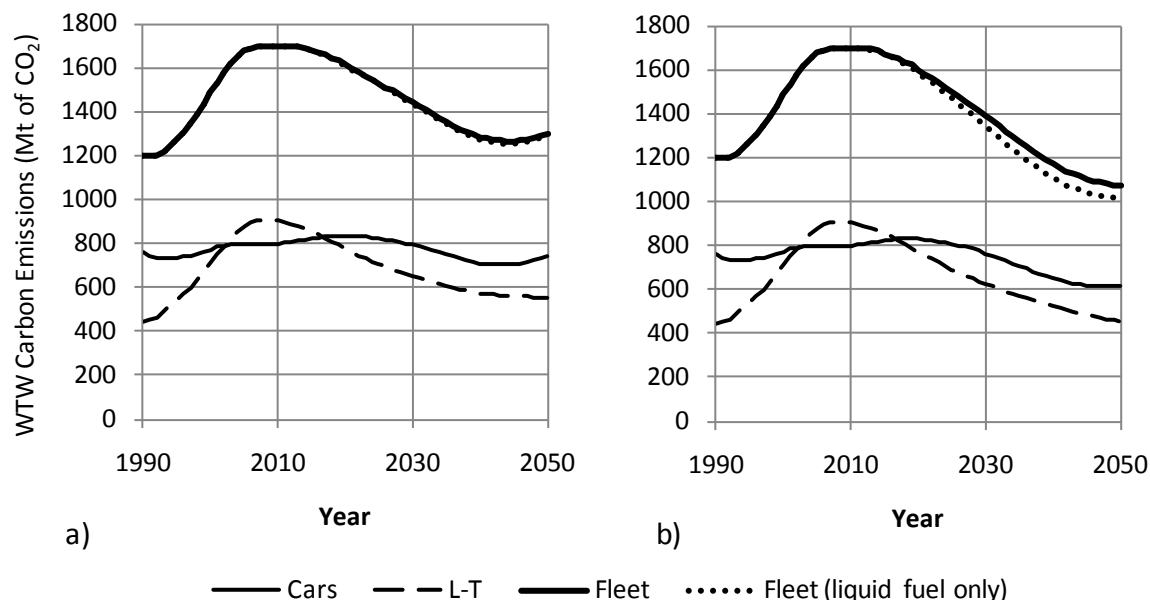


Figure 34. U.S. LDV Fleet GHG emissions under (a) HEV and (b) PHEV Scenarios Limited to Automotive Technology Improvements

8.2 Automotive technology and Recharging Infrastructure

In this scenario, we examine the effect of the electric grid infrastructure improvements that enable opportunity charging in the PHEV scenario. HEV scenario results remain unchanged

from Section 8.1 and are included only for comparison. Since there are 50 million PHEVs on the road in 2031, at least 100 million electric plugs are required to charge a vehicle twice a day, assuming charging at home and charging at work. While these plugs are expected to carry a significant cost, the gradual introduction of the PHEV would enable a gradual rollout. The higher price of the fast charging outlets further increases the associated cost of the infrastructure.

PHEV fuel use is reduced by 49% by allowing opportunity charging. The total fuel use is reduced by 15% in 2050 compared to the previous section (Figure 35). This is a very significant reduction in fuel consumption, thus, the infrastructure change is well justified. In fact, the annual liquid fuel consumption in the PHEV scenario at 292 billion liters is lower than gasoline use in 1990 at 407 billion liters and in 2000 at 503 billion liters. This result is particularly impressive given the sustained growth of the number of vehicles. Nevertheless, the less efficient advanced conventional vehicles that comprise 46% of 2035 new vehicle sales are still on the road in the 2040s and, therefore, consume a significant amount of gasoline and other liquid fuels.

In the PHEV scenario, the automotive technology changes coupled with the recharging infrastructure growth reduce well-to-wheels GHG emissions from the LDV transportation by 21% between 1990 and 2050 (Figure 36). We observe that this value remains far below the policy stated goal of 80% reduction (43). We remind the reader that the electric generation sector is assumed to have achieved 80% reduction in the GHG emissions with mechanisms not related to transportation (26).

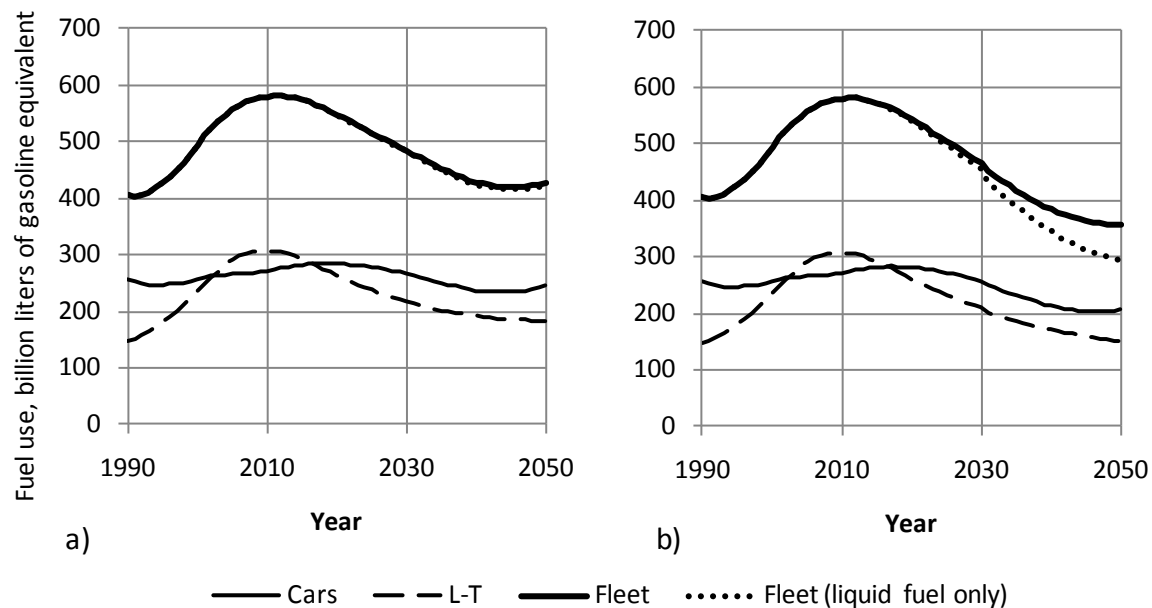


Figure 35. U.S. LDV Fleet Fuel Use Enabled by Automotive Technology and Infrastructure Improvements in (a) HEV and (b) PHEV Scenarios

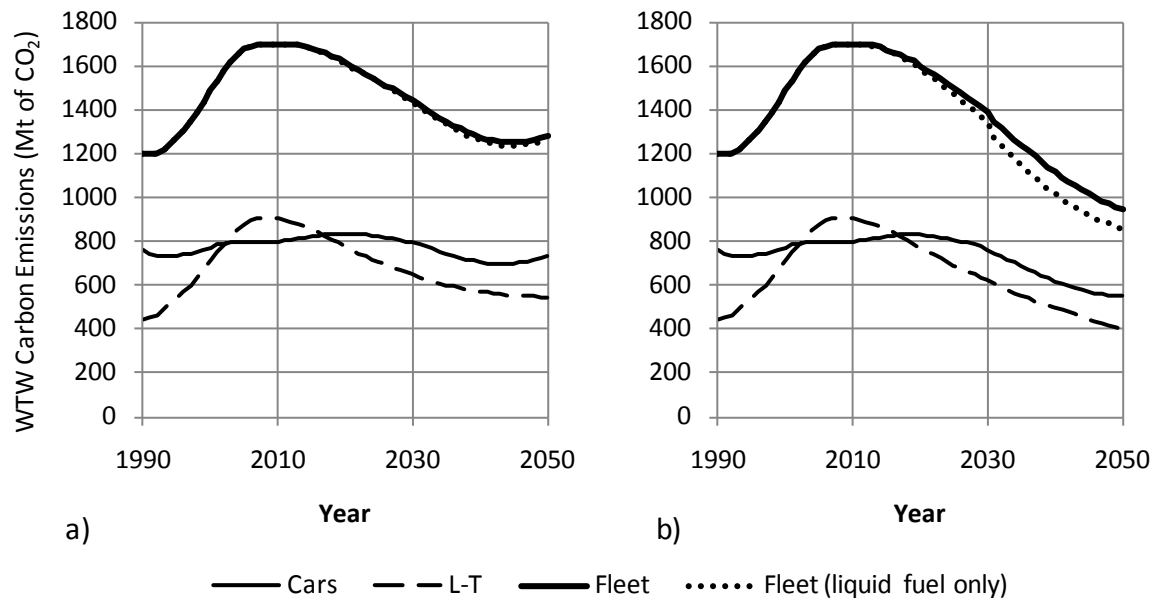


Figure 36. U.S. LDV Fleet GHG emissions under (a) HEV and (b) PHEV Scenarios Limited to Automotive Technology and Infrastructure Improvements

8.3 Automotive Technology and Advanced Biofuels

In this scenario, we examine contributions from advanced biofuels to the HEV and PHEV scenarios. Consistent with the previous assumptions, the HEV scenario is associated with greater low carbon liquid fuels available, and is therefore matched with the “Extended RFS” scenario of Chapter 6. The PHEV scenario is matched with the “Delayed RFS” as electricity becomes a preferred energy source in lieu of limited advanced biofuels. However, we do not consider opportunity charging in this section; therefore, the PHEV scenario results are provided only for comparison with those of the HEV scenario.

Since the fuel use is measured in gasoline equivalent volume, the total fuel use in the HEV scenario is unchanged (Figure 37). However, the composition of the fuel is different, and the total fuel volume required is also different since ethanol’s energy density is only 70% of that of the gasoline. The difference is best illustrated by Figure 38 and Figure 39. In 2050, the fuel mix consists of 35% of biofuels and 62% of oil-based liquid fuels.

A significant growth in advanced biofuels reduces 2050 well-to-wheel GHG emissions to those below the 1990 levels by 21% (Figure 40a), which is the best result achievable in the HEV scenario within the assumption framework of this study. The effect of advanced biofuels, that is, the difference between Section 8.1 and these results is illustrated on Figure 41.

If the PHEV scenario is constrained to one-a-day (night) charging, it fails to outperform the HEV scenario (Figure 40b). The combination of recharging infrastructure and availability of advanced biofuels will be examined in the next section.

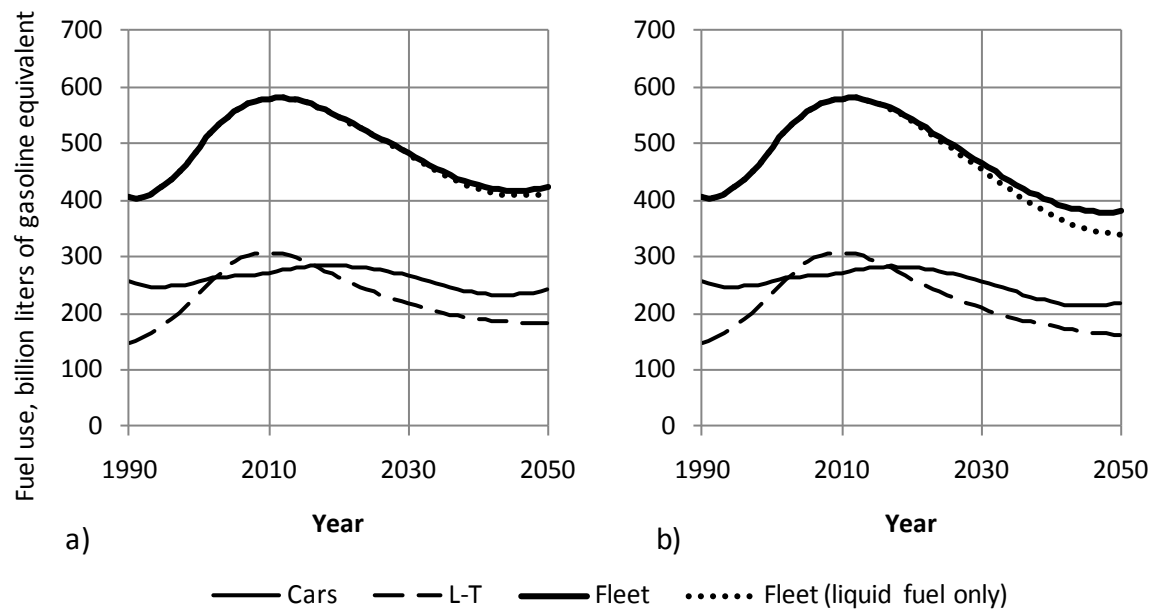


Figure 37. U.S. LDV Fleet Fuel Use Enabled by Automotive Technology Improvements and Advanced Biofuels in (a) HEV and (b) PHEV Scenarios

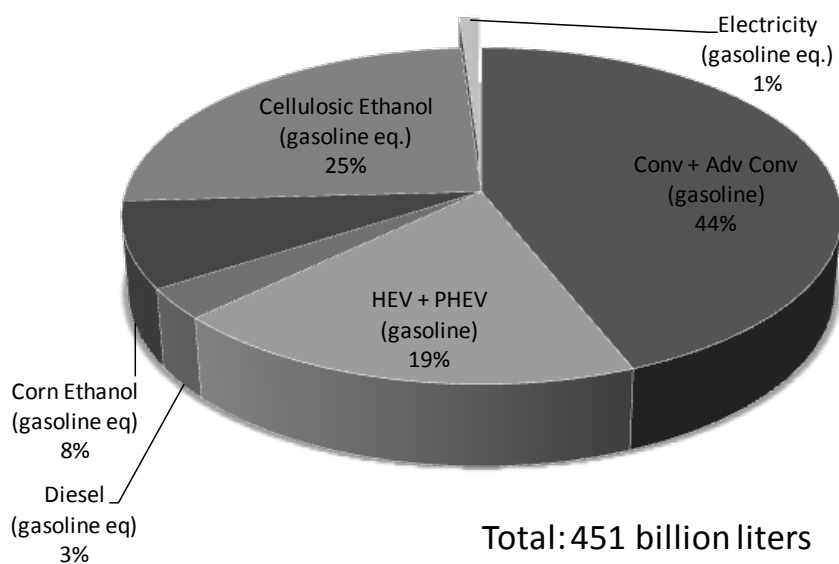


Figure 38. U.S. LDV Fleet Fuel Mix in the HEV Scenario in 2035

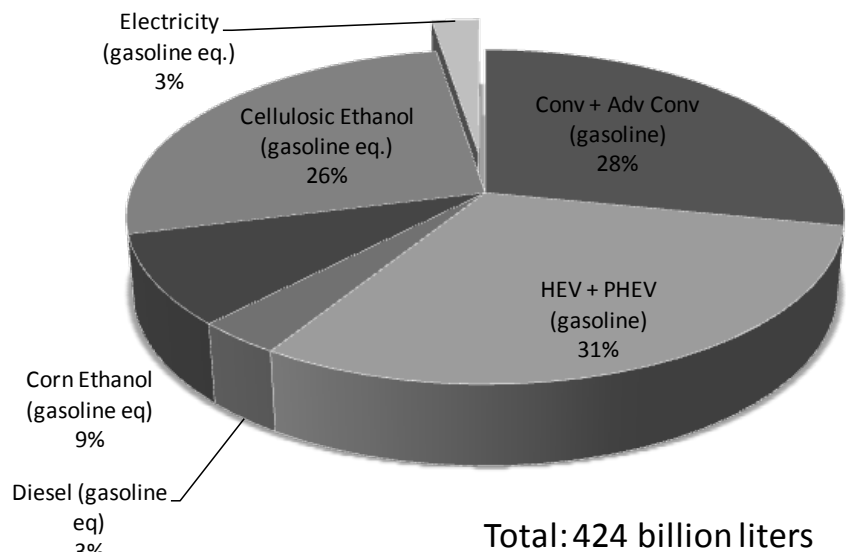


Figure 39. U.S. LDV Fleet Fuel Mix in the HEV Scenario in 2050

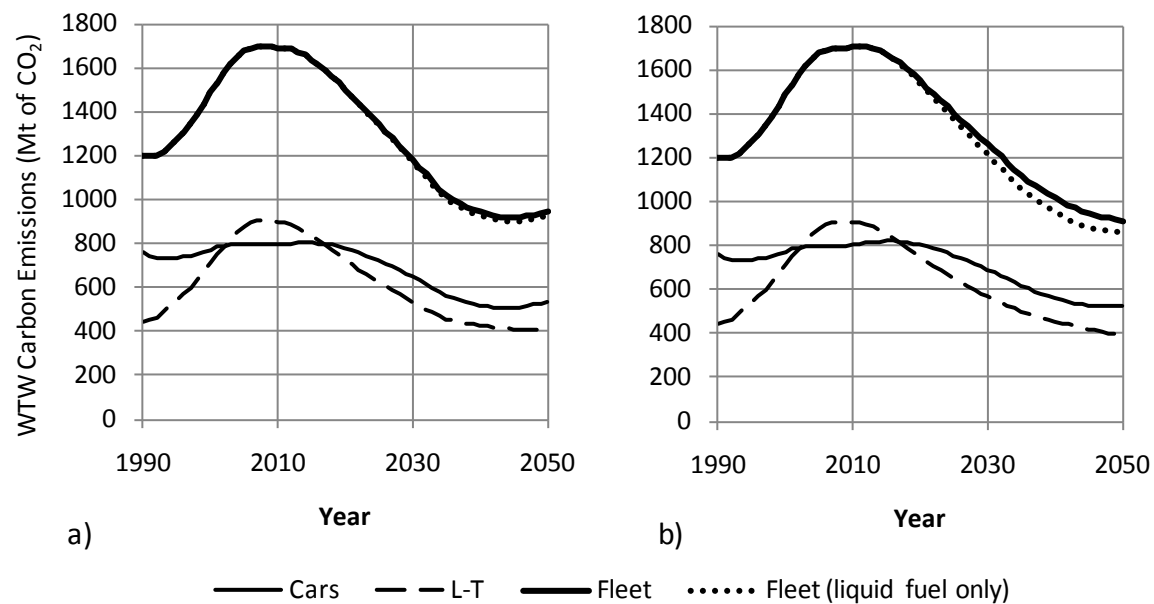


Figure 40. U.S. LDV Fleet GHG Annual Emissions under (a) HEV and (b) PHEV Scenarios Limited to Automotive Technology Improvements and Advanced Biofuels

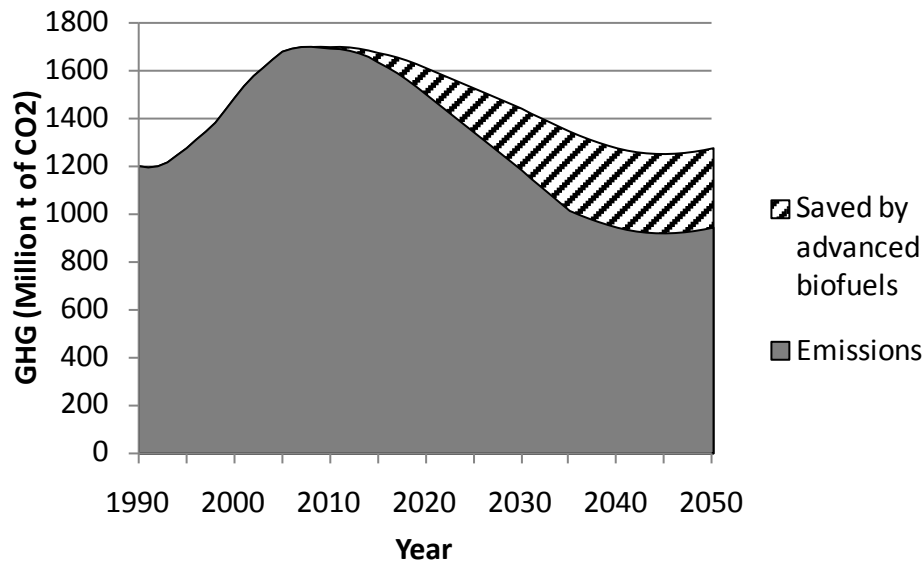


Figure 41. U.S. LDV Fleet GHG Annual Emissions Reduced by Advanced Biofuels in the HEV and “Extended RFS” Scenario

8.4 Automotive technology, Recharging Infrastructure and Advanced Biofuels

In this scenario, we examine contributions from advanced biofuels and opportunity charging in the PHEV scenarios. In order to provide a complete picture, we examine effects of both “Delayed RFS” and “Extended RFS” availability of advanced biofuels. One must keep in mind that costs of the PHEV Scenario and Extended RFS are likely much higher than those of other scenarios since the fuel supply chain, as well as fuel and electric grid infrastructures are being changed.

Fuel use measured as gasoline equivalent is identical in both scenarios. Only 292 billion liters is consumed in 2050, which is less than the 1990 or even the 1970 light duty vehicle consumption level. The fuel mix is different in these two scenarios, and the total fuel volume required is also different, as discussed in the previous section. The variation in the fuel mix in

2035 is shown on Figure 43 and in 2050 on Figure 44. In 2050, the more practical combination of the PHEV scenario and “Delayed RFS” biofuels demonstrates a fuel mix comprises 25% of biofuels, 18% of electricity and 57% of oil-based liquid fuels. The more challenging combination of the PHEV scenario and “Enhanced RFS” biofuels results in a fuel mix with 44% biofuels, 18% electricity and only 40% oil-derived fuels. Such change in energy sources for transportation would be dramatic and has not occurred since the inception of the auto industry in 1900s.

The associated reductions in the GHG emissions are very significant. The scenarios achieve reductions of 34% and 49% compared to 1990 emissions for “Delayed RFS” and “Extended RFS” correspondingly. Note that 80% reduction compared to 1990 has not been reached even in the most aggressive scenario.

Contribution by advanced biofuels, that is, the difference between Section 8.1 and these results is illustrated on Figure 46. A comparison between scenarios in this section and an HEV scenario in Section 8.3 is provided on Figure 47 (in 2035) and on Figure 48 (in 2050). The figures also compare the results to the liquid fuel use by the LDV fleet in 1990, 2000 and 2009.

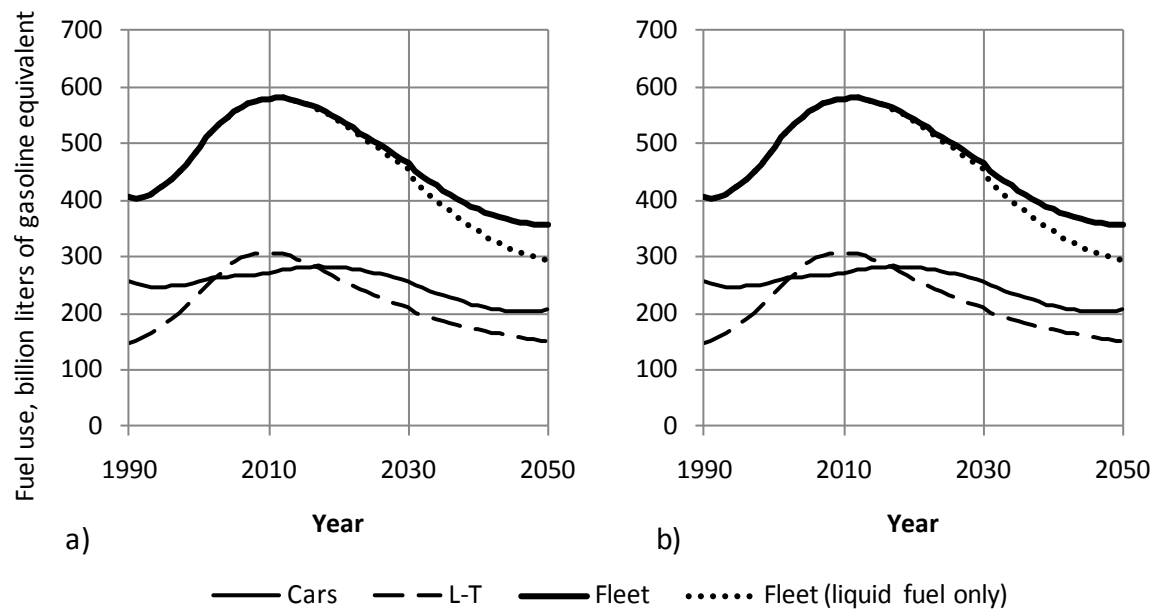
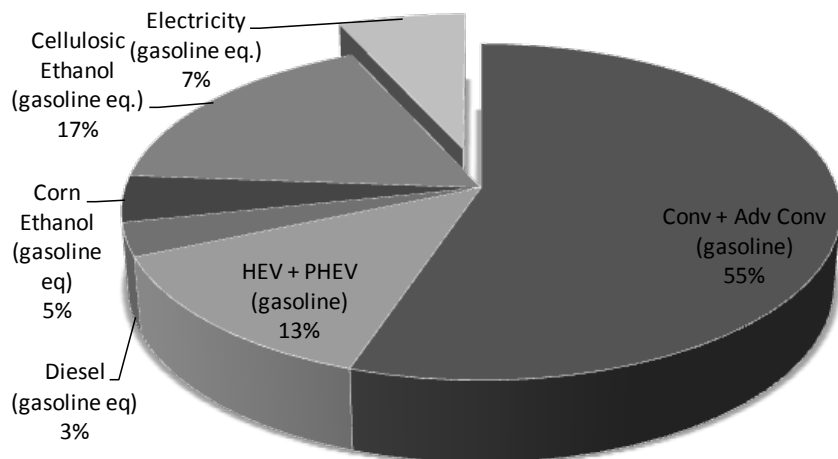
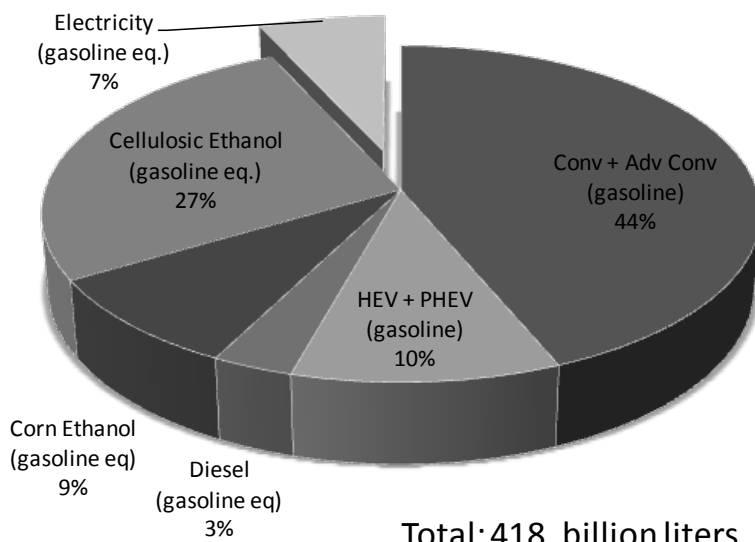


Figure 42. U.S. LDV Fleet Fuel Use Enabled by Automotive Technology Improvements and Recharging Infrastructure in PHEV Scenario with (a) “Delayed RFS” and (b) “Extended RFS” Availability of Advanced Biofuels



a)



b)

Figure 43. U.S. LDV Fleet Fuel Mix in the PHEV Scenario in 2035 for (a) "Delayed RFS" and (b) "Extended RFS" Availability of Advanced Biofuels

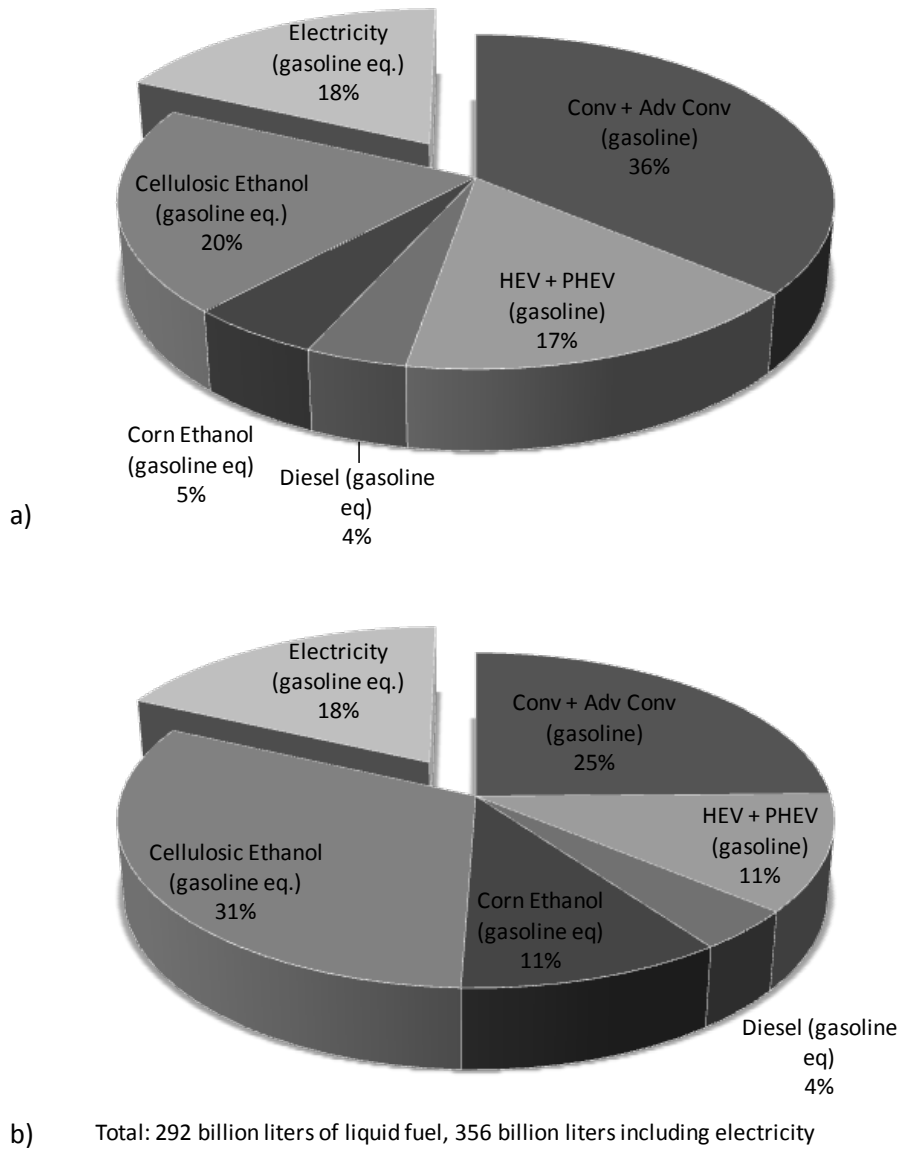


Figure 44. U.S. LDV Fleet Fuel Mix in the PHEV Scenario in 2050 for (a) "Delayed RFS" and (b) "Extended RFS" Availability of Advanced Biofuels

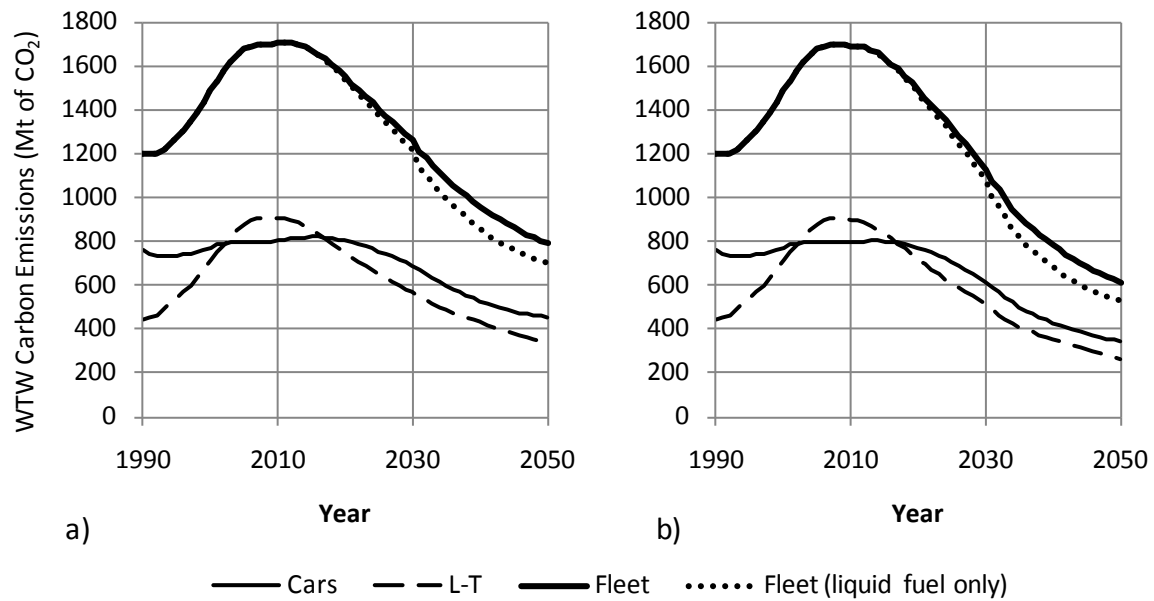


Figure 45. U.S. LDV Fleet GHG Annual Emissions under PHEV Scenarios with Automotive Technology and Recharging Infrastructure Improvements under (a) “Delayed RFS” and (b) “Extended RFS” Availability of Advanced Biofuels

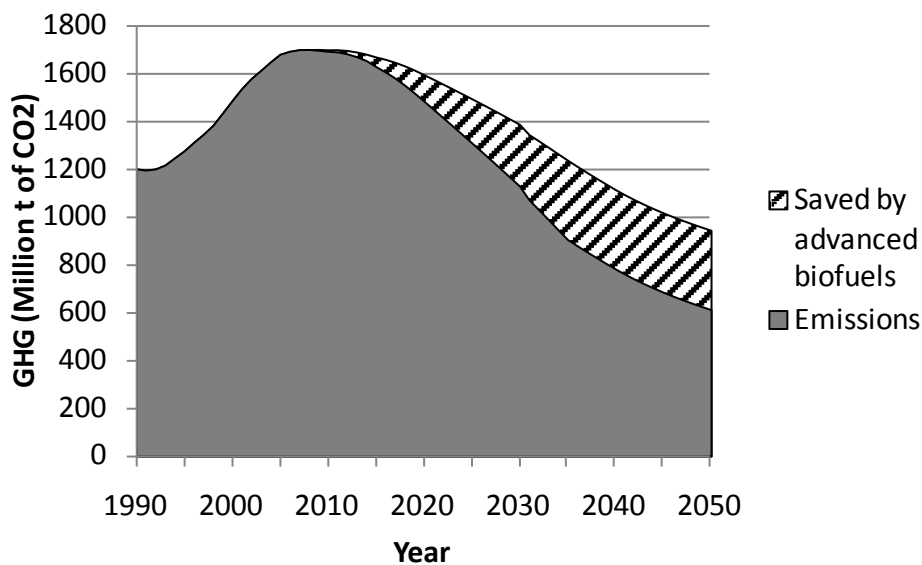


Figure 46. U.S. LDV Fleet GHG Annual Emissions Reduced by Advanced Biofuels in the PHEV and “Extended RFS” Scenario

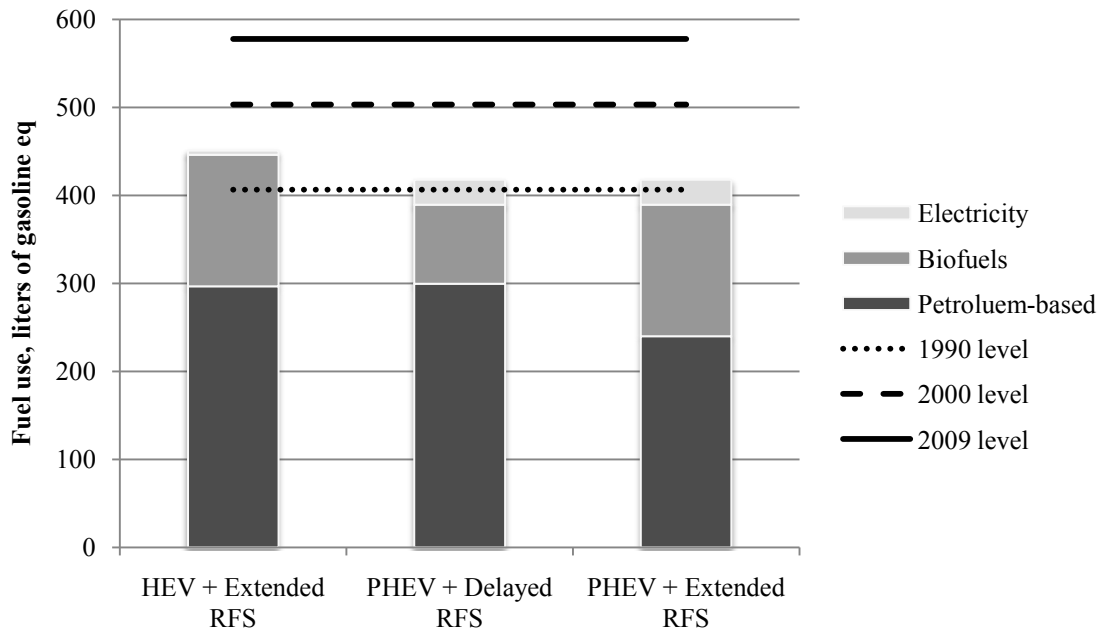


Figure 47. Comparison of U.S. LDV Fleet Fuel Utilization in 2035

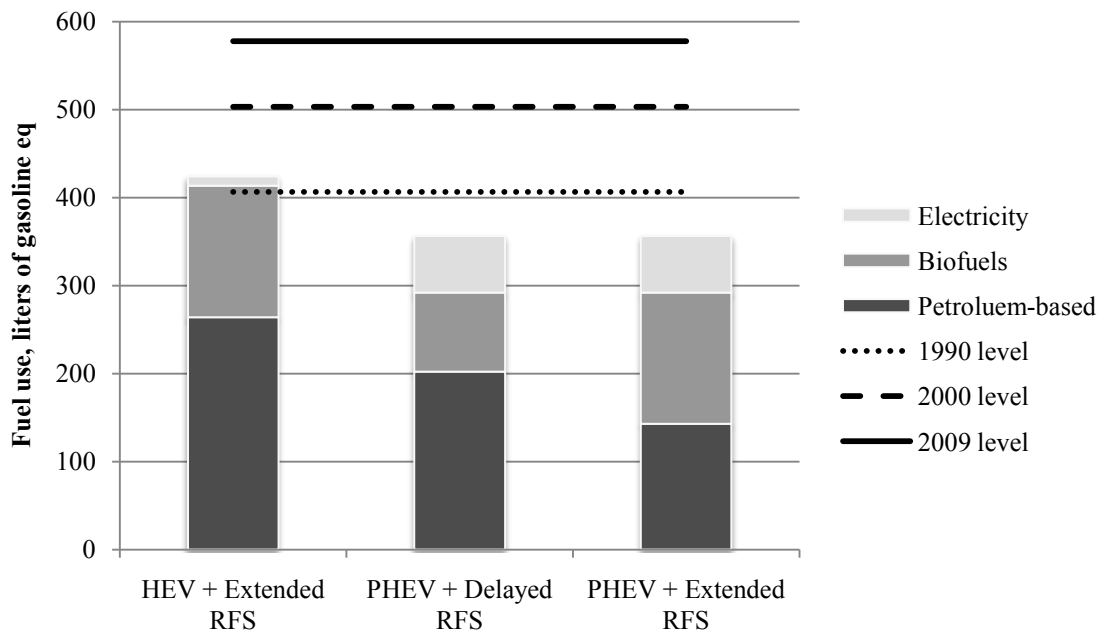


Figure 48. Comparison of U.S. LDV Fleet Fuel Utilization in 2050

8.5 Electricity demand by PHEV Charging

In the previous section, we described the electricity use by the PHEVs in terms of the liters of gasoline equivalent. This is a useful comparison to the liquid fuels. In this section, we will elaborate on the same data in units common for the electricity generation industry. The electricity consumption by the PHEVs, or “electricity demand” by PHEVs data on Figure 49 is shown in billions kWh. It is compared demand to the electricity supply from the EPRI Full Portfolio case (26). A rapid increase in 2031 coincides with introduction of opportunity charging. The total electricity demand from the PHEVs reaches 574 billion kWh in 2050.

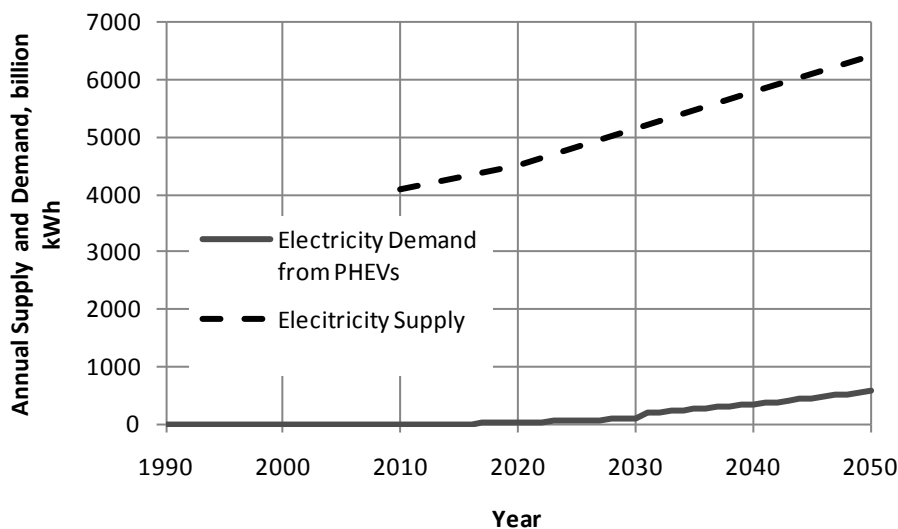


Figure 49. U.S. LDV Fleet Electricity Usage in the PHEV Scenario

9 Summary

The main conclusion of this study relates to the reduction of the greenhouse gas emissions from the light-duty vehicle sector of transportation. Multiple optimistic assumptions were made: continued rapid technology development of the ICE, hybrid and plug-in hybrid vehicles; higher emphasis on reducing fuel economy than that observed in the past thirty years; rapid adoption of the PHEVs by the consumers; as well as very significant reduction of the emissions from the electric power generation. One might speculate that 80% reduction of greenhouse gas emissions in 2050 below the 1990 levels can be readily achieved with such assumptions. On the contrary, not a single scenario achieved the stated target. The most optimistic scenario illustrated reduction of 49% below the 1990 levels, which is still quite large, in part because the same value corresponds to the 64% reduction below the today's level as of 2009. One must note that the most optimistic scenario also assumes significant developments in charging infrastructure and in biofuels production, and therefore carries a significantly larger price tag than other potentials. A detailed economic study may reveal the total cost, including, but not limited to government subsidies, that would enable the scenario with a combination of three primary contributors: high proportion of PHEVs, extensive charging infrastructure and large volumes of biofuels.

There are several factors that contribute to the gap between desired 80% and achieved 49% emissions reduction in 2050 in the illustrated scenario. The first factor is a significant number of non-hybrid vehicles in the LDV fleet in 2050. Even though PHEVs comprise 70% of the new vehicle sales and HEVs are another 10%, the lifecycle turnover limits the number of PHEVs to 50% of the U.S. LDV fleet. Considering the LDV fleet growth, which coincides with the

projected U.S. population growth, the ICE vehicles comprise 40% of the 2050 fleet, or 135 million vehicles. The ICE vehicles consume liquid fuels and produce CO₂ emissions from the tailpipe. Even though these automobiles of 2050 are significantly better than today's cars and trucks, in both better performance and better fuel economy, but their emissions are still higher compared to emissions from HEVs and PHEVs. As a consequence, ICE vehicles contribute 54% of the total emissions.

The second factor contributing to the emissions is limitation of the PHEV electric range, which is, in turn, caused by the limitations of the battery technology. While electricity comprises 18% of the total energy, it results in only 14% of the emissions. Therefore, from the environmental considerations it is more advantageous to travel on the electricity than on liquid fuels. While we selected a simplified model for a PHEV and its associated share of travel on electricity versus liquid fuel, the actual market of 2050 may include BEVs as well as PHEVs with a shorter electric range. The long trips, such as those that exceed the battery capacity in the PHEVs, will inevitably consume liquid fuels, and contribute to the greenhouse gas emissions as much as HEVs.

The third reason for persistently increased levels of emissions is the ever-growing automotive travel, quantified as annual vehicle kilometers traveled in this study. VKT has grown consistently from 1970s until the oil crisis of 2008. Even though there was a significant reduction in the VKT during 2008, the growing trend resumed in 2009(44). The study assumed lower rate of the VKT growth compared to the historical rate for the next decade, and, optimistically, further reduction in the growth rate in the following decades. Nevertheless, it is important to note that the VKT continues to increase under our model, that is, vehicles travel more annually in 2050 than they do today. Since travel linearly contributes to the greenhouse

gas emissions, the VKT increases offset gains by the technology and the infrastructure improvements.

The second primary conclusion relates to the additional capacity required from the electric grid to power vehicles with electric propulsion. Previous studies indicated that today's grid can support 73% of total U.S. fleet if they were PHEVs, assuming 24-hour charging, or 43% of the fleet assuming night charging (5). Another study suggested no to moderate increases in the generation (6). This study considers progressive development of both automotive technologies and the U.S. electric grid. Other assumptions, such as charging profile that includes both night and day charging, but excludes charging during the peak hours, differ as well. This study concurs with the other studies that only modest additions to the U.S. electric power generation due to vehicle charging are expected over the next few decades. As a corollary, the battery capacity of the PHEVs and BEVs is unlikely to strongly influence the electricity generation industry and electric power markets. Impacts on the U.S. electricity distribution network should be further examined.

A qualitative observation about sensitivities can be observed by comparing battery progress, biofuels availability and charging infrastructure development. From this study, it is evident that abundant biofuel technology provides greatest benefits for the HEVs. The uncertainties of the biofuel availability, especially those associated with its production costs versus cost of petroleum (45), may affect the technology selection of HEVs versus PHEVs. An automotive choice to favor HEVs may slow down investment in the high energy battery technology, which may slow down the benefits from battery technology learning and create an additional barrier to the PHEV adoption. The reverse causal path may be realized in case of breakthrough achievements in the battery technology or disruptions/unavailability of the biofuels. A highly detailed analysis of the

costs focused on the variability of the oil price, may reveal the complex interrelated behavior of the biofuels, electricity, hybrid and plug-in hybrid technologies. In the two competing cases, an HEV scenario with “Extended Renewable Fuel Standard” and a PHEV scenario with “Delayed Renewable Fuel Standard”, oil-based fuel use reductions from today’s value of 577 billion liters by 54% to 65% can be achieved without requiring simultaneous biofuels availability, significant progress in battery technology and charging infrastructure. Alternatively, a 75% reduction in use of petroleum-based fuels may be attained when all three factors are combined, at higher cost, in the PHEV scenario with “Extended Renewable Fuel Standard”.

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