CALIFORNIA ENERGY COMMISSION

California Energy Commission

**CONSULTANT REPORT**

# Advanced Vehicle Technologies

**Prepared for: California Energy Commission**

**Prepared by: National Renewable Energy Laboratory**

**December 2021 | CEC-600-2021-043**

# California Energy Commission

Jeffrey Gonder
Adam Ragatz
Aaron Brooker
Jenny Heeter
Marc Melaina
Yongling Sun
**Primary Authors**

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401

**Contract Number: 600-11-002**

Jim McKinney
**Task/Agreement Manager**

Charles Smith
**Office Manager**
**TRANSPORTATION POLICY & ANALYSIS OFFICE**

Hannon Rasool
**Deputy Director**
**FUELS AND TRANSPORTATION**

Drew Bohan
**Executive Director**

# PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program. The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to $20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about $100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets to alternative technologies or fuel use.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued 600-11-002, issued in September 13, 2012, to provide program support on specific Clean transportation Program topics, including a technical and market assessment of advanced vehicle technologies.

# ABSTRACT

This report provides an overview of advanced vehicle technologies considered by the CEC, that may be worthy of consideration in the future. The report describes the current status of these technologies and summarizes their potential petroleum consumption/greenhouse gas emission impacts. Technologies considered include light-duty hybrid and plug-in electric vehicles, medium- and heavy-duty hybrid and PEVs, alternative fuel vehicles including diesel, gasoline blends containing up to 85 percent ethanol, liquefied petroleum gas, compressed natural gas, liquefied natural gas, and hydrogen. The report further compares various advanced vehicle technology penetration scenarios and describes a consumer preference modeling approach (validated against historical vehicle sales data) planned for use in ongoing market impact assessment activities. Emerging technologies discussed in the report that have not been included previously but may be worth considering in the future include roadway electrification and dimethyl ether engines. The report closes with an overview of government regulations and incentives influencing the advanced vehicle market.

**Keywords:** Advanced Vehicle Technologies, alternative fuels, greenhouses gases, fuel cell electric vehicles

Please use the following citation for this report:

Gonder, J.; Ragatz, A.; Brooker, A.; Heeter, J.; Melaina, M.; Sun, Y. (National Renewable Energy Laboratory). 2021. *Advanced Vehicle Technologies*. California Energy Commission. Publication Number: CEC-600-2021-043.

# TABLE OF CONTENTS

Page

Preface ... i

Abstract ... iii

Table of Contents ... v

List of Figures ... vi

List of Tables ... vii

Executive Summary ... 1

CHAPTER 1: Introduction to Advanced Vehicle Technology ... 5

Report Structure ... 5

CHAPTER 2: Current Technology Status ... 6

Light Duty Hybrid and Plug-In Electric Vehicles ... 6

Baseline Information ... 6

Number and Types of Vehicles ... 6

Key Vehicle Manufacturers ... 11

Geographic Information on Distribution of End-Users ... 13

Barriers to Widespread Commercialization and Deployment ... 18

Average Petroleum, GHG and Air Pollution Reduction Estimates ... 19

Medium- and Heavy-Duty Hybrid and Electric Vehicles ... 20

Technology Status ... 21

Payback Analysis ... 23

Average Petroleum, and GHG Reduction Estimates ... 25

Alternative Fuels (FFV, LPG, CNG, and LNG) and Light-Duty Diesel ... 25

Baseline Number and Types of Vehicles ... 26

Energy Density and Storage on the Vehicle ... 32

Average Petroleum and GHG Reduction Estimates ... 33

Hydrogen Fuel Cell Electric Vehicles ... 34

Data Products and Findings from the FCEV Learning Demonstration ... 34

Performance Status of Fuel Cell Electric Buses in Transit ... 36

Recent FCEV Production Plans from Automakers ... 38

CHAPTER 3: Advanced Vehicle Deployment Projections ... 40

Review of Recently Developed Technology Penetration Scenarios ... 40

EPA Technical Assessment Report ... 42

National Petroleum Council ... 46

National Research Council ... 52

Vehicle Choice Modeling Comparison ... 60

CHAPTER 4: Technologies for Potential Future Consideration ... 63

Electric Roadway ... 63

Dimethyl Ether Engines ........ 64
CHAPTER 5: Government and Corporate Incentives Impacting Advanced Vehicle Technologies ........ 66
An Assessment of the Range of Public Incentives Available to Advanced Technology Vehicle Producers and Consumers ........ 66
An Assessment of Government or Corporate Sustainability Policies That Influence Advanced Vehicle Procurement Decisions ........ 69
Glossary ........ 75

# LIST OF FIGURES

Page

Figure 1: Location of Hybrid and Plug-in Electric Vehicles ........ 7
Figure 2: Light-Duty Hybrid and Plug-In Vehicles per 1,000 People ........ 8
Figure 3: U.S. Hybrid and Battery Electric Vehicle Sales and Take Rates ........ 9
Figure 4: Top Selling Hybrid Vehicles in the United States ........ 9
Figure 5: Top Selling Plug-In Electric Vehicles in the United States ........ 10
Figure 6: California Hybrid Sales by Model Year ........ 12
Figure 7: Leading Models of Hybrids with Valid 2012 California Registrations ........ 12
Figure 8: Density of Registered HEVs and PHEVs in California ........ 13
Figure 9: Density of Registered BEVs in California ........ 14
Figure 10: National Charging Station Locations ........ 19
Figure 11: Location of Diesel Passenger Cars in the United States ........ 27
Figure 12: Location of Diesel Vehicles in the United States ........ 27
Figure 13: Top-Selling Diesel Passenger Cars in the United States ........ 28
Figure 14: California Sales of Light-Duty Diesel Vehicles by Model Year and Type ........ 28
Figure 15: California MY 2011 Sales of Diesel Vehicles by Make ........ 29
Figure 16: Flexible Fueled Vehicles per Capita ........ 30
Figure 17: Natural Gas and Propane Reported Vehicles in Operation ........ 31
Figure 18: 2011 Reported Vehicles in Operation by Type and Fuel ........ 32
Figure 19: Fuel Energy Density Comparison (not including the Containment Vessel) ........ 33
Figure 20: NPC-Estimated Ranges of LDV On-Road Fleet Fuel Economy in 2050 ........ 47
Figure 21: NPC-Estimated Fleet Shares in 2050 ........ 47

Figure 22: NPC-Estimated Ranges of Medium- and Heavy-Duty Vehicle Fleet Fuel Economy in 2050 ........ 48

Figure 24: NPC-Estimated Range of 2050 On-Road Fuel Consumption ........ 49

Figure 25: NPC-Estimated GHG Emissions for LDV Fleet (a) and Medium- and Heavy-Duty Vehicle Fleet (b) in 2050 ........ 50

Figure 26: NPC-Estimated Cost of Driving (LDV) ........ 51

Figure 27: NRC-Estimated Car Incremental Cost Versus 2010 Baseline ($26,341) for Midrange (a) and Optimistic (b) Assumptions ........ 54

Figure 28: NRC-Estimated Light Truck Incremental Cost Versus 2010 Baseline ($32,413) for Midrange (a) and Optimistic (b) Assumptions ........ 55

Figure 29: NRC-Estimated U.S. LDV Petroleum Use in 2030 and 2050 Under Different Policies ........ 56

Figure 30: NRC-Estimated U.S. LDV GHG Emissions in 2050 under Different Policies ........ 57

Figure 31: NRC-Estimated Vehicle Sales by Powertrain with Midrange Technology Assumptions Business as Usual ........ 57

Figure 32: NRC- Estimated Vehicle Sales by Powertrain under Efficiency ........ 58

Figure 33: NRC-Estimated Vehicle Sales by Powertrain under PHEVs ........ 58

Figure 34: NRC-Estimated Vehicle Sales by Powertrain under Low-Carbon Hydrogen FCEV ... 59

Figure 35: NRC-Estimated Vehicle Sales by Powertrain under CNGVs ........ 59

Figure 36: NRC-Estimated Vehicle Sales by Powertrain under PHEV, FCEV, and Biofuels ....... 60

# LIST OF TABLES

Page

Table 1: MY 2011 Sales of Select Vehicles ........ 10

Table 2: Leading Hybrid and Electric Vehicle Battery Packs ........ 15

Table 3: U.S. EPA Estimated Performance for Leading PEVs ........ 16

Table 4: U.S. EPA Estimated Charge Time and Calculated Average Load ........ 18

Table 5: Petroleum and GHG Displacement Estimates for Leading HEVs and PEVs........ 20

Table 6: American Recovery and Reinvestment Act Demonstration BEV Specifications and Select Results ........ 23

Table 7: Medium- and Heavy-Duty Hybrid and Electric Vehicle Fuel Savings ........ 24

Table 8: Estimated Vehicle Incremental Cost ........ 24

Table 9: Fuel and Carbon Dioxide Displacement for Select Vehicles ........ 25

Table 10: MY 2011 Top-Selling Light-Duty Flexible Fuel Vehicles in California ........ 30

Table 11: Average Annual Petroleum Displacement per Vehicle ........................................ 33
Table 12: Average Annual GHG Emissions Displaced per Vehicle ........................................ 34
Table 13: Summary of FCEVs and Hydrogen Fueling Infrastructure Performance ................ 35
Table 14: Fuel Cell Electric Bus Performance and Federal Transit Administration Targets ...... 37
Table 15: Comparison of U.S. EPA, NPC and NRC Studies ................................................ 40
Table 16: Projections for MY 2025 .......................................................................... 44
Table 17: Technology Penetration Estimates for MY 2025 Vehicle Fleet ............................... 45
Table 18: NRC-Estimated Vehicle Fuel Efficiency on U.S. EPA 2 Cycle Tests* ........................ 53
Table 19: Consumer Incentives to Purchase an Advanced Technology Vehicle ..................... 66
Table 20: Public Incentives Targeting Developers of Advanced Technology Vehicles............ 69
Table 21: Alternative Vehicle Procurement by Clean Fleets Partners ................................... 70
Table 22: Federal Fleet Vehicle Type and Configuration (FY12) .......................................... 72
Table 23: Federal Government Alternative Fuel Vehicle Purchasing .................................... 72

# EXECUTIVE SUMMARY

A wide range of advanced vehicle technologies can contribute to the near- and long-term social and environmental goals of the Alternative and Renewable Fuel and Vehicle Technology Program. These include hybrid electric vehicle, plug-in hybrid electric vehicle, and battery electric vehicle drivetrains for light-duty and medium-/heavy- duty vehicles. Other technologies include non-traditional and alternative fuels such as efficient light-duty diesel vehicles, ethanol blends in flexible-fuel vehicles, liquefied petroleum gas, compressed natural gas, liquefied natural gas, and hydrogen fuel cell electric vehicle drivetrains. Additional technologies that may warrant consideration include roadway electrification and vehicles that operate on dimethyl ether. The present report reviews the capabilities and market status of each of these technologies, as well as estimates from future deployment scenarios, and relevant government and corporate incentives. Given the promising advances to date and projections for additional improvements and market growth, a range of advanced vehicle technologies can be relied upon to meet California's air quality, petroleum reduction, and greenhouse gas reduction goals.

California accounted for 9.7 percent of national model year 2011 Light Duty vehicle sales but had a much greater take rate of hybrid electric vehicles and plug-in hybrid electric vehicles (23 percent) and accounted for over half (54 percent) of all battery electric vehicle sales. The diversity of hybrid and electrified vehicle makes, and models has increased significantly since 2009, and the availability of public electric vehicle supply equipment has grown significantly in recent years. Though recent sales have been strong, further progress is needed to overcome barriers to significantly higher levels of commercialization and deployment. These challenges include continuing to reduce the cost increment between conventional and electrified vehicle powertrains, and further improving driving range, recharge time and electric vehicle supply equipment availability for battery electric vehicles. Justifications for continued public support to overcome these barriers include petroleum and greenhouse gas reductions, which can respectively reach around 2,000 gallons of gasoline and 50,000 pounds of carbon dioxide for a single hybrid electric vehicle. Petroleum savings for plug-in vehicles can reach twice this amount, and if charged using renewably produced electricity, greenhouse gas emissions from battery electric vehicle operation can drop to zero.

Bolstered by federal and state programs such as the American Recovery and Reinvestment Act and the Hybrid Voucher and Incentive Program, a number of medium duty/heavy duty commercial applications have also deployed hybrid and plug-in vehicles in recent years.

Extrapolated to a 15-year lifetime, recent medium duty hybrid electric vehicle deployments suggest per-vehicle petroleum and greenhouse gas emission reductions around 4,000 gallons of diesel and 90,000 pounds of carbon dioxide, respectively. Similar commercial battery electric vehicle data suggest fuel savings as high as 14,000 gallons of diesel if the vehicle can achieve a 15-year life. Technology barriers are similar to those for the light-duty market, with incremental vehicle cost in the absence of incentives remaining a particularly significant barrier for these vehicles (which have lower sales volumes relative to the light-duty market).

Petroleum and greenhouse gas emissions reductions can also be achieved with combustion engine vehicles utilizing alternative fuels. Diesel is the standard fuel used for medium duty/heavy duty conventional vehicles but is a non-traditional fuel in the light duty market, where it can improve vehicle fuel economy when used in vehicles with advanced emissions control systems. Relative to every other state, California possesses the highest percentage (10 percent) of the national light duty diesel passenger car market, however on a per capita basis California's penetration for diesel cars and light trucks is relatively low compared to the rest of the country. The story is similar for flexible-fuel vehicles that are capable of operating on gasoline blends containing up to 85 percent ethanol. For propane and natural gas (both compressed natural gas and liquefied natural gas), vehicles may be converted from their original fuel type to operate on these alternative fuels (to reduce petroleum consumption and operating costs). Over the past decade California has seen a rise in compressed natural gas and liquefied natural gas vehicles, with liquefied petroleum gas vehicles holding steady (in the U.S. as a whole compressed natural gas and liquefied natural gas vehicles have held steady while liquefied petroleum gas vehicle use has declined). Considerations for these vehicles include the cost of the vehicle conversion to operate on the alternative fuel, and whether the conversion is performed by an original equipment manufacturer or certified installer who will ensure things such as the criteria emissions control system are working properly. Relative to a comparable plug-in vehicle charged by the average U.S. mix of grid electricity sources, propane and natural gas vehicles can actually achieve a few times greater greenhouse gas emissions reduction.

Hydrogen is an alternative fuel that can be used in a fuel cell electric vehicle to produce electricity with no tailpipe emissions (and with vehicle range limited only by hydrogen availability). Over the past decade of development and prototype vehicle deployment, both light-duty hydrogen fuel cell electric vehicles and fuel cell electric buses have made steady progress toward meeting the U.S. Department of Energy's goals for successful commercialization. Critical remaining barriers for large-scale deployment include reducing vehicle and hydrogen costs and increasing hydrogen infrastructure availability. Nevertheless, manufacturers including Toyota, Honda and Hyundai have announced their intention to begin selling and/or leasing production vehicles to customers within the next few years.

Though each of these advanced vehicle technologies continue to make inroads, the current market remains dominated by conventional vehicles. Three recent high-profile reports have developed projection scenarios to estimate potential advanced vehicle market growth based on continued performance and cost improvements. These studies include the joint *Technical Assessment Report* prepared by the U.S. Environmental Protection Agency and California Air Resources Board, the *Advanced Technology for America's Transportation Future* report prepared through the National Petroleum Council, and the Transitions to Alternative Vehicles and Fuels report prepared by the National Research Council[1]. Each report was developed to address a unique set of research questions, but each considered a similar set of vehicle and fuel technologies. The Technical Assessment Report projected technology and market trends to 2025, while the and National Research Council reports projected to 2050. Each study focused on light duty vehicle technologies and markets, while the National Petroleum Council study also addressed medium duty/heavy duty technologies and markets.

[1] National Research Council of the National Academies. (2013). "Transitions to Alternative Vehicles and Fuels." Committee on Transitions to Alternative Vehicles and Fuels, Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences.

The studies all included unique ranges of technology development and market growth scenarios, relying to a greater or lesser extent on different vehicle and fuel types to achieve greater market share increases over time. The Technical Assessment Report market penetration scenarios are based upon distinct levels of tailpipe carbon dioxide emissions reductions per year, starting at 250-grams/mile for market year 2016 and projecting various pathways to achieving 3 percent, 4 percent, 5 percent and 6 percent per year reduction targets for market year 2020 and 2025. Results suggest greater per-vehicle costs, but also greater vehicle lifetime owner savings (due to fuel savings), for the higher reduction targets.

The National Petroleum Council study was broader in scope than the Technical Assessment Report and National Research Center studies, and included three task groups focusing on demand, supply and infrastructure, and technology. Analytic assumptions assumed "aggressive but not disruptive" improvements in advanced vehicle-fuel systems, concluding that plug in hybrid electric vehicles, battery electric vehicles, and fuel cell electric vehicles were not likely to account for more than about 15-20 percent of the total vehicle fleet by 2050. In contrast, the National Research Council study examined scenarios capable of meeting an 80 percent reduction in light-duty vehicle greenhouse gas emissions by 2050, with 25-50 percent market share being achieved by hybrid electric vehicles, battery electric vehicles, compressed natural gas vehicles, or fuel cell electric vehicles across a number of different scenarios by 2050. Ongoing market impact assessments for the clean transportation program will leverage National Renewable Energy Laboratory's Automotive Deployment Options Projections Tool, which estimates vehicle market penetration based on a well-validated consumer choice model. When the using similar input assumptions, Automotive Deployment Options Projections Tool's market penetration estimates overlap with comparable deployment scenarios from these studies.



The present report also considered two promising advanced vehicle technologies at fairly early stages of development and deployment. The first of these is the concept of electric roadways, from which electrified vehicles could receive electricity without having to use a cord and plug. This technology could include stationary inductive power transfer over air gaps greater than half a foot, which has reached first generation commercial maturity. Vehicle electrification would be transformed by successful extension to in-motion power transfer using either similar induction approaches or using conduction (as is being pursued by Siemens through overhead catenary lines and by Volvo and Alstom through inroad conductive rails). The second early-phase concept discussed is the potential to use dimethyl ether as an alternative engine fuel. Dimethyl ether is a synthetically generated fuel produced from methanol, and can be derived from coal, natural gas, biogas, and biomass via gasification into syngas. Attractive features of this fuel include relatively clean combustion requiring minimal after treatment, and the ability to store it as a liquid under modest pressures.

The final section of this report contains a summary of government and corporate incentives impacting advanced vehicle technologies. The wide range of incentives available at the local, state and federal level include tax credits, rebates, grants, "buy green" policies and infrastructure incentives. Advanced vehicle technologies greatly benefit from these types of programs as well as information resources such as the Alternative Fuels Data Center (www.afdc.energy.gov), which compiles data on incentives, alternative fueling station locations and related resources. These resources help early generation advanced vehicles begin competing in the same market with much more mature and higher volume conventional vehicles.

Of the advanced vehicle technologies described in this report, hybrid electric vehicles have provided some of the largest-scale fuel and greenhouse gas emission reductions, but still have considerable room for increased market penetration both in California and nationally. Continued efforts to promote development and deployment off all advanced vehicle technologies will help each further mature, realize larger production volumes and ultimately increased cost effectiveness. This report provides pertinent information on recent advancements, current status and available incentives for these various advanced vehicle technologies, and also reviews recent studies of potential increased deployment scenarios. The next steps include building on this information and leveraging a well-validated consumer preference model for ongoing market impact assessment activities. Doing so will help realistically assess the steps needed to achieve the clean transportation program petroleum and greenhouse gas emission reduction goals.

# CHAPTER 1: Introduction to Advanced Vehicle Technology

California is home to approximately 11.5 percent of the over 250 million motor vehicles registered in the United States[2]. However, California makes up a significantly higher percentage—and leads the way—in advanced technologies such as gasoline hybrid, diesel hybrid, all-electric, and natural gas vehicles. These technologies reduce U.S. petroleum use as well as greenhouse gas (GHG) emissions. The following chapters will investigate these technologies in greater detail and outline the current status of these technologies and their penetration into the California market.

## Report Structure

Chapter 1 provides a general overview of the report structure and topics covered. Chapter 2 will discuss the current status of advanced vehicle technologies starting with light-duty hybrid and electric vehicles (EVs), followed by medium- and heavy-duty hybrid and EVs, and finally alternative fuel vehicles including diesel, gasoline blends containing up to 85 percent ethanol (E85), liquefied petroleum gas (LPG), compressed natural gas (CNG), liquefied natural gas (LNG), and hydrogen. Chapter 3 will examine recent advanced vehicle deployment scenarios produced by the U. S. Environmental Protection Agency (U.S. EPA), National Petroleum Council (NPC), and National Research Council (NRC) and how their methodology compares with the National Renewable Energy Laboratory's (NREL's) Automotive Deployment Options Projection Tool (ADOPT), the primary deployment estimation tool used in this report and planned for use in ongoing market impact assessment activities. Chapter 4 covers topics which may not currently reside in the CEC's advanced vehicle technology portfolio, but that may be worth considering in the future for their potential to positively impact the advanced vehicle market. Chapter 5 discusses government regulations and incentives influencing the advanced vehicle market.

[2] U.S. Department of Transportation - FHA. (2011). *State Motor-Vehicle Registrations*. Retrieved December 2013, from Highway Statistics Series: http://www.fhwa.dot.gov/policyinformation/statistics/2011/mv1.cfm

# CHAPTER 2: Current Technology Status

This chapter discusses the locations of registered advanced vehicles as well as recent sales based upon the best available data. Specifically examined topics include the status of each technology and additional required components, vehicle performance tradeoffs, and barriers to widespread adoption. The following technologies will be covered: light-duty hybrid and EVs; medium- and heavy-duty hybrid and EVs; and finally, alternative fuel vehicles including diesel, E85, LPG, CNG, LNG, and hydrogen.

## Light Duty Hybrid and Plug-In Electric Vehicles

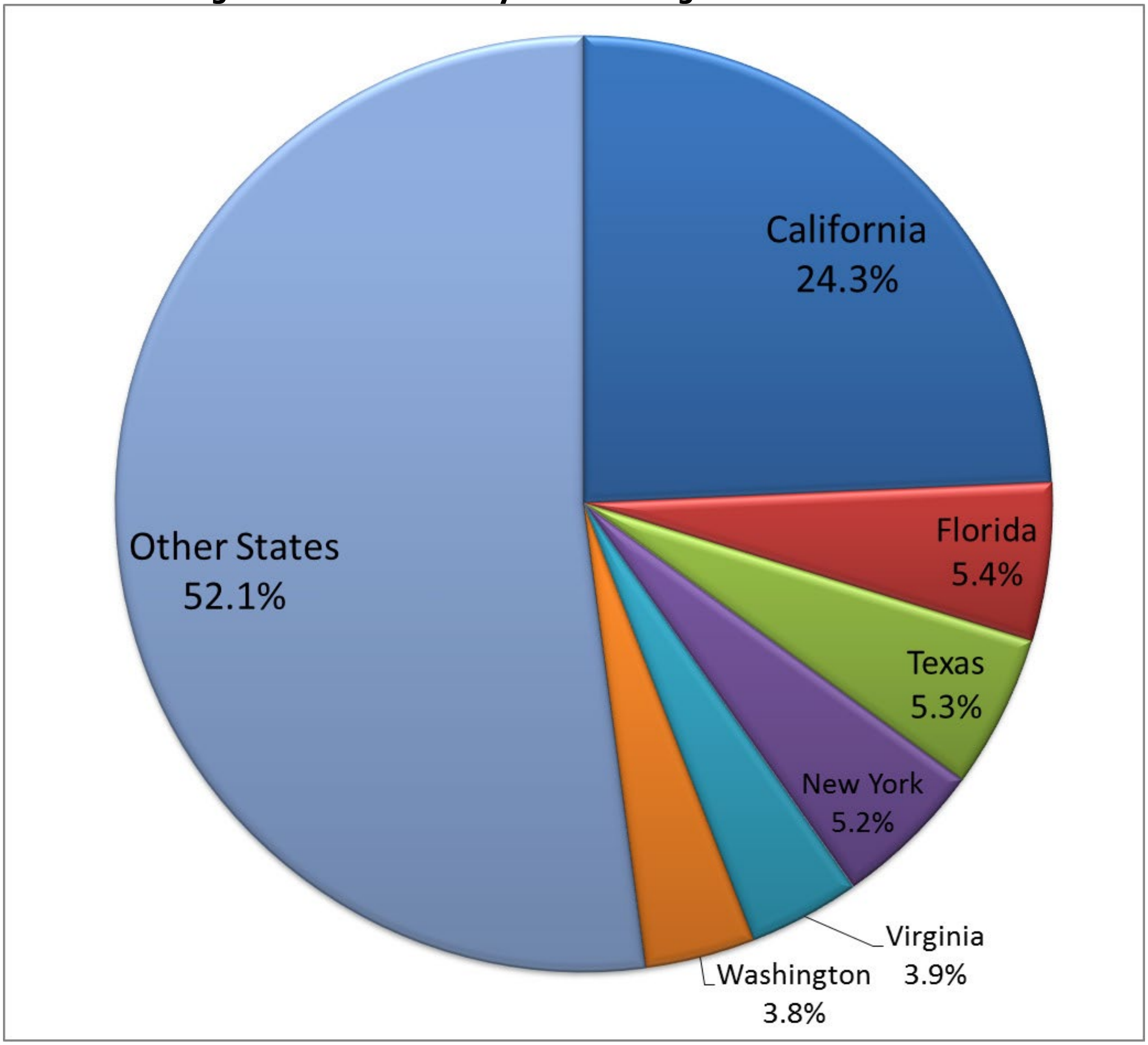
Hybrid electric vehicles (HEVs) rely on a combustion engine for propulsion power but also possess electric motors and energy storage systems (typically batteries) to help them run more efficiently. HEV energy storage systems alternately provide and absorb electrical power during operation, but the engine helps maintain a steady average charge over long periods of driving. Plug-in electric vehicles (PEVs) utilize a power source external from the vehicle to replenish the vehicle's energy storage. This typically involves drawing power from the electrical utility grid to charge batteries on-board the vehicle through an EV charger. For battery electric vehicles (BEVs), this is the sole source of energy, and the vehicle's range is determined by the useful battery capacity and energy consumption rate of the vehicle. Plug-in hybrid electric vehicles (PHEVs) represent another category of PEVs. PHEVs also utilize stored electrical energy to help propel the vehicle forward, but similar to HEVs, they carry an additional power source, typically an internal combustion engine, which may be used during times of high-power demand or once the useful battery energy has been depleted. Both PEVs and HEVs are able to recover some portion of the vehicle's braking energy, known as regenerative braking, where kinetic energy is transformed to electricity through a motor/generator and used to charge the batteries. In a conventional braking system this energy would be dissipated as heat. The following section examines additional details, including locations of registered vehicles, recent sales, market leaders, technology status, and remaining barriers for the electrified vehicle sector.

## Baseline Information

### Number and Types of Vehicles

There are currently over 2.4 million HEVs and PEVs registered in the United States. The majority are light-duty passenger vehicles, with California having a significantly higher penetration of HEVs and PEVs than other states. Figure 1 shows that only six states account for nearly half of the registered light-duty HEVs and PEVs in the United States, and one quarter of them are in California.

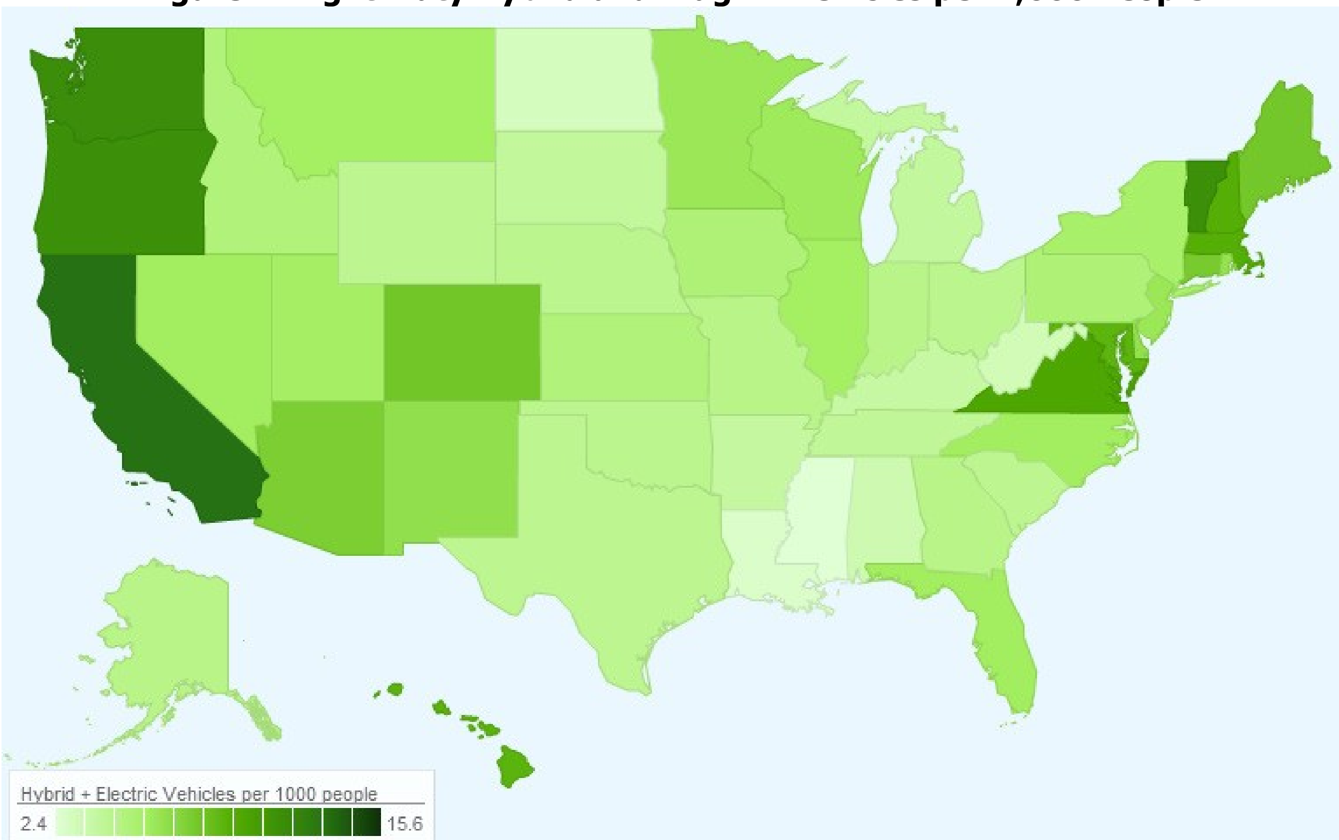
**Figure 1: Location of Hybrid and Plug-in Electric Vehicles**




Source: R. L. Polk, C. (2012, November 15). Vehicle Registration Database.

California also leads in terms of the per-capita distribution of HEVs and PEVs, with 15.6 vehicles per 1,000 people, followed by Washington (13.4), Oregon (13.2), Vermont (13.2), and the District of Columbia (12.3). This is shown in Figure 2 below. Population estimates come from the U.S. Census Bureau[3].

**Figure 2: Light-Duty Hybrid and Plug-In Vehicles per 1,000 People**




Source: R. L. Polk, C. (2012, November 15). Vehicle Registration Database.

The overall take rate of HEVs and PEVs has increased since 2011 (Figure 3). Hybrid vehicle sales maintained a relatively steady annual average from 2007 through 2011, followed by a generally upward trend from the final quarter of 2011 to the final quarter of 2013. PEVs did not come on the market in significant quantities until the latter part of 2010 and have been steadily gaining in popularity ever since.

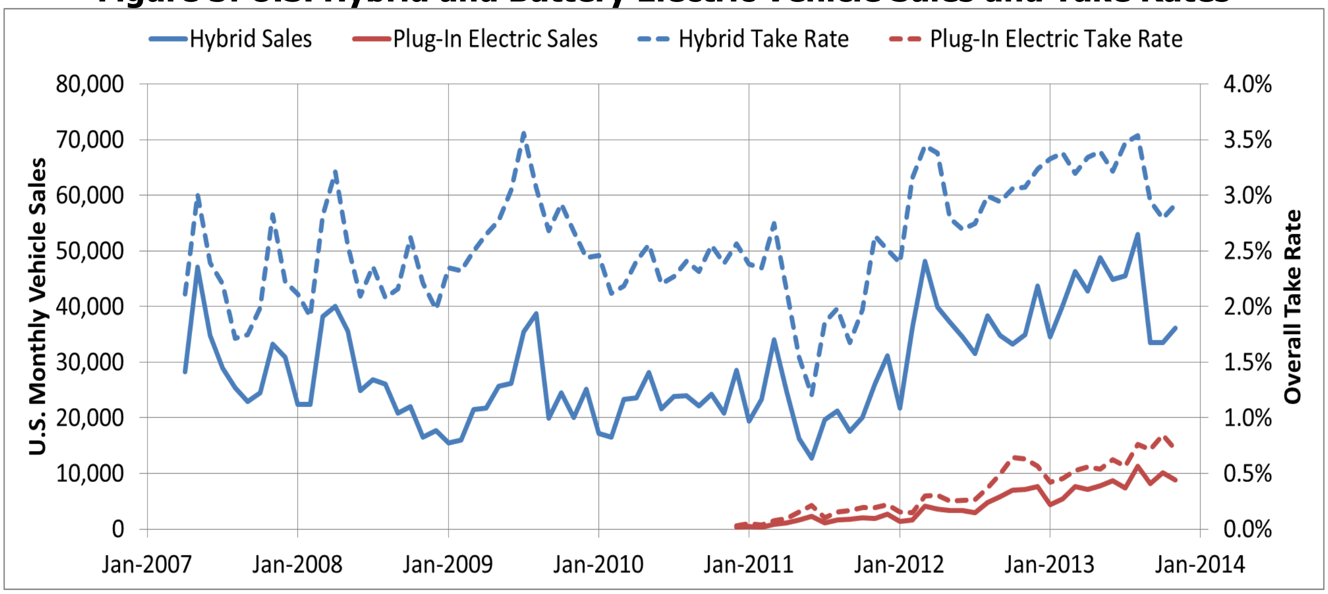
The Toyota Prius has long been the top-selling hybrid passenger vehicle, consistently claiming 40 percent to 60 percent of hybrid sales (Figure 4). The traditional Prius Hatchback model has fallen to around a 30 percent market share of hybrid vehicles, mainly due to the increased popularity of new models entering the market. At the end of 2006, only 10 models of HEVs posted sales figures, but by November 2013 there were over 40 models. When including the latest Prius C and Prius V models, the Prius lineup still claims over 40 percent of hybrid sales.

---

[3] *Population Estimates*. (2012, July 1). Retrieved December 5, 2013, from United States Census Bureau: http://www.census.gov/popest/

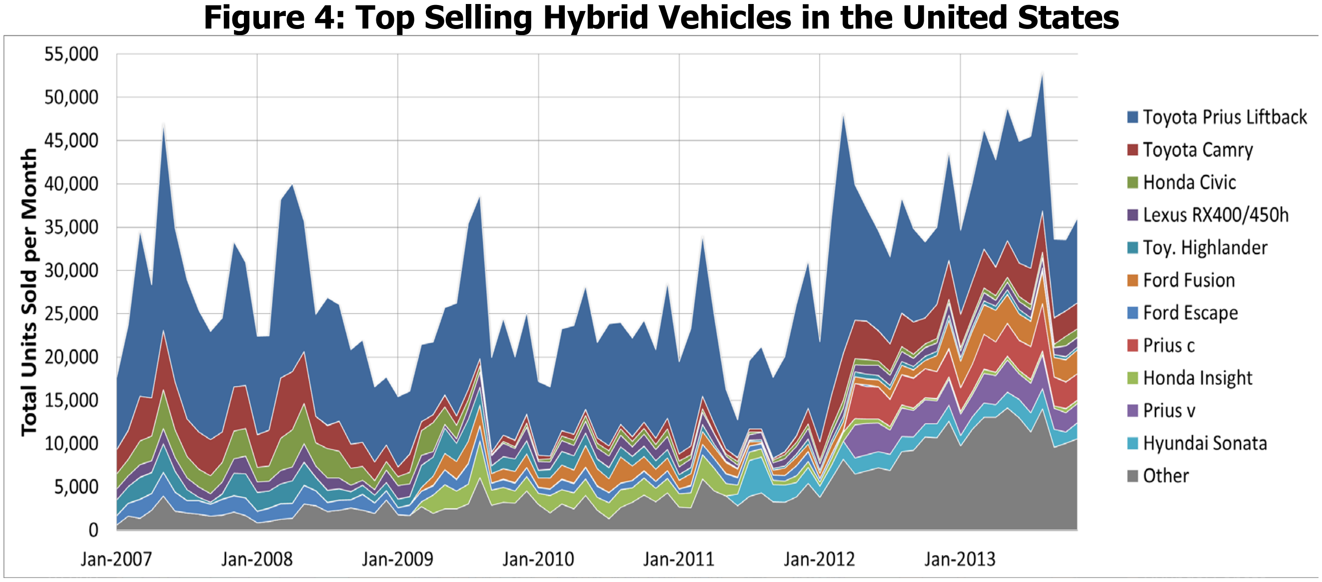
Sales of the top-selling PEVs are shown in Figure 5. The Chevrolet Volt, Prius Plug-In, and Ford Energy are all PHEVs that also include a gasoline internal combustion engine. The Nissan Leaf, Tesla S, and Ford Focus Electric are all strictly BEVs

**Figure 3: U.S. Hybrid and Battery Electric Vehicle Sales and Take Rates**



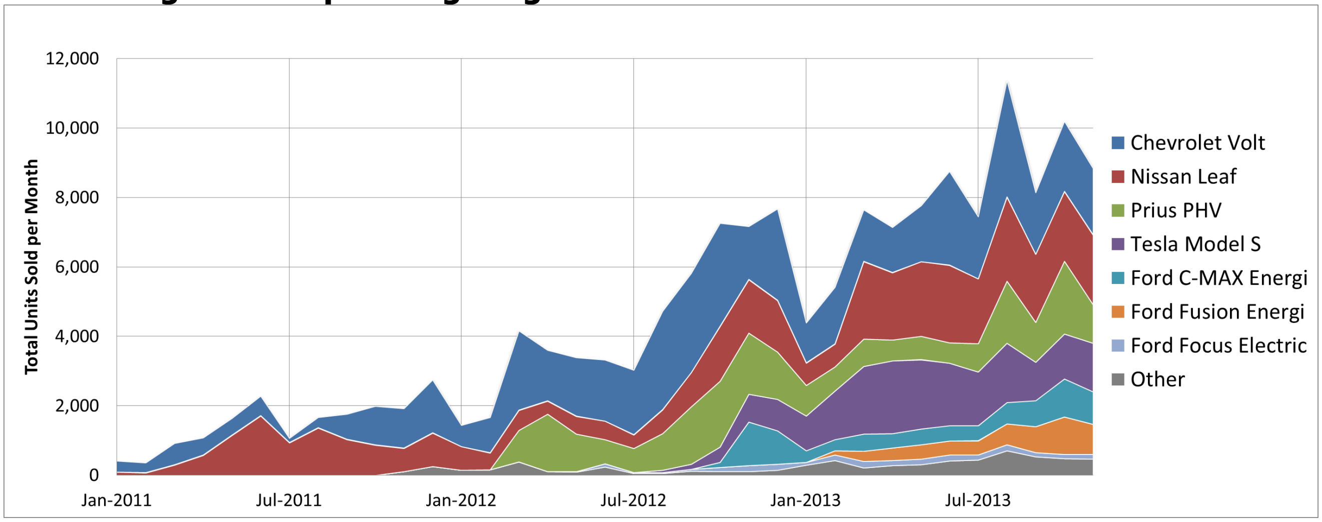

Source: Cobb, J. (n.d.). Electric Vehicle Sales Dashboard. Retrieved December 5, 2013

**Figure 4: Top Selling Hybrid Vehicles in the United States**




Source: Cobb, J. (n.d.). Electric Vehicle Sales Dashboard. Retrieved December 5, 2013

**Figure 5: Top Selling Plug-In Electric Vehicles in the United States**




Source: Cobb, J. (n.d.). Electric Vehicle Sales Dashboard. Retrieved December 5, 2013

Sales figures at the state and zip code level were estimated from the vehicle registration database using the previous vehicle model-year (MY). For example, MY 2011 vehicles that appear in the 2012 registration database are assumed to be the total sales for MY 2011. The three top-selling light-duty MY 2011 vehicles in California of any fuel type were the Toyota Camry (conventional), Prius (hybrid), and Corolla (conventional). Table 1 shows these sales figures followed by the next highest ranking HEV and PEV sales in California for the same model year (Polk, 2012). California accounted for 9.7 percent of MY 2011 light-duty vehicle sales nationwide but had a much greater take rate of HEVs and PHEVs (23 percent) and an even larger percentage of BEV early adopters, who purchased over half of the all-electric vehicles sold in the United States.

**Table 1: MY 2011 Sales of Select Vehicles**

| Make | Model | Fuel Type | US | CA | CA Market Share |
|---|---|---|---|---|---|
| TOYOTA | CAMRY | Gasoline | 449,529 | 64,299 | 14.3 percent |
| TOYOTA | PRIUS | Electric Gas Hybrid | 134,808 | 35,361 | 26.2 percent |
| TOYOTA | COROLLA | Gasoline | 212,044 | 32,747 | 15.4 percent |
| NISSAN | LEAF | Electric | 8,455 | 4,588 | 54.3 percent |
| HONDA | INSIGHT | Electric Gas Hybrid | 12,568 | 2,652 | 21.1 percent |
| TOYOTA | CAMRY | Electric Gas Hybrid | 15,025 | 2,643 | 17.6 percent |
| LEXUS | CT | Electric Gas Hybrid | 9,950 | 2,623 | 26.4 percent |
| HONDA | CR-Z | Electric Gas Hybrid | 15,837 | 2,603 | 16.4 percent |

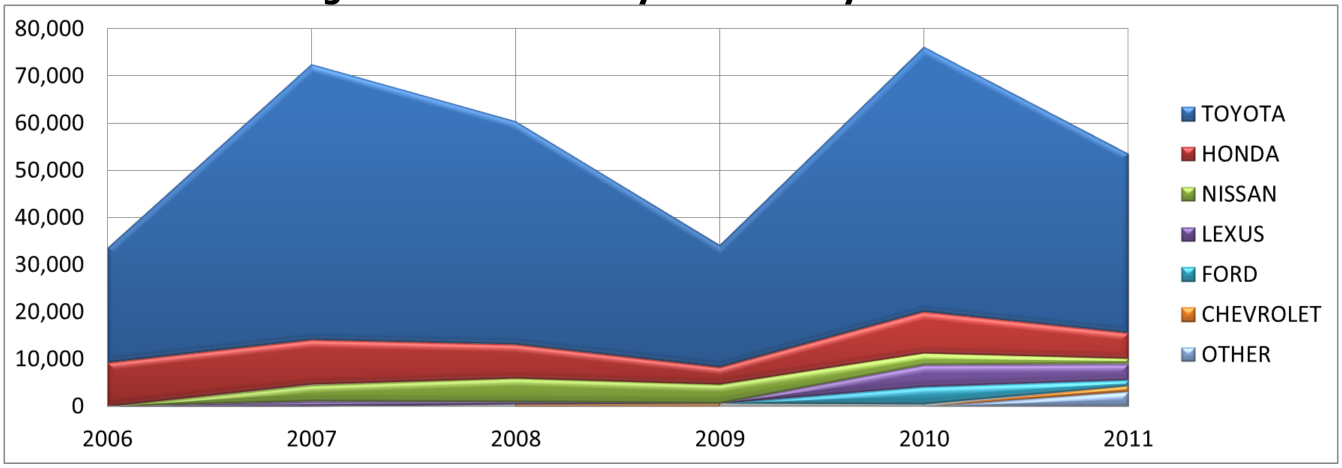
| Make | Model | Fuel Type | US | CA | CA Market Share |
|---|---|---|---|---|---|
| LEXUS | RX | Electric Gas Hybrid | 9,134 | 2,073 | 22.7 percent |
| FORD | FUSION | Electric Gas Hybrid | 8,281 | 1,239 | 15.0 percent |
| CHEVROLET | VOLT | Electric Gas Hybrid | 3,931 | 1,216 | 30.9 percent |
| FORD | ESCAPE | Electric Gas Hybrid | 7,063 | 1,167 | 16.5 percent |
| NISSAN | ALTIMA | Electric Gas Hybrid | 4,203 | 1,129 | 26.9 percent |
| HYUNDAI | SONATA | Electric Gas Hybrid | 11,400 | 1,093 | 9.6 percent |
| KIA | OPTIMA | Electric Gas Hybrid | 3,802 | 924 | 24.3 percent |
| LINCOLN | MKZ | Electric Gas Hybrid | 4,661 | 729 | 15.6 percent |
| TOYOTA | HIGHLANDE R | Electric Gas Hybrid | 3,001 | 706 | 23.5 percent |
| LEXUS | HS | Electric Gas Hybrid | 2,297 | 606 | 26.4 percent |
| SMART | FORTWO | Electric | 503 | 416 | 82.7 percent |
| BMW | ACTIVE E | Electric | 659 | 414 | 62.8 percent |
| All Makes & Models | | Electric Gas Hybrid | 252,954 | 58,298 | 23.0 percent |
| All Makes & Models | | Electric | 10,609 | 5,732 | 54.0 percent |

Source: R. L. Polk, C. (2012, November 15). Vehicle Registration Database.

## Key Vehicle Manufacturers

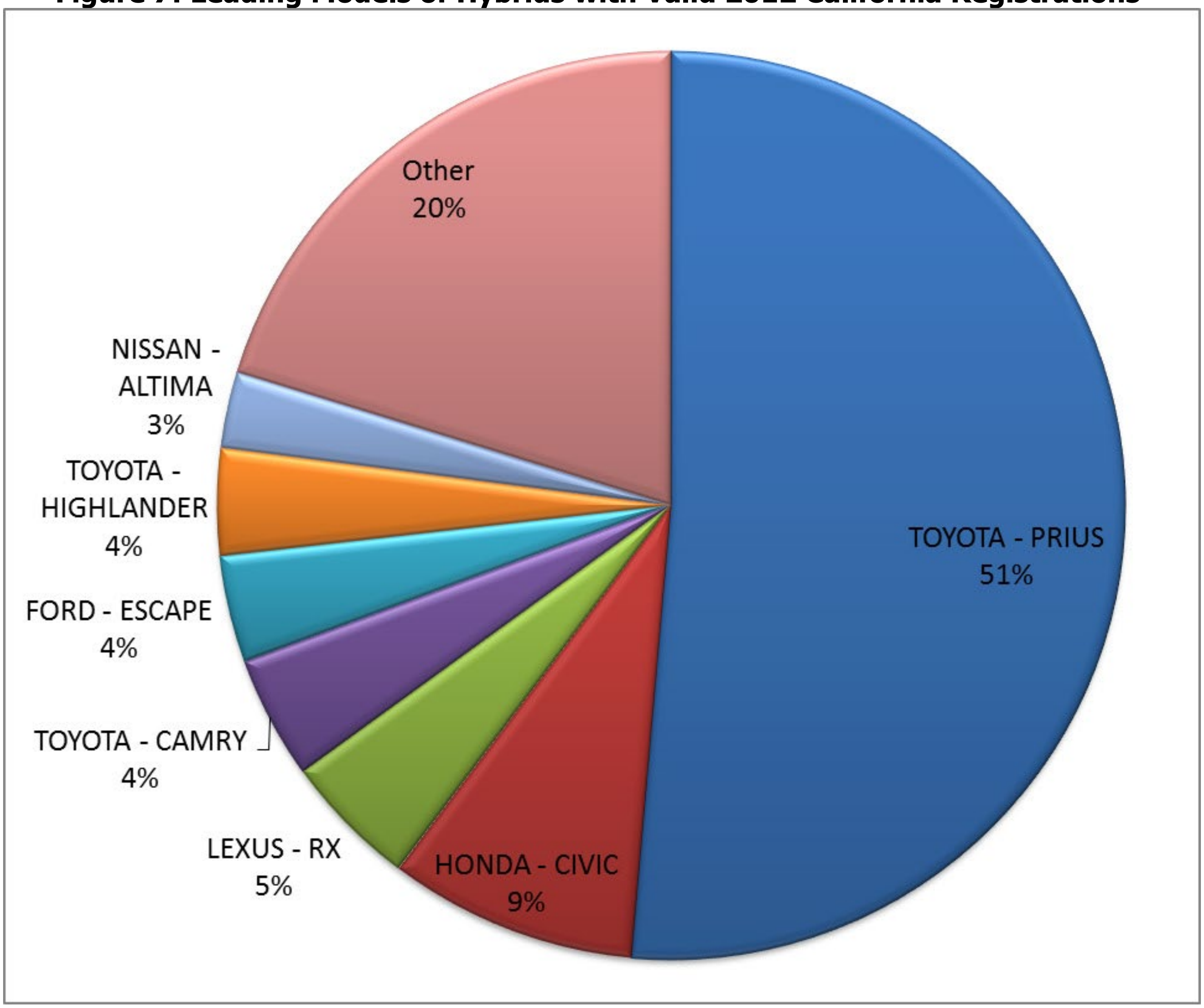
Consistent with the national-level data presented above, Toyota has maintained its position as a key hybrid vehicle manufacturer in California. Figure 6 shows California hybrid vehicle sales by make for several recent years (with the decline in sales shown in 2009 aligning with the national economic downturn). Toyota demonstrates a commanding lead, primarily due to the success of the Prius platform. Figure 7 shows the breakdown of valid 2012 California vehicle registrations for hybrid vehicles. Over half of the vehicles registered as hybrids in the state of California are Toyota Priuses, followed distantly by the Honda Civic.

**Figure 6: California Hybrid Sales by Model Year**




Source: R. L. Polk, C. (2012, November 15). Vehicle Registation Database.

**Figure 7: Leading Models of Hybrids with Valid 2012 California Registrations**

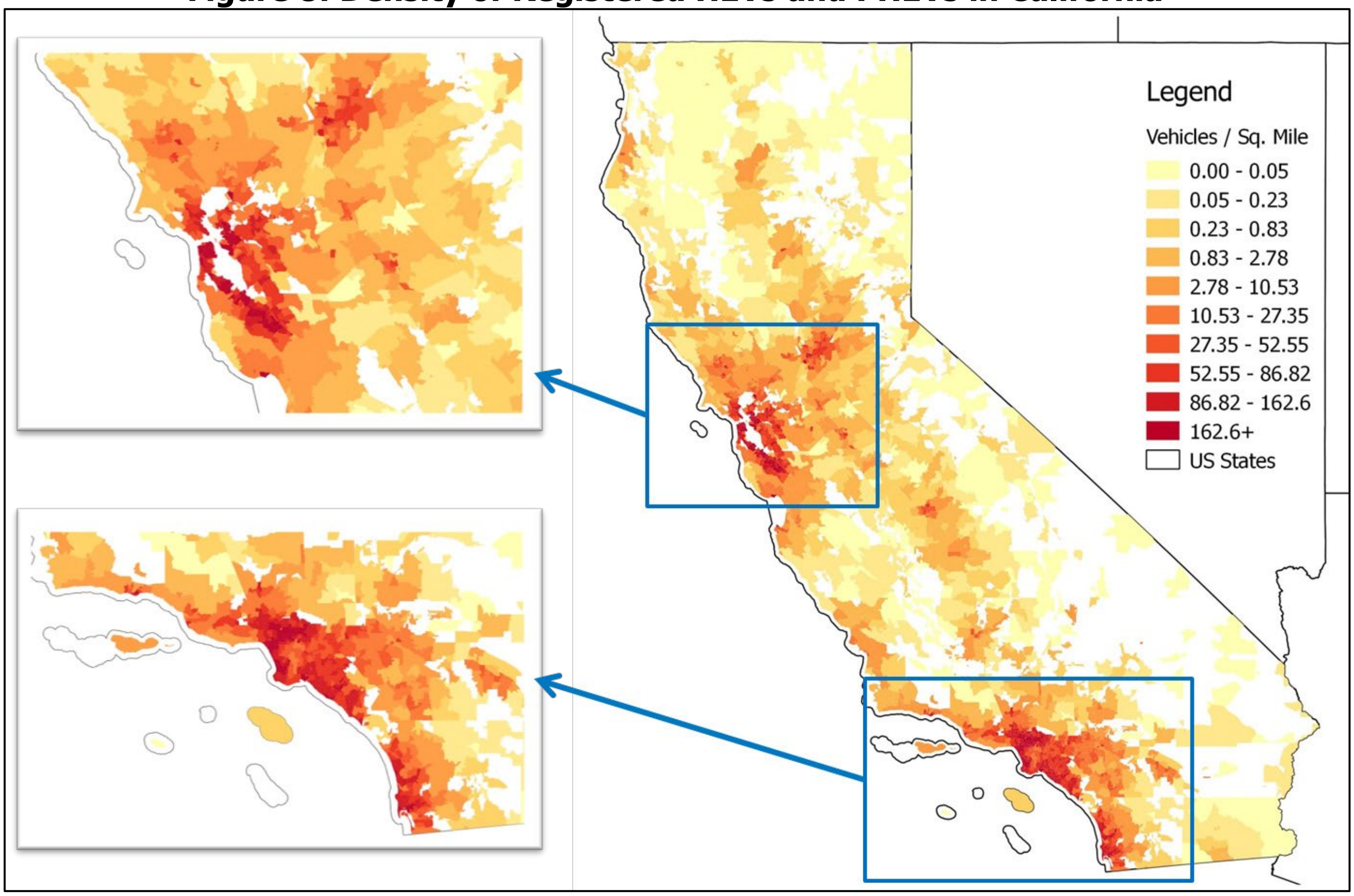



Source: R. L. Polk, C. (2012, November 15). Vehicle Registration Database.

## Geographic Information on Distribution of End-Users

Geographically, the majority of HEVs and PEVs are located near large population centers. Therefore, if the goal is to reach the largest number of customers with limited resources, charging stations and services related to HEVs and PEVs could be located in and around major city centers. Major highways may also be a logical choice for charging locations, which aim to extend the all-electric range of these vehicles. Figure 8 shows the registered number of HEVs and PHEVs in each zip code divided by the corresponding land area. Figure 9 shows the same for BEVs along with the locations of public, private, and planned charging stations from the Alternative Fuel Data Center[4].

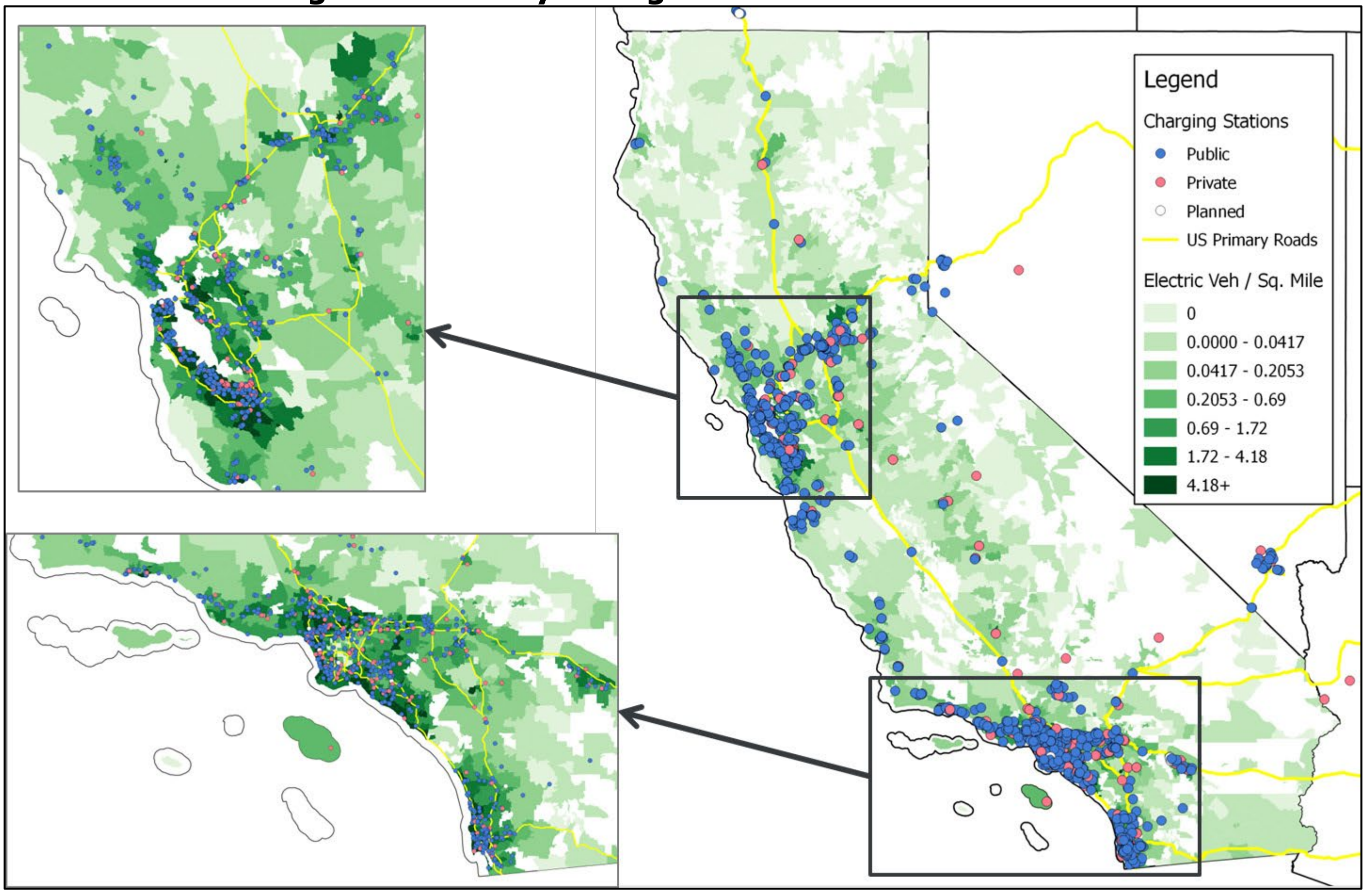
**Figure 8: Density of Registered HEVs and PHEVs in California**




Source: R. L. Polk, C. (2012, November 15). Vehicle Registration Database.

[4] U.S. Department of Energy (DOE), Energy Efficiency & Renewable Energy (EERE): *Alternative Fuels Data Center*. (2013, December 9). Retrieved December 10, 2013. http://www.afdc.energy.gov/

**Figure 9: Density of Registered BEVs in California**




Source: R. L. Polk, C. (2012, November 15). Vehicle Registration Database.

The most common electrical storage devices onboard HEVs and PEVs are rechargeable nickel–metal hydride and lithium-ion battery packs. Nickel– metal hydride batteries are commonly used in HEVs and offer a balance between cost and energy density. However, many leading PEVs use lithium-ion battery packs, which offer higher energy density, resulting in either an extended range or more interior room in the vehicle. Table 2 shows battery pack capacities for leading PEV and EV models.

**Table 2: Leading Hybrid and Electric Vehicle Battery Packs**

| Vehicle | Type | Battery Pack | Supplier |
|---|---|---|---|
| 2013 Toyota Prius | HEV | 1.3 kWh nickel– metal hydride | Primearth |
| 2013 Honda Insight | HEV | 0.6 kWh nickel– metal hydride | Sanyo |
| 2013 Chevrolet Volt | PHEV | 16.5 kWh Lithium-Ion | LG Chem |
| 2013 Toyota Prius Plug-In Hybrid | PHEV | 4.4 kWh Lithium-Ion | Primearth |
| 2013 Ford C-Max Energi Plug-In Hybrid | PHEV | 7.6 kWh Lithium-Ion | Panasonic |
| 2013 Ford Fusion Energi Plug-In Hybrid | PHEV | 7.6 kWh Lithium-Ion | Panasonic |
| 2013 Nissan Leaf | EV | 24 kWh Lithium-Ion | AESC |
| 2013 Tesla Model S | EV | 60 or 85 kWh Lithium-Ion | Panasonic |
| 2013 Ford Focus Electric | EV | 23 kWh Lithium-Ion | LG Chem |

Source: Davis, S., Diegel, S., & Robert, B. (2013). 2012 VEHICLE TECHNOLOGIES MARKET REPORT.

Official U.S. EPA estimates of vehicle range and equivalent fuel economy are derived from chassis dynamometer testing over a set of prescribed driving profiles. Note, however, that the actual on-road fuel economy vehicle owners will experience depends on their specific climate, travel behavior, and driving style. Table 3 details the official fuel economy and range estimates for seven leading PEVs.

**Table 3: U.S. EPA Estimated Performance for Leading PEVs**

| | Combined | Electricity | | Miles per Gallon (mpg) Gasoline Only | | | Vehicle Range (miles) | |
|---|---|---|---|---|---|---|---|---|
| | Miles per Gallon Equivalent (MPGe) | kWh/ 100 miles | Watt-hour/ miles | City | Combined | Hwy | Electric | Total |
| 2013 Chevrolet Volt | 98 | 35 | 350 | 35 | 37 | 40 | 38 | 380 |
| 2013 Toyota Prius Plug-In Hybrid | 95 | 29 | 290 | 51 | 50 | 49 | 11 | 540 |
| 2013 Ford C-Max Energi Plug-In Hybrid | 100 | 34 | 340 | 44 | 43 | 41 | 21 | 620 |
| 2013 Ford Fusion Energi Plug-In Hybrid | 100 | 34 | 340 | 44 | 43 | 41 | 21 | 620 |
| 2013 Nissan Leaf | 115 | 29 | 290 | All Electric | | | 75 | N/A |
| 2013 Tesla Model S | 89 | 38 | 380 | | | | 265 | |
| 2013 Ford Focus Electric | 105 | 32 | 320 | | | | 76 | |

Source: U.S. Department of Energy (fueleconomy.gov/)

PEVs are typically charged using utility-grid power through a standard connector. However, other power sources can include local micro-grids, such as an array of solar panels or local wind turbines, to supplement utility power when available. The requirements for the standard connector used by most vehicles is described in Society of Automotive Engineers (SAE) International's "SAE Surface Vehicle Recommended Practice J1772, SAE Electric Vehicle Conductive Charge Coupler," commonly referred to as SAE J1772. The standard connector has five pins. AC Line 1, AC Line 2, and Ground make up the three large pins; Proximity Detection and Control Pilot make up the two smaller pins. Proximity Detection prevents the vehicle from moving while connected to the charger, and the Control Pilot allows the vehicle and supply equipment to communicate and negotiate the maximum allowable current, known as ampacity.

Currently J1772 has two finalized levels:

- AC Level 1: uses single phase 120 volts alternating current with a peak current rating of 16 amps (A)(1.9 [kilowatts] kW).
- AC Level 2: uses split phase 240 volts alternating current and was originally defined with a 32 A capacity (7.7 kW) but was revised in 2009 to accommodate up to 80 A (19.2 kW).

A connector based on SAE J1772 that utilizes direct current (DC) voltage has been proposed, but not finalized yet. The proposed levels are as follows.

- DC Level 1: 200-450 voltage direct current with a current rating of 80 A (36 kW).
- DC Level 2: 200-450 voltage direct current with a current rating of 200 A (90 kW).

CHAdeMO is another proposed global standard that would support up to 62.5 kW of high-voltage DC. Both of these proposed high-voltage DC fast-charging standards aim to move the rectifier circuitry, which transforms AC to DC, out of the vehicle. Currently, alternating current, which is native to the utility grid, is transformed to direct current, which is native to the vehicle batteries, inside the vehicle's on-board charger. This adds cost, weight, a considerable thermal load and corresponding inefficiencies during charging. A centrally located unit shared by multiple vehicles helps to distribute the cost and is more accessible to external cooling for the power electronics.

The EV Project, which is the largest on-going EV infrastructure demonstration project in the world, set out to monitor the usage trends from approximately 13,000 AC Level 2 electric vehicle supply equipment (EVSE) residential and commercial chargers, as well as 200 DC fast chargers, and collect usage data from approximately 8,300 light-duty EVs. As of September 2013, the project has nearly 8,200 residential and over 3,750 commercial chargers online, as well as 87 DC fast chargers, logging over 2.9 million charging events. Data analysis and quarterly reports on the data gathered through the EV Project are available through Idaho National Laboratory.[5] Understanding vehicle charging, and usage trends is important for predicting how these vehicles will affect the utility grid as market penetration continues to rise. Adverse effects to the grid can be mitigated by using techniques such as smart charging. Smart charging waits to charge a vehicle expected to be connected for an extended duration, such as overnight, until grid demand and/or electricity pricing has come down. In a smart charging system, special care still needs to be taken to ensure a large number of vehicles are not coming online simultaneously, but are instead staggered, to minimize the impacts to the grid. An active area of research, which goes one step further, is vehicle-to-grid where a vehicle could sell energy back to the utility grid under conditions of peak demand helping to smooth the demand seen by the power company. Estimates of the value this could potentially provide to the utility company reach as high as $4,000 a year per vehicle[6].

Along with estimated fuel economy and range, the U.S. EPA provides estimated charge times to fully recharge a completely depleted PEV using an AC Level 2 (240 volts alternating current)

[5] EV Project https://www.energy.gov/eere/vehicles/avta-ev-project
[6] Boyle, E. (2007, December 9). *Car Prototype Generates Electricity, And Cash*. Retrieved from University of Delaware: http://www.udel.edu/PR/UDaily/2008/nov/car112807.html

system. Estimated charge times are shown in Table 4 along with calculated average power and current based on the advertised battery capacity.

**Table 4: U.S. EPA Estimated Charge Time and Calculated Average Load**

| Vehicle | Advertised Battery Capacity (kWh) | EPA Estimated Charge Time (hours) @ 240 volts alternating current | Calculated Average Power (kW) | Calculated Average Current (A) |
|---|---|---|---|---|
| 2013 Chevrolet Volt | 16.5 | 4 | 4.1 | 17.2 |
| 2013 Toyota Prius Plug-In Hybrid | 4.4 | 1.5 | 2.9 | 12.2 |
| 2013 Ford C-Max Energi Plug-In Hybrid | 7.6 | 2.5 | 3.0 | 12.7 |
| 2013 Ford Fusion Energi Plug-In Hybrid | 7.6 | 2.5 | 3.0 | 12.7 |
| 2013 Nissan Leaf | 24 | 7.25 | 3.3 | 13.8 |
| 2013 Tesla Model S | 85 | 12 | 7.1 | 29.5 |
| 2013 Ford Focus Electric | 23 | 4 | 5.8 | 24.0 |

Source: U.S. Department of Energy (fueleconomy.gov/)

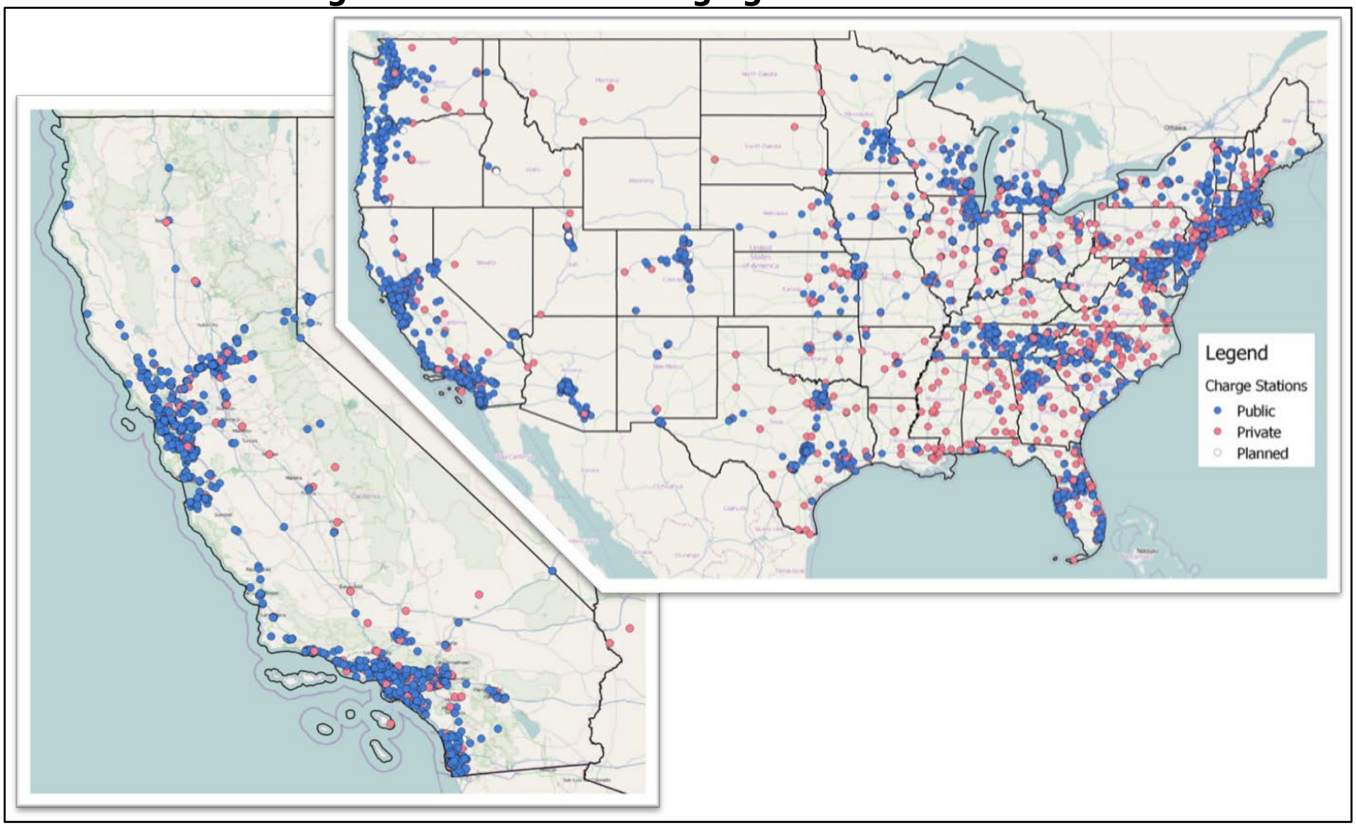
## Barriers to Widespread Commercialization and Deployment

Particularly in the absence of purchase incentives and/or elevated fuel prices, the incremental cost of PEVs (and to a lesser extent HEVs) can serve to hinder their market penetration. This barrier will diminish to the extent that continued cost reductions can be achieved in components such as vehicle batteries, electric motors, and power electronics. The combination of limited range and slow recharging can be an additional barrier for BEVs. Unlike a gasoline vehicle that can be refueled in minutes, or a PHEV that can seamlessly switch fuels, BEV recharge times can be considerable and a concern for potential purchasers, especially if one only has access to an AC Level 1 connection. Charging for a number of hours at home overnight may not be an issue for instance an 8-hour Level 1 charge could provide 50 miles of driving range. However, when a daily drive-cycle requires more than one charge to provide the desired range, then further conditions become necessary to promote market growth and maximize the miles of electrified driving that can be achieved. These may include:

- Access to charging stations at the workplace.
- Access to charging stations while running errands such as at grocery, and convenience stores, as well as public shopping centers.
- Access to fast charging and/or battery swapping accommodations for long trips.

Nationwide, there is an ever-expanding network of public charging sites. However, there are still areas of the country where long-distance trips in an all-electric vehicle can be challenging. Figure 10 shows California and U.S. public, private, and planned charging locations.

**Figure 10: National Charging Station Locations**




Source: U.S. Department of Energy, Energy Efficiency & Renewable Energy: *Alternative Fuels Data Center*. (2013, December 9). Retrieved December 10, 2013.

## Average Petroleum, GHG and Air Pollution Reduction Estimates

Using [ADOPT](http://www.nrel.gov/adopt) (http://www.nrel.gov/adopt), which will be discussed in further detail in Chapter 3, a baseline estimate of the lifetime petroleum savings and vehicle emission savings for the leading HEVs and BEVs was established. The following analysis incorporates a number of assumptions, including:

- Average vehicle miles traveled (VMT) of 12,510 miles / year[7]
- Average passenger vehicle lifetime of 15 years[7]
- U.S. Energy Information Administration (EIA) GHG coefficients[8]

Lifetime fuel use was calculated for each HEV or PEV and its comparable conventional vehicle using U.S. EPA fuel economy estimates, average VMT, and average passenger vehicle lifespan. Corresponding GHG coefficients for gasoline and electricity were used to calculate the lifetime

---

[7] U.S. Department of Transportation. (2005). *ANNUAL VEHICLE DISTANCE TRAVELED IN MILES AND RELATED DATA*. Retrieved from U.S. Department of Transportation Federal Highway Administration: https://www.fhwa.dot.gov/ohim/hs00/vm1.htm

[8] EIA. (n.d.). *Voluntary Reporting of Greenhouse Gases Program Fuel Emission Coefficients*. Retrieved from U.S. Energy Information Administration: https://www.eia.gov/environment/pdfpages/0608s(2009)index.php

carbon dioxide emissions. The analysis in Table 5 shows how simple displacement estimates can be made for specific make-model combinations using the assumptions above.

**Table 5: Petroleum and GHG Displacement Estimates for Leading HEVs and PEVs**

| | | | **Lifetime Displaced per Vehicle** | |
|---|---|---|---|---|
| **Technology** | **Vehicle** | **Comparable Vehicle** | **Gasoline (gal)** | **$CO_2$ (pounds)** |
| Gas Electric Hybrid | Toyota Prius Hatchback | Toyota Corolla/Matrix | 2,560 | 50,288 |
| | Toyota Camry Hybrid | Toyota Camry | 1,806 | 35,484 |
| Plug-In Hybrid | Chevrolet Volt | Chevrolet Cruze | 3,843 | 23,032 |
| | Toyota Prius Plug-In Hybrid | Toyota Corolla/Matrix | 3,502 | 51,003 |
| | Ford C-Max Energi Plug-In Hybrid | Ford Fiesta | 3,014 | 23,990 |
| Battery Electric | Nissan Leaf | Nissan Versa | 5,354 | 19,672 |
| | Tesla Model S | BMW z4 | 6,849 | 38,976 |
| | Ford Focus Electric | Ford Focus | 5,873 | 34,905 |

Source: U.S. Department of Energy (fueleconomy.gov/)

More extensive well-to-wheel studies, taking into account a large number of factors including regional power generation mixtures and the petroleum distribution network, have developed displacement estimates for the PHEV market as a whole using the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed by Argonne National Laboratory. Results have shown recharging PHEVs from a utility that utilizes a large share of efficient natural gas, such as the Western Electric Coordinating Council, which serves California, produces comparable GHG emissions to gasoline HEVs, but significantly lower GHG emissions than those of baseline gasoline vehicles (-25 percent to -40 percent). PHEVs recharging from an energy source mixture comparable to the U.S. average mix still produce lower GHG emissions than baseline gasoline vehicles (-20 percent to -25 percent) but by a smaller margin[9].

## Medium- and Heavy-Duty Hybrid and Electric Vehicles

Medium-duty and heavy-duty commercial vehicles offer an additional market for HEVs and PEVs. The ability to recapture kinetic energy during a braking event, store that energy, and later release it to assist vehicle propulsion yields particularly significant benefits on routes that include frequent stops. For this reason, commercial HEVs and PEVs have seen the greatest

---

[9] Elgowainy, A., Han, J., Poch, L., Wang, M., Vyas, A., Mahalik, M., et al. (2010, June). *Well-to- Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Plug-In Hybrid Electric Vehicles*. *ANL/ESD/10-1*. http://www.afdc.energy.gov/pdfs/argonne_phev_evaluation_report.pdf.

market penetration in sectors such as product delivery, municipal, utility, and telecommunications vehicles (CALSTART, 2012). Relative to light-duty vehicles, the commercial HEV and PEV market size and data availability is much more limited. As a result, this section will feature a more abbreviated discussion of hybridization and electrification benefits in medium- and heavy-duty vehicles, drawing largely on in-use operating data for recent commercial HEVs and PEVs.

As part of the Hybrid Voucher Incentive Program funded through California AB118, a subset of over 80 HEV's were instrumented with data collection devices for 2–3 weeks and collected 1-hertz in-use CAN bus and GPS data. While collecting data from the HEVs, a number of conventional diesel vehicles were also instrumented for comparison. This resulted in a final dataset that included over 120 unique vehicles from eight different fleets covering beverage, linen, food, and parcel delivery (Thornton, TBD)[10]. Additionally, data collected through American Recovery and Reinvestment Act-funded deployment and demonstration projects by Smith Electric Vehicles and Navistar have supplied second-by-second in-use data from BEVs being used in delivery applications. Quarterly and cumulative summaries of the data are made publicly available.[11]

## Technology Status

To provide insight into technology status for commercial vehicle applications, this section details evaluation results from the aforementioned recent HEV and BEV deployment programs. A preliminary look at the results from in-use data collected in support of the Hybrid Voucher Incentive Program project have shown that the benefits from hybridization can be wide ranging depending on the route and driver behavior. Chassis dynamometer tests were also performed at the Center for Environment Research & Technology at University of California Riverside. Chassis dynamometer testing offers the opportunity to conduct a more tightly controlled side-by-side comparison of hybrid and conventional diesel vehicles over the same test cycle. The majority of the vehicles from the in-use data collection that received Hybrid Voucher Incentive Program vouchers were Freightliner MT45 or MT55 chassis in a step-van configuration with Cummins ISB diesel engines and Eaton Hybrid Drive Systems.

NREL's Drive-Cycle Rapid Investigation, Visualization, and Evaluation[12] analysis tool was used to process the collected 1-hertz real-world in-use driving data and determine which standard test cycles would be most representative for the chassis dynamometer testing. Both the conventional diesel vehicles and HEVs were then tested using a chassis dynamometer on the resulting standard test cycles. Preliminary results have shown that increases to fuel economy are highly dependent on the test cycle with results ranging from a 2 percent to 40 percent increase in fuel economy with an average of 22 percent for HEVs with an Eaton Hybrid Drive System.

The first generation of Smith Newton BEVs participating in the American Recovery and Reinvestment Act demonstration project, were equipped with 80-kWh lithium-ion (iron

---

[10] Thornton, M. (TBD). *Report on Data Collection, Testing and Analysis of Hybrid Electric Trucks Operating in California Fleets.*

[11] NREL Electric and Plug-In Hybrid Electric Fleet Vehicles https://www.nrel.gov/transportation/fleettest-electric.html

[12] NREL Drive-Cycle Rapid Investigation, Visualization and Evaluation https://www.nrel.gov/transportation/drive.html

phosphate [$LiFePO_4$]) battery packs from Valence Energy Storage Solutions. The packs used two parallel strings of 24x U27-12XP packs.

Subsequent models offered three parallel strings for a total capacity of 120 kWh. The Smith Vehicles utilize an onboard charger that conforms to the SAE J1772 standard. All vehicles in this American Recovery and Reinvestment Act Smith Newton study are in weight class 6 with 80-kWh battery packs and had an advertised range of 40–100 miles.

Navistar eStar BEVs participating in the American Recovery and Reinvestment Act demonstration project had 80-kWh lithium-ion battery packs from A123 Systems. These vehicles also used an onboard charger that conformed to the J1772 standard. The Navistar eStar, which is in weight class 3, is considerably smaller than the Smith Newton. Its smaller size reduces the payload; however, the smaller form factor and reduced weight demonstrated a lower AC energy use per mile than the Smith Newton.

The Navistar eStar had an advertised all-electric range of 100 miles. The Navistar eStar is no longer in production but the initial deployment of vehicles is still in operation.

Specifications and results from the Smith Newton and Navistar eStar BEVs are shown side-by-side in Table 6.

**Table 6: American Recovery and Reinvestment Act Demonstration BEV Specifications and Select Results**

| Vehicle Specifications | Smith Newton - Class 6 | Navistar eStar - Class 3 |
|---|---|---|
| |  Source: NREL Photo 22851 |  Source: NREL Photo 18624 |
| GVWR | 22,000 – 26,000 pounds | 12,122 pounds |
| Payload | 12,000 – 16,000 pounds | 5,100 pounds |
| Charging Standards | J1772 or 3-phase | J1772 |
| Onboard Charger Power | 5 – 6 kW | 7 kW |
| Battery Capacity | 80 kWh | 80 kWh |
| Battery Technology | Lithium-Ion Iron Phosphate | Lithium-Ion |
| Peak Motor Power | 134 kW | 70 kW |
| **Results** | | |
| Reporting Period | 11/1/2011 – 9/29/2013 | 7/1/2012 – 9/30/2013 |
| Number of Vehicles | 259 | 101 |
| Number of Cities | 81 | 35 |
| Vehicle Days Driven | 59,518 | 10,713 |
| Total Miles Driven | 1,541,146 | 196,659 |
| Overall AC Energy Use | 1.83 kWh/mile | 0.915 kWh/mile |
| Average Daily Distance | 25.9 miles | 18.4 miles |
| Average Stops per Day | 49 | 116 |
| Average Stops per Mile | 2.4 | 6.3 |

Source: NREL [Electric and Plug-In Hybrid Electric Fleet Vehicles](https://www.nrel.gov/transportation/fleettest-electric.html) (https://www.nrel.gov/transportation/fleettest-electric.html)

## Payback Analysis

Using the in-use observed performance of the Hybrid Voucher Incentive Program hybrid and conventional vehicles along with the American Recovery and Reinvestment Act BEVs, estimates of annual fuel and cost savings have been determined for both the HEV and BEV technologies. Note that the lesser of the two vehicles observed VMT was assumed for this calculation, and that a higher mileage assumption would increase the savings estimate (which underscores the importance of strategically deploying advanced vehicle technologies into duty profiles that maximize their efficiency benefit). Fuel economy values for HEVs, BEVs and conventional vehicles were calculated from observed in-use results for the HEVs and conventional vehicles in the Hybrid Voucher Incentive Program study and also form the American Recovery and Reinvestment Act BEVs. Annual savings were calculated from 2013 average California diesel ($4.23/gallon) and commercial electricity (16.14 ¢/kWh) prices[13]. Results are shown in Table 7.

**Table 7: Medium- and Heavy-Duty Hybrid and Electric Vehicle Fuel Savings**

| Weight Class | Base Vehicle | Alternative Vehicle | Assumed VMT (mi) | Displaced Diesel (gal) | Annual Savings |
|---|---|---|---|---|---|
| 5/6 | Baseline Medium-Duty Diesel Step Van | HEV - Diesel Step Van | 10,306 | 267 | $ 1,128 |
| 5/6 | Baseline Medium-Duty Diesel Step Van | BEV - Smith Electric Newton | 6,752 | 955 | $ 2,045 |
| 3 | Diesel - Isuzu Reach | BEV - Navistar eStar | 4,797 | 425 | $ 1,087 |

Source: California Air Resources Board. (2012, November 14). Implementation Manual for Fiscal Year 2011-12 California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project.

Table 8 shows that the estimated present-day incremental cost associated with purchasing a commercial medium-duty HEV or BEV can be considerable and may not pay back in the lifetime of the vehicle with fuel savings alone. However, through the Hybrid Voucher Incentive Program and in some cases with additional co-funding from other public incentives such as local air districts, up to 90 percent of a qualifying vehicle's cost could be covered, in which case the owner could realize payback and cost savings over the vehicle's usable lifetime. Actual incentive amounts depend heavily on vehicle specifications, and additional co-funding would be dependent on location and available incentives. For more information, please refer to the Implementation Manual for Fiscal Year 2011-12 California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project.

**Table 8: Estimated Vehicle Incremental Cost**

| Class | GVWR | Hybrid | Zero-Emission |
|---|---|---|---|
| 3 | 10,001 - 14,000 pounds | $30,000 | $65,000 |
| 4/5 | 14,001 - 19,500 pounds | $40,000 | $75,000 |
| 6 | 19,501 - 26,000 pounds | $50,000 | $100,000 |

Source: California Air Resources Board. (2012, November 14). Implementation Manual for Fiscal Year 2011-12 California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project.

---

[13] EIA. (2013, November 20). *Electric Power Monthly*. Retrieved December 5, 2013, from U.S. Energy Information Administration: http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a

### Average Petroleum, and GHG Reduction Estimates

Using the same methodology as the fuel and cost savings approach in the previous section, estimates of annual tailpipe GHG reductions are shown in Table 9.

**Table 9: Fuel and Carbon Dioxide Displacement for Select Vehicles**

| Weight Class | Base Vehicle | Alternative Vehicle | Displaced Diesel (gal) | $CO_2$ Reduction (pounds) |
|---|---|---|---|---|
| 5/6 | Baseline Medium-Duty Diesel Step Van | HEV - Diesel Step Van | 267 | 5,969 |
| 5/6 | Baseline Medium-Duty Diesel Step Van | BEV - Smith Electric Newton | 955 | 4,811 |
| 3 | Diesel - Isuzu Reach | BEV - Navistar eStar | 425 | 3,618 |

Source: California Air Resources Board. (2012, November 14). Implementation Manual for Fiscal Year 2011-12 California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project.

As discussed earlier, the characteristics of a particular drive-cycle or route can greatly influence the potential savings of switching to an alternative vehicle. The U.S. Department of Energy's Clean Cities program examined the use of over 141,000 HEVs and almost 18,000 EVs in 2012 over a wide range of applications and vehicle weight classes. Their finds estimated the average petroleum displacement to be 280 gallons of gasoline equivalent (gge) per HEV and 662 gge per EV. Using GREET, the study also found the average estimated GHG reductions to be 3.5 tons of carbon dioxide equivalent (CO2e) per HEV and 1.3 tons CO2e per EV (Johnson, 2013)[14].

## Alternative Fuels (FFV, LPG, CNG, and LNG) and Light-Duty Diesel

This section examines a number of alternative fuels already being used on-road, including flexible-fuel vehicles, LPG, CNG, and LNG, as well as light-duty diesel use. Diesel has always had a large presence in the medium- and heavy-duty markets, especially in long-haul applications, and has been gaining in popularity as an alternative to gasoline for light-duty vehicles in recent years. Increased efficiency from diesel engines compared with gasoline engines combined with diesel having a higher volumetric energy density offers higher fuel economy and extended range from a fuel already readily available at the pump.

flexible-fuel vehicles are able to operate on regular gasoline, which contains up to 10 percent ethanol, as well as blends containing up to 85 percent ethanol, commonly referred to as E85. This can be readily achieved in a traditional spark ignition engine so long as material compatibility is ensured, and the engine has the ability to detect and adjust the fuel-air ratio as the stoichiometric ratios for gasoline and ethanol are significantly different. Recently, blends

[14] Johnson, C. (2013). *Clean Cities 2012 Annual Metrics Report (NREL/TP-5400-60274).* National Renewable Energy Laboratory.

containing up to 15 percent ethanol have been approved by the U.S. EPA for use in gasoline vehicles MY 2001 and newer, as well as all flexible-fuel vehicles.[15]

LPG or propane can be injected into a spark ignition engine as a gas; however, under moderate pressures, propane can easily be stored onboard the vehicle as a liquid. On-road vehicles are not typically sold from the OEM as using propane but can be ordered ready to accept a conversion kit. Typically, a qualified system retrofitter will install a conversion kit that is already approved by the U.S. EPA. The cost to convert a light-duty vehicle from gasoline to propane ranges from $4,000 to $12,000 (Alternative Fuels Data Center, 2013[16]).

Natural gas can also be readily injected into a spark ignition engine as a gas. The natural gas is stored on the vehicle in one of two ways, either under high pressure known as CNG or at cryogenic temperatures where natural gas turns to liquid known as LNG. A joint venture by Cummins-Westport offers an OEM natural gas solution for medium-duty and heavy-duty applications. Vehicles such as the Honda Civic can be purchased as a light-duty OEM vehicle, or natural gas vehicles can be converted in the same way as propane vehicles, by a qualified system retrofitter who installs a conversion kit approved by the U.S. EPA.

## Baseline Number and Types of Vehicles

Ten states are home to approximately half of the diesel passenger cars in the United States. California ranks number one in terms of the absolute number of diesel passenger vehicles, Figure 11. However, per capita California's penetration for diesel cars and light trucks is relatively low compared with the rest of the country (Figure 12). Population estimates come from the U.S. Census Bureau[17].

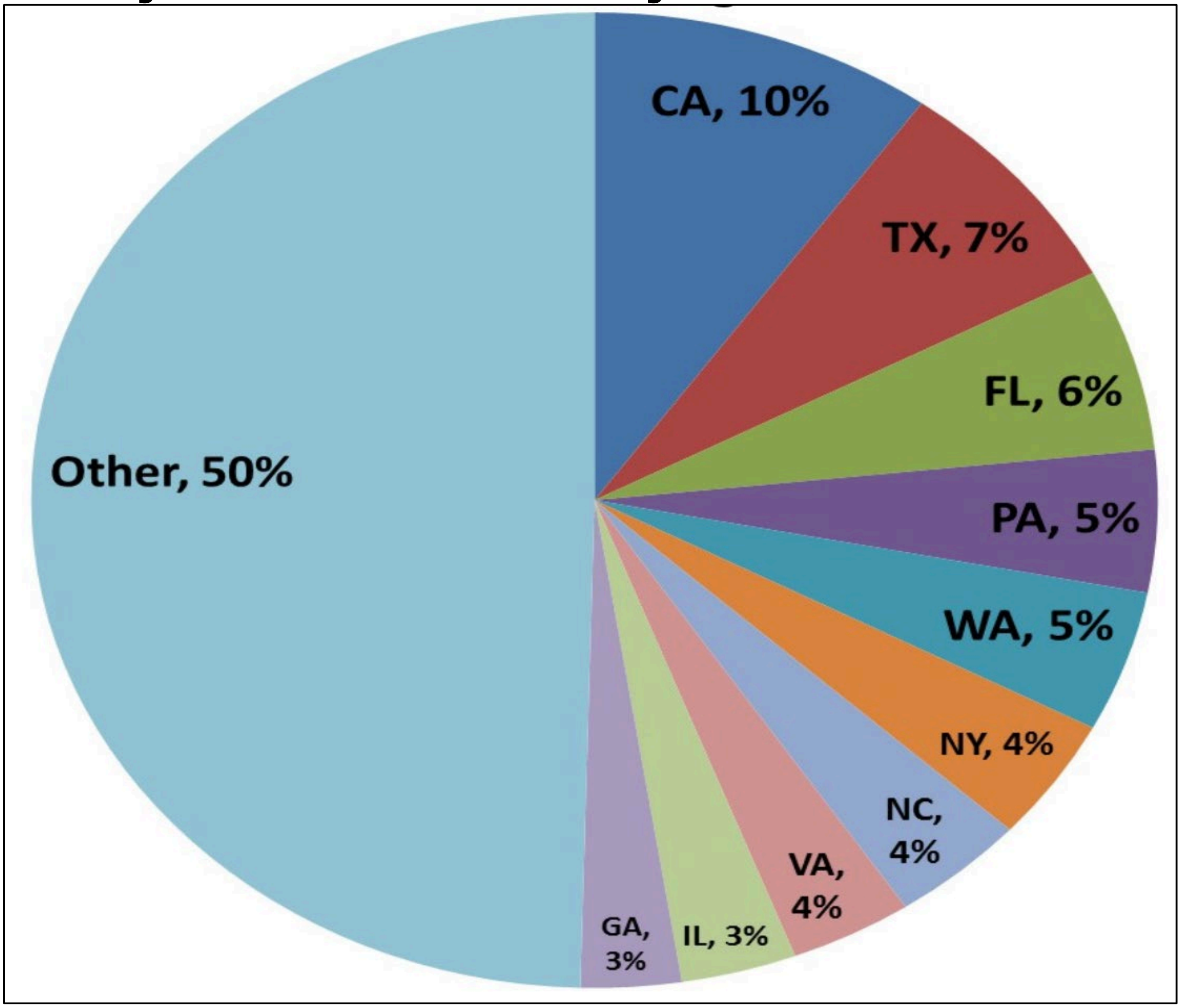
---

[15] U.S. EPA Transportation, Air pollution, and Climate Change http://www.epa.gov/otaq/regs/fuels/additive/e15/

[16] AFDC. (2013, 2 27). *Fuel Properties Comparison*. Retrieved December 5, 2013, from U.S. Department of Energy Alternative Fuels Data Center: http://www.afdc.energy.gov/fuels/fuel_properties.php *Oak Ridge National Laboratory ORN gyL/TM-2013/51*.

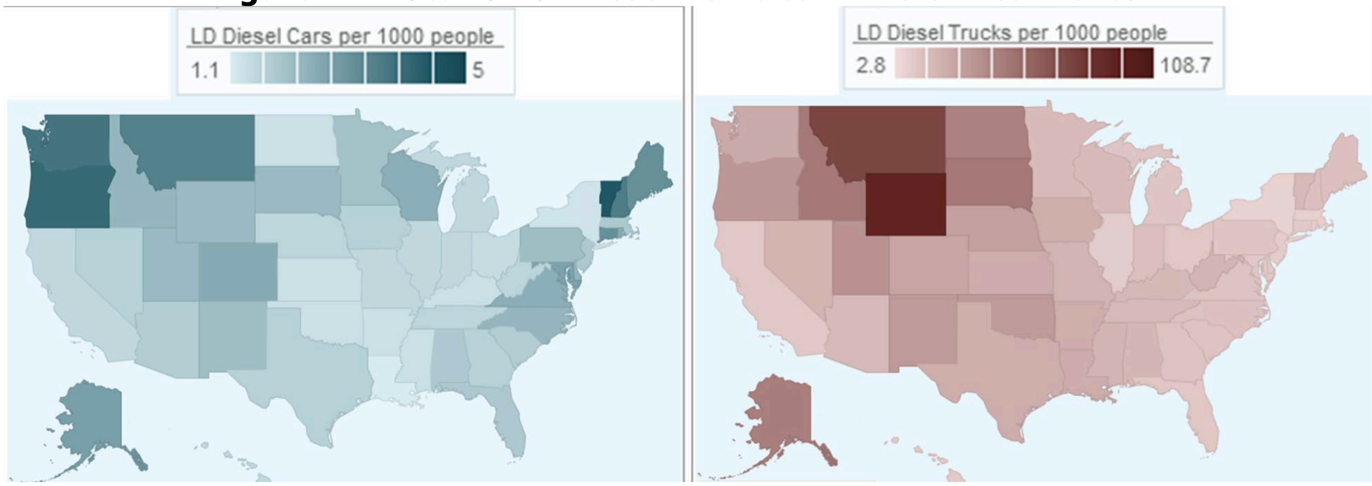
[17] *Population Estimates*. (2012, July 1). Retrieved December 5, 2013, from United States Census Bureau: http://www.census.gov/popest/

**Figure 11: Location of Diesel Passenger Cars in the United States**




Source: R. L. Polk, C. (2012, November 15). Vehicle Registation Database.

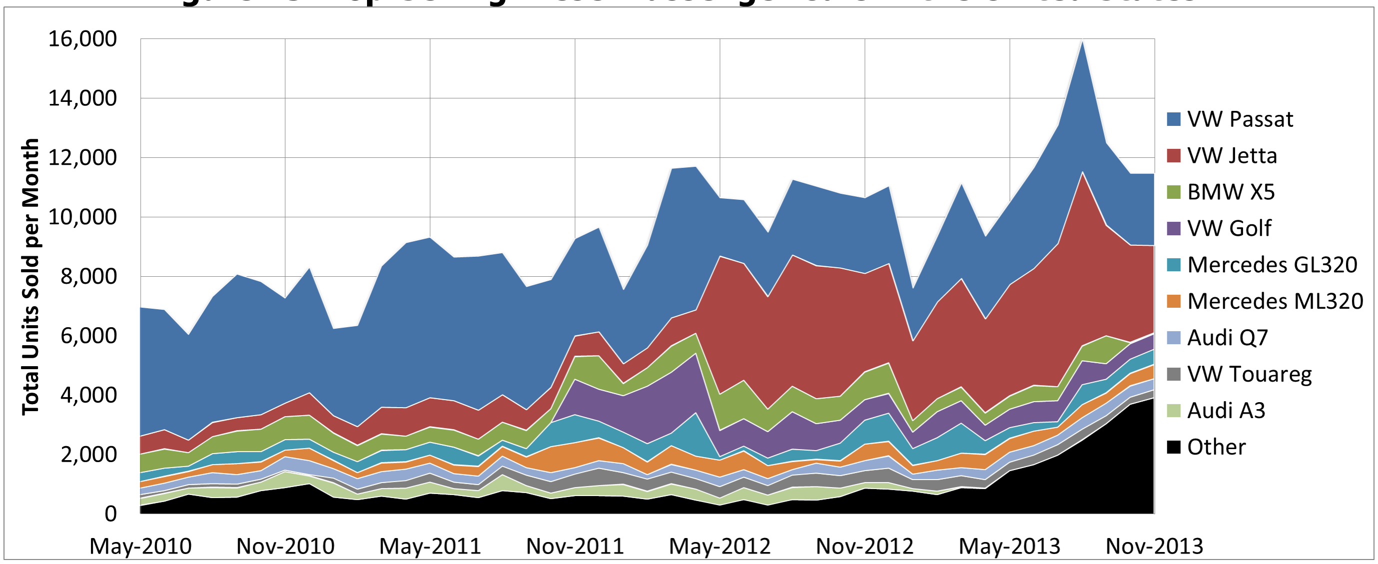
**Figure 12: Location of Diesel Vehicles in the United States**




Source: R. L. Polk, C. (2012, November 15). Vehicle Registation Database.

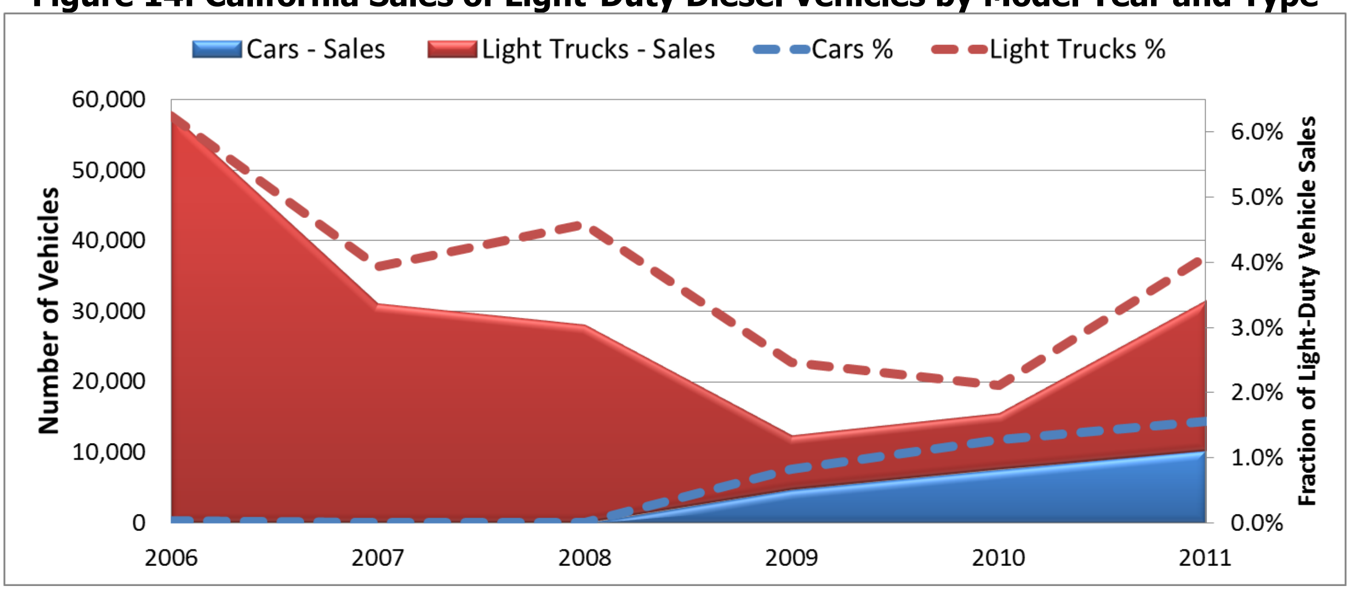
National sales of diesel passenger cars have been on the rise, with the Volkswagen Passat and Jetta leading the way in recent years (Figure 13). Diesel car sales in California have followed suit, steadily increasing since 2009. However, diesel light-truck sales saw a dip around that time and have not returned to the highs seen in 2006 (Figure 14). California sales of MY2011 diesel passenger cars fell between California sales of BEVs and HEVs for the same model year.

**Figure 13: Top-Selling Diesel Passenger Cars in the United States**




Source: Cobb, J. (n.d.). Electric Vehicle Sales Dashboard. Retrieved December 5, 2013

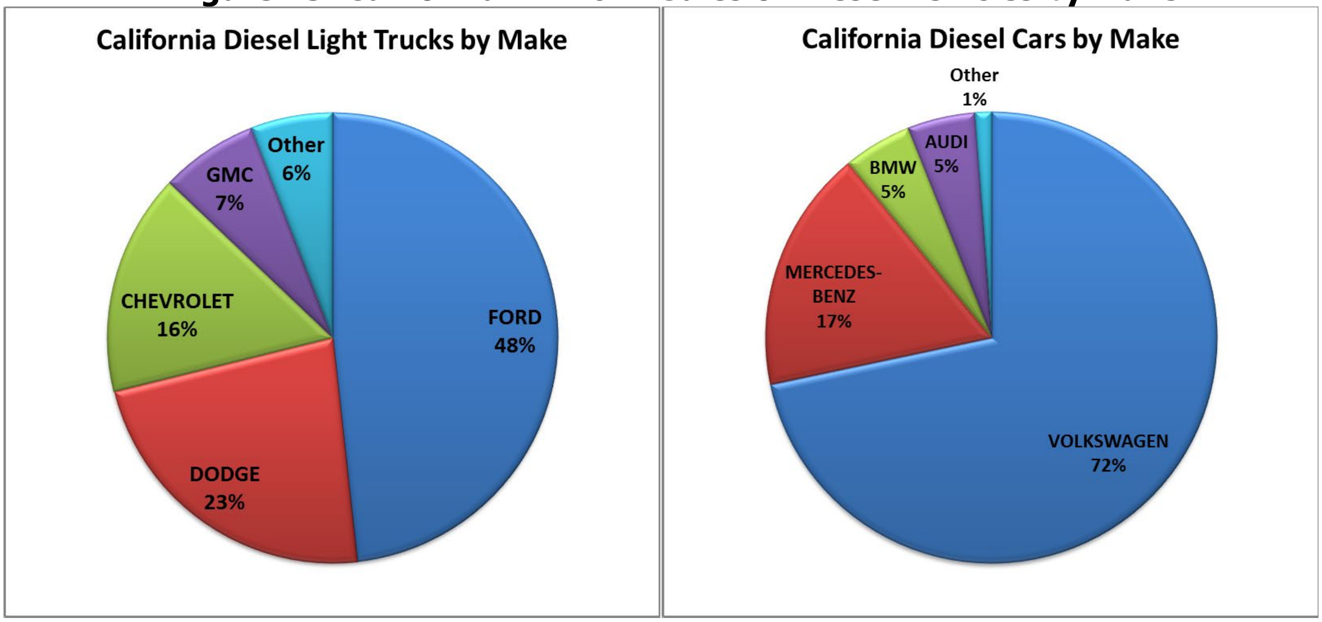
**Figure 14: California Sales of Light-Duty Diesel Vehicles by Model Year and Type**




Source: R. L. Polk, C. (2012, November 15). Vehicle Registation Database.

California registered diesel passenger cars and light trucks are grouped by vehicle make (Figure 15). Diesel car registrations are led by Volkswagen, namely the Jetta, Golf, and Passat models, all of which use the turbocharged direct injection diesel engine. Diesel light-truck registrations are led by trucks in weight class 2b and up, which includes the Ford F-250 and F-350, along with the Dodge Ram 2500 and Ram 3500, leaving a gap of weight class 2a, which has not seen significant penetration into the light-duty diesel market even though class 2a trucks such as the Ford F-150 and Dodge Ram 1500 do well nationally in the gasoline market.

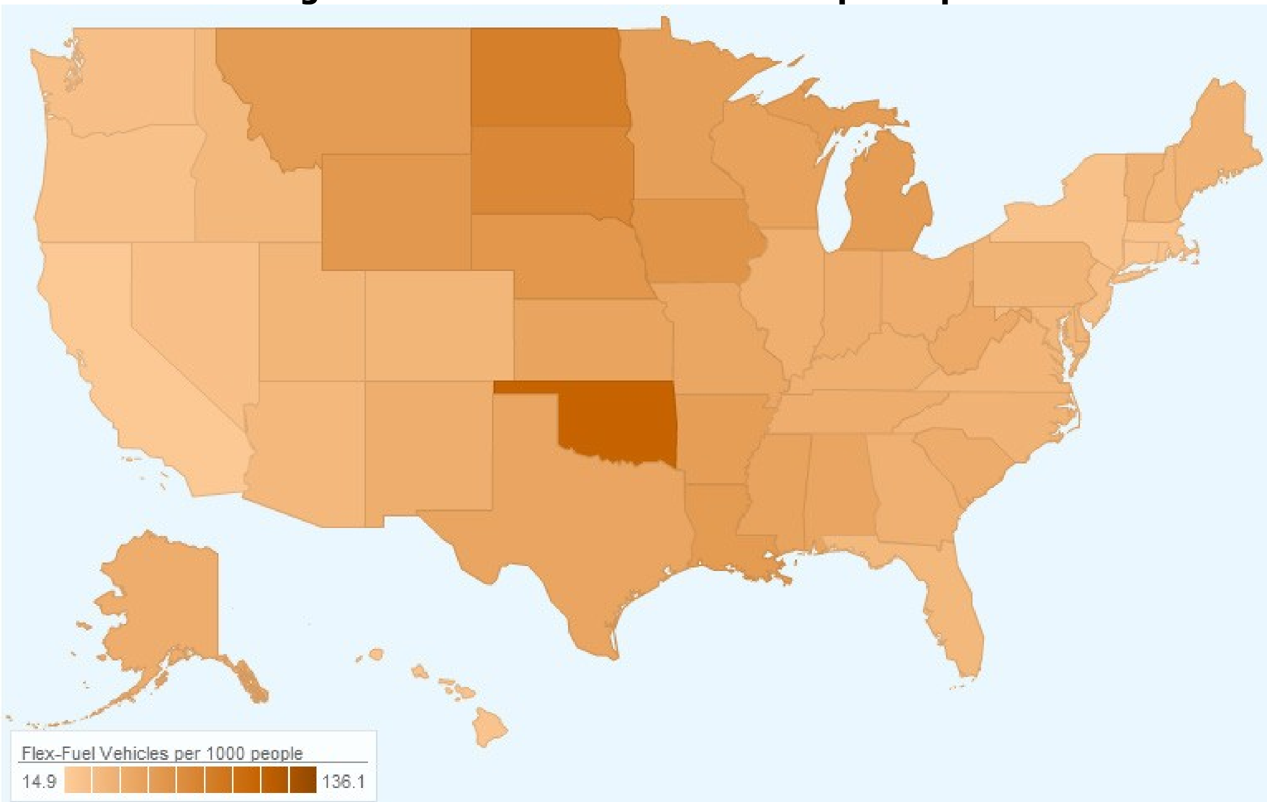
**Figure 15: California MY 2011 Sales of Diesel Vehicles by Make**




Source: R. L. Polk, C. (2012, November 15). Vehicle Registation Database.

As shown in Figure 16, per capita FFV sales have been most significant in the Midwest and surrounding states, which happen to also be locations where much of the ethanol feedstock is produced. Table 10 shows MY 2011 top-selling flex-fuel vehicles. California has a below-average take rate on almost all of the top 10 models except the Ford Crown Victoria, which is commonly purchased by large fleets such as taxi companies and law enforcement.

**Figure 16: Flexible Fueled Vehicles per Capita**




Source: R. L. Polk, C. (2012, November 15). Vehicle Registation Database.

**Table 10: MY 2011 Top-Selling Light-Duty Flexible Fuel Vehicles in California**

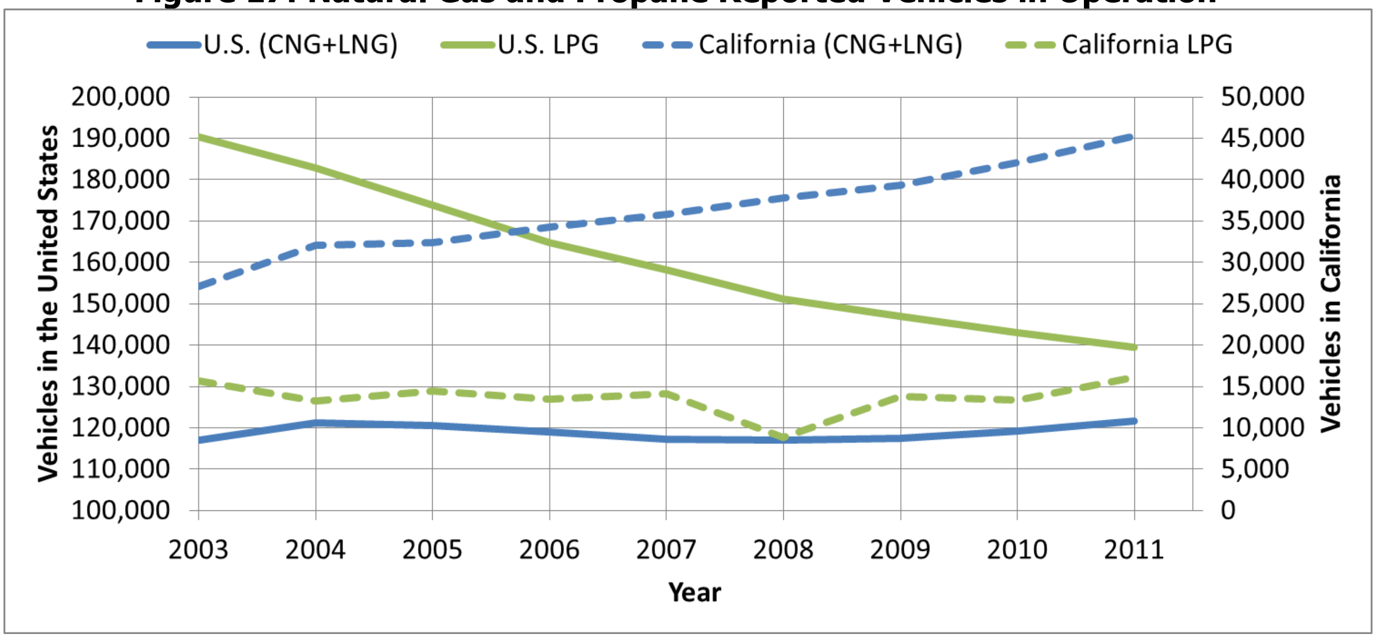
| Make | Model | CA | US | CA Market Share |
|---|---|---|---|---|
| CHEVROLET | SILVERADO | 20,319 | 392,071 | 5 percent |
| FORD | F150 | 14,462 | 252,755 | 6 percent |
| FORD | CROWN VICTORIA | 6,794 | 53,936 | 13 percent |
| GMC | SIERRA | 6,611 | 140,265 | 5 percent |
| CHEVROLET | TAHOE | 5,764 | 84,140 | 7 percent |
| CHEVROLET | IMPALA | 5,295 | 170,387 | 3 percent |
| CHEVROLET | HHR | 5,197 | 66,736 | 8 percent |
| FORD | ESCAPE | 4,731 | 98,655 | 5 percent |
| JEEP | GRAND CHEROKEE | 4,643 | 98,520 | 5 percent |
| DODGE | GRAND CARAVAN | 3,841 | 65,836 | 6 percent |

Source: R. L. Polk, C. (2012, November 15). Vehicle Registation Database.

Organizations that operate alternatively fueled vehicles are required by the Federal Energy Administration Act of 1974 to complete form EIA-886. The EIA then makes this information public, which is the basis for the following charts. This information is self-reported and helps to obtain data about vehicles that have been converted from their original fuel type, which is especially important for propane and natural gas vehicles. Figure 17 shows propane vehicles (LPG) have been in steady decline across the United States since 2003, but they have held steady in California. Conversely, natural gas vehicles (CNG and LNG) have held steady across the United States but have seen a significant increase in California.

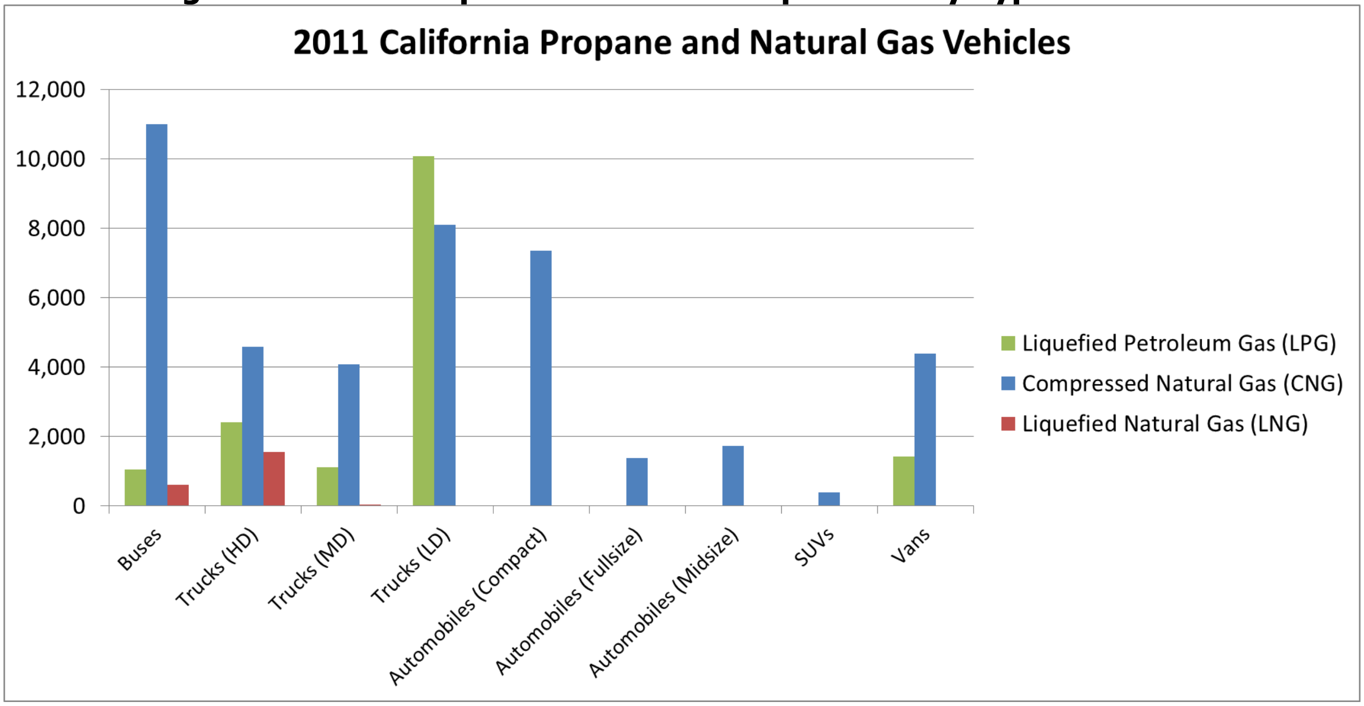
Figure 18 shows reported vehicle type by fuel. CNG has seen the most significant penetration into the bus market. Propane is often used in utility vehicles and shows its most significant gains in the light-duty truck market. LNG is less common but offers a higher energy density than CNG and would make sense for applications where CNG might be a constraint on range, like heavy-duty trucks traveling longer distances.

**Figure 17: Natural Gas and Propane Reported Vehicles in Operation**




Source: U.S. Energy Information Administration. *Alternative Fuel Vehicle Data*. (2013, April 8). Retrieved December 5, 2013

**Figure 18: 2011 Reported Vehicles in Operation by Type and Fuel**

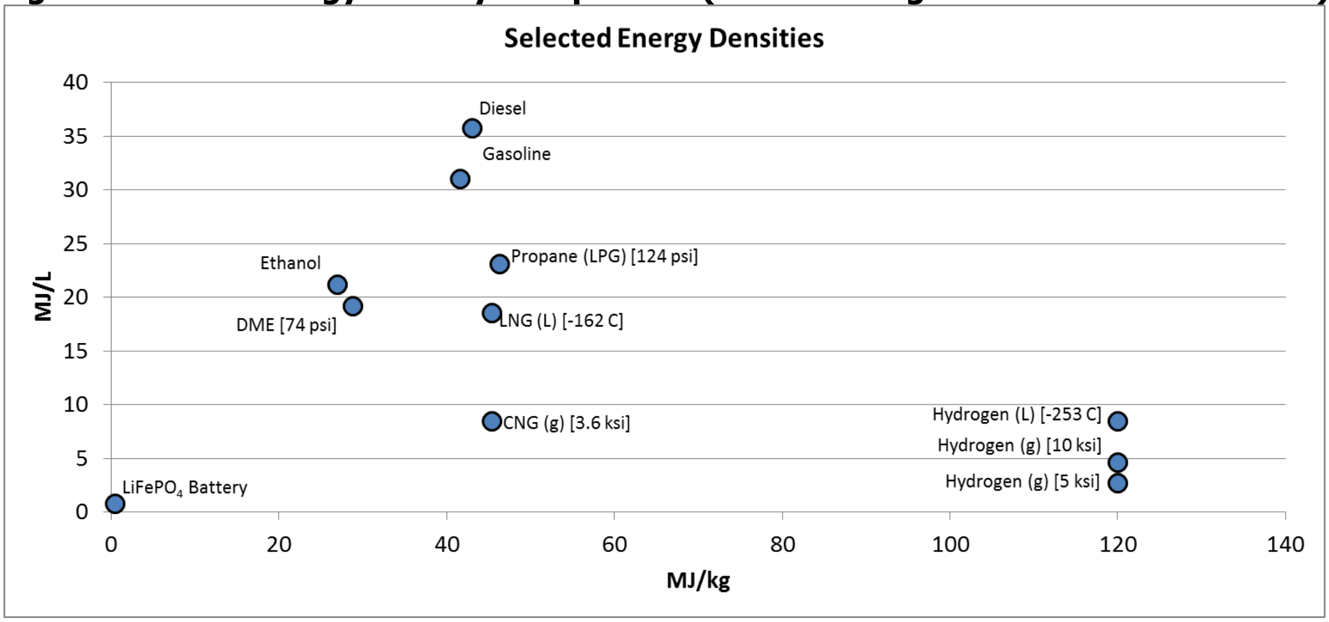



Source: U.S. Energy Information Administration. *Alternative Fuel Vehicle Data*. (2013, April 8). Retrieved December 5, 2013

## Energy Density and Storage on the Vehicle

Figure 19 compares the energy density of a number of fuels both on a mass and volume basis. When space is the dominating constraint, diesel fuel offers the most effective solution, followed by gasoline. Propane requires only moderate pressure, ~124 pounds per square inch, to be stored as a liquid at room temperatures whereas natural gas and hydrogen require high pressures to achieve volumetric energy densities at room temperature, which allow for a reasonable vehicle range. Cryogenic storage can be an effective way of increasing the volumetric energy density; however, the fuel needs to be stored in a vacuum-insulated Dewar tank. This type of tank is more expensive than the simple single-layer metal or plastic tanks used with low pressure fuels. Also, the thermal insulation is not perfect, and cryogenic fuels will eventually boil off if they are not used.

**Figure 19: Fuel Energy Density Comparison (not including the Containment Vessel)**




Source: Robert Bosch GmbH. (2007). *Automotive Handbook.*

## Average Petroleum and GHG Reduction Estimates

There are a number of factors affecting the quantity of petroleum and GHGs displaced by an alternative fuel vehicle. As discussed earlier, these vehicles may be used in a wide range of applications spanning the full range of weight classes from light-duty personal vehicles to heavy-duty commercial vehicles. Therefore, the fuel economy of each vehicle as well as the number of miles traveled annually will play an important role. The Clean Cities *2012 Annual Metrics Report* compiles submitted data from a number of sources to put together estimated petroleum displacement by fuel type under the real-world conditions and applications these vehicles are operating in. Table 11 expresses the annual petroleum displacement per vehicle in gallons of gasoline equivalent (gge), by fuel type.

**Table 11: Average Annual Petroleum Displacement per Vehicle**

| **Fuel** | **GGEs Reduced per Vehicle** |
|---|---|
| LNG | 6,210 |
| CNG | 3,202 |
| Propane | 1,620 |
| Electricity | 662 |
| E85 | 195 |

Source: Johnson, C. (2013). *Clean Cities 2012 Annual Metrics Report (NREL/TP-5400-60274).* National Renewable Energy Laboratory.

Using a variation of the GREET model, well-to-wheel GHG emission displacement can be estimated from the same compiled dataset. Table 12 shows the estimated average annual GHG emissions that have been displaced by replacing a conventional vehicle with an alternative fuel vehicle.

**Table 12: Average Annual GHG Emissions Displaced per Vehicle**

| Fuel | GHGs Reduced per Vehicle (Tons CO2e) |
|---|---|
| LNG | 11.5 |
| CNG | 6.0 |
| Propane | 3.4 |
| Electricity | 1.3 |
| E85 | 0.5 |

Source: Johnson, C. (2013). *Clean Cities 2012 Annual Metrics Report (NREL/TP-5400-60274).* National Renewable Energy Laboratory.

## Hydrogen Fuel Cell Electric Vehicles

As opposed to the aforementioned alternative fuel vehicles which burn fuel in a combustion engine to produce usable energy, a hydrogen fuel cell electric vehicle (FCEV) relies on an electrochemical reaction between hydrogen (from the fuel tank) and oxygen (typically from the air) to produce useful electrical energy along with water and heat as waste products. While production light-duty FCEVs have yet to go on sale, significant OEM research, development and demonstration activities have taken place in the U.S. and around the world. Specific activities in California include the California Fuel Cell Partnership, which is a public-private partnership to promote hydrogen FCEVs in California. Nationally, the U.S. Department of Energy's (U.S. DOE's) FCEV Learning Demonstration project has tracked technology progress on hydrogen FCEVs and is further examined in this section to describe the current status of various hydrogen FCEV technologies.

### Data Products and Findings from the FCEV Learning Demonstration

The FCEV Learning Demonstration project was initiated in 2004 to benchmark FCEVs and hydrogen fueling infrastructure. Many achievements and challenges were identified for the current technologies through this seven-year project that concluded in 2011. The three primary objectives were to evaluate fuel cell durability, vehicle driving range, and on-site hydrogen production cost as compared to DOE's targets (2,000-hour, 250-mile, and $3/gge based on volume production). Real-world data received from four teams (automotive OEM and energy partner) were analyzed, and key results were included in a report covering 99 composite data products[18]. The project deployed 183 FCEVs that traveled 3.6 million miles in more than 500,000 individual vehicle trips and placed 25 hydrogen fueling stations in use producing or dispensing 152,000 kg of hydrogen. Table 13 presents a summary of key performance during the learning demonstration. Note that two teams completed their projects by 2009 while the other two teams extended their projects for another two years. The last blue column in the table was from the last two project teams.

[18] K. Wipke, S. Sprik, J. Kurtz, T. Ramsden, C. Ainscough, and G. Saur, National Fuel Cell Electric Vehicle Learning Demonstration Final Report, Technical Report, NREL/TP-5600-54860, July 2012.

**Table 13: Summary of FCEVs and Hydrogen Fueling Infrastructure Performance**

| Vehicle Performance Metrics | Gen 1 Vehicle | Gen 2 Vehicle | 2009 Target | After 2009Q4 |
|---|---|---|---|---|
| ***Fuel Cell Stack Durability*** | | | 2,000 hours | |
| Max Team Projected Hours to 10% Voltage Degradation | 1,807 hours | 2,521 hours | | -- |
| Average Fuel Cell Durability Projection | 821 hours | 1,062 hours | | 1,748 hours |
| Max Hours of Operation by a Single FC Stack to Date* | 2,375 hours | 1,261 hours | | 1,582 hours |
| ***Driving Range*** | | | 250 miles | |
| Adjusted Dyno (Window Sticker) Range | 103-190 miles | 196-254 miles | | -- |
| Median On-Road Distance Between Fuelings | 56 miles | 81 miles | | 98 miles |
| *Fuel Economy (Window Sticker)* | 42 – 57 mi/kg | 43 – 58 mi/kg | no target | -- |
| *Fuel Cell Efficiency at ¼ Power* | 51 – 58% | 53 – 59% | 60% | -- |
| *Fuel Cell Efficiency at Full Power* | 30 – 54% | 42 – 53% | 50% | -- |
| **Infrastructure Performance Metrics** | | | **2009 Target** | **After 2009Q4** |
| ***$H_2$ Cost at Station (early market)*** | On-site natural gas reformation **\$7.70 – \$10.30/kg** | On-site Electrolysis **\$10.00 – \$12.90/kg** | \$3/gge | -- |
| *Average $H_2$ Fueling Rate* | 0.77 kg/min | | 1.0 kg/min | 0.65 kg/min |

**$H_2$ Cost:** Outside of this project, DOE independent panels concluded that for 500 replicate stations/year:
Distributed natural gas reformation at 1500 kg/day: **\$2.75-\$3.50/kg** (2006)
Distributed electrolysis at 1500kg/day: **\$4.90-\$5.70** (2009)

*Note that time available to demonstrate fuel cell systems from Gen 2 vehicles and post-2009Q4 vehicles was limited.

**Gen 1 Vehicle refers to 2003-2005 stack technology and Gen 2 Vehicle to 2005-2007 stack technology.**

Source: K. Wipke, S. Sprik, J. Kurtz, T. Ramsden, C. Ainscough, and G. Saur, National Fuel Cell Electric Vehicle Learning Demonstration Final Report, Technical Report, NREL/TP-5600-54860, July 2012.

For fuel cell stack durability, the longest stack durability was 2,375 hours accumulated without repair from a first-generation fuel cell stack with 2003–2005 stack technology. NREL researchers found that the fuel cell power degradation rate is similar to the voltage degradation: higher in the first 200 hours and then much lower. The more gradual secondary degradation occurs after around 1,000 hours of stack operation. At 1,900-2,000 hours, significant power degradation occurs. The maximum hours of second-generation fuel cell stacks with 2005–2007 stack technology ranged from about 800 to over 1,200 hours. The highest single-team average projected time to 10 percent voltage degradation was 2,521 hours, and a multi-team average projection was 1,062 hours. Stack technology in 2007–2009 improved significantly over the first- and second-generation stacks with an average projected time to 10 percent voltage degradation of 1,748 hours.

The second-generation vehicle driving range was 196–254 miles based on fuel economy from dynamometer testing and on-board hydrogen storage amounts in fiscal year 2008. An on-road driving range evaluation in 2009 indicated a possible 431-mile driving range in Southern California.

Regarding hydrogen costs, the Hydrogen Analysis (H2A) production model version 2.1 (www.hydrogen.energy.gov/h2a_production.html) with cost inputs from the learning demonstration energy company partners presented a cost range of around $8–$10/kg for onsite natural gas reformation and $10–$13/kg for onsite electrolysis, not meeting the DOE cost target. However, more optimistic results were concluded by two external independent review panels:

$2.75–$3.50/kg could be achieved for distributed natural gas reformation[19] and $4.90-$5.70/kg for distributed electrolysis[20].

Ongoing FCEV and hydrogen infrastructure technology validation occurs through the NREL-hosted National Fuel Cell Technology Evaluation Center.

## Performance Status of Fuel Cell Electric Buses in Transit

A 2012 NREL report[21] summarized the current status of fuel cell electric bus deployment in the U.S. and discussed achievements and challenges of fuel cell propulsion introduction in transit. Generally, the 2012 status did not meet the DOE/Federal Transit Administration 2016 targets.

In 2012, there were 25 active fuel cell electric buses in demonstrations at eight locations. The NREL report covered 21 of the 25 fuel cell electric buses with results from four demonstrations at three transit agencies from August 2011 through July 2012, accounting for over 248,200 miles traveled and 24,930 hours of fuel cell power system operation. Table 14 summarizes performance results as compared to interim (for 2016) and ultimate (for commercialization) targets established by DOE and the Federal Transit Administration.

A single fuel cell power plant reached 12,000 hours of durability as of July 2012, and two additional fuel cell power plants approached 10,000 and 8,000 hours. The report defined availability as "the percentage of days that buses are planned for operation compared to the percentage of days the buses are actually available." Availability ranged from 53 percent to 67 percent with the overall average at 57 percent, much lower than the target of 90 percent. Unavailability was often caused by bus-related and battery issues instead of by the fuel cell (FC) system. Table 14 includes two targets for roadcalls frequency: miles between roadcalls for the entire bus and miles between roadcalls for the fuel cell system only. NREL included an additional one: propulsion system miles between roadcalls, including all roadcalls due to propulsion-related bus systems. The miles between roadcalls values were 2,288 for overall bus, 3,239 for propulsion system, and 12,328 for the fuel cell system. The fuel cell electric buses' fuel economy was in the range of 5.97–7.84 miles per diesel gallon equivalent with an average of 7.41 miles per diesel gallon equivalent.

---

[19] Fletcher, J., and Callaghan, V., "Evaluation Cost of Distributed Production of Hydrogen from Natural Gas – Independent Review," NREL/BK-150-40382, October 2006.

[20] Genovese, J., Harg, K., Paster, M., and Turner, J., "Current (2009) State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis – Independent Review," NREL/BK-6A1- 46676, September 2009.

[21] L. Eudy, K. Chandler and C. Gikakis, Fuel Cell Buses in U.S. Transit Fleets: Current Status 2012, Technical Report, NREL/TP-5600-56406, November 2012.

**Table 14: Fuel Cell Electric Bus Performance and Federal Transit Administration Targets**

| | Units | November 2012 Report[a] (Range) | 2012 Status[1] | 2016 Target[1] | Ultimate Target[1] |
|---|---|---|---|---|---|
| Bus lifetime | years/miles | <1–2.5/ 8,669–54,927[c] | 5/100,000 | 12/500,000 | 12/500,000 |
| Power plant lifetime[b] | hours | 940–12,038[c,d,e] | 12,000 | 18,000 | 25,000 |
| Bus availability | % | 53–71 | 60 | 85 | 90 |
| Fuel fills[f] | per day | 1 | 1 | 1 (< 10 min) | 1 (< 10 min) |
| Bus cost[g] | $ | 2,000,000 | 2,000,000 | 1,000,000 | 600,000 |
| Power plant cost[b,g] | $ | N/A[h] | 700,000 | 450,000 | 200,000 |
| Hydrogen storage cost | $ | N/A[h] | 100,000 | 75,000 | 50,000 |
| Roadcall frequency (bus/fuel cell system) | miles between roadcalls | 1,692–2,479/ 6,838–19,005 | 2,500/ 10,000 | 3,500/ 15,000 | 4,000/ 20,000 |
| Operation time | hours per day/days per week | 7–19/ 5–7 | 19/7 | 20/7 | 20/7 |
| Scheduled and unscheduled maintenance cost[i] | $/mile | N/A[j] | 1.20 | 0.75 | 0.40 |
| Range | miles | 227–346[k] | 270 | 300 | 300 |
| Fuel economy | miles per gallon diesel equivalent | 5.97–7.84 | 7 | 8 | 8 |

[a] Summary of the results in this report: data from August 2011–July 2012.
[b] For the DOE/FTA targets, the power plant is defined as the fuel cell system and the battery system. The fuel cell system includes supporting subsystems such as the air, fuel, coolant, and control subsystems. Power electronics, electric drive, and hydrogen storage tanks are excluded.
[c] Accumulated totals for existing fleet through July 2012; these buses have not reached end of life.
[d] The status for power plant hours is for the fuel cell system only; battery lifetime hours were not available.
[e] The highest-hour power plant was transferred from an older generation bus that had accumulated more than 6,000 hours prior to transfer.
[f] Multiple sequential fuel fills should be possible without increase in fill time.
[g] Cost targets projected to a production volume of 400 systems per year. This production volume is assumed for analysis purposes only and does not represent an anticipated level of sales.
[h] Capital costs for subsystems are not currently reported by the manufacturers.
[i] Excludes mid-life overhaul of power plant.
[j] Maintenance costs are not available for this report. See individual project reports on the NREL website.
[k] Based on fuel economy and tank capacity.

Source: L. Eudy, K. Chandler and C. Gikakis, Fuel Cell Buses in U.S. Transit Fleets: Current Status 2012, Technical Report, NREL/TP-5600-56406, November 2012 (http://www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf)

Despite the continuing improvements in performance and fuel cell system durability, challenges remain for broad commercialization of FCEV technology. These include system integration and optimization, and access to hydrogen fuel. As for the first challenge, a characteristic break-in period can take many months for manufacturers to optimize and correct issues that were not found in laboratory testing. The second issue, access to fuel, presents a big hurdle to any fuel cell vehicle adoption. However, it is easier to design hydrogen fueling stations for buses because capacity and fueling patterns are known and fueling for buses is usually done at one location; this also applies for forklifts at warehouses.

## Recent FCEV Production Plans from Automakers

In spite of FCEV performance and cost challenges and limited fueling availability, Toyota, Honda, and Hyundai plan to sell FCEVs starting around 2015. At the 2013 Tokyo Motor Show, Toyota unveiled a concept fuel cell powered car with about 300 miles of range on a full tank of hydrogen that can be refueled within minutes[22], Toyota has announced it plans to begin commercial sales of fuel cell cars by 2015. According to FoxNews[23], Honda displayed its FCEV concept at the 2013 Los Angeles Auto Show as a preview of the company's next generation hydrogen-powered vehicle that was set to go on sale in the United States and Japan in 2015. Honda said that the FCEV's range will be more than 300 miles and a fill-up takes less than three minutes at a hydrogen fueling station. On November 20, 2013, Hyundai unveiled the Tucson, a hydrogen-powered SUV at the Los Angeles Auto Show. The company announced a plan to lease the FCEV at $499 a month for three years with $3,000 down plus unlimited free hydrogen fuel[24], starting in the Los Angeles area next year[25], TimesColonist). Hyundai plans to start mass production of the fuel cell-powered SUV next February[25], set to go on commercial sale in the US market[26].

On December 19, 2013, three new reports (energy.gov) were released by the U.S. DOE, including the *2012 Fuel Cell Technologies Market Report*[27], *State of the States*, *Fuel Cells in America 2013* report, and *Pathways to Commercial Success: Technologies and Products Supported by the Fuel Cell Technologies Office*. These reports show strong growth in the U.S. fuel cell market production and deployment. In 2012, nearly 80 percent of total investment in the global fuel cell industry was made in U.S. companies. Significant advances in fuel cell and hydrogen technologies have already been achieved to reduce costs and improve performance. Automotive fuel cell costs ($47/kWnet) have been reduced by over 50 percent since 2006 ($108/kWnet) and by over 30 percent since 2008 ($73/kWnet) under high volume production (500,000 units per year). With doubled fuel cell durability, platinum use in fuel cells (0.2g per kW) has decreased by 80 percent since 2005.

Internationally, some spotlights regarding hydrogen vehicle fueling infrastructure are as follows:

---

[22] The New York Times. (2013). "Toyota Shows Off Fuel-Cell Automobile" https://www.nytimes.com/2013/11/21/business/international/toyota-unveils-fuel-cell-concept-automobile.html?partner=rss&emc=rss&smid=tw-nytimes&_r=1&, Elgowainy, A., Han, J., Poch, L., Wang, M., Vyas, A., Mahalik, M., et al. (2010, June). *Well-to- Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Plug-In Hybrid Electric Vehicles*. *ANL/ESD/10-1*. http://www.afdc.energy.gov/pdfs/argonne_phev_evaluation_report.pdf.

[23] Fox News. (2013). "Honda's Next Hydrogen Car Coming in 2015" https://www.foxnews.com/auto/hondas-next-hydrogen-car-coming-in-2015

[24] Automotive News, (2013) "Hyundai Salvo may Signal the Start of a Fuel Cell Fight" https://www.autonews.com/article/20131125/OEM05/311259930/hyundai-s-salvo-may-signal-the-start-of-a-fuel-cell-fight

[25] Bloomberg. (2013). "Hyundai to Lease Fuel-Cell SUV for $499 as Hydrogen Race Widens" https://www.bloomberg.com/news/articles/2013-11-21/hyundai-to-lease-fuel-cell-suv-for-499-as-hydrogen-race-widens

[26] BBC News. (2013). "Toyota Eyes Mass Production of Fuel Cell Car by 2015" http://www.bbc.co.uk/news/business-25023673

[27] U.S. DOE. (2013). "Energy Dept. Reports: U.S. Fuel Cell Market Production and Deployment Continues Strong Growth" http://energy.gov/articles/energy-dept-reports-us-fuel-cell-market-production-and-deployment-continues-strong-growth

- More than 50 public hydrogen stations are in operation collectively by Germany, Japan, the U.K., and Scandinavia, with more planned.
- Nine public stations are open in California.
- Zero Emissions Vehicle (ZEV) Action Plan in California: ZEV-ready by 2015 and 1.5 million ZEVs by 2025.
- Japan's goal: 100 stations by 2015.
- Germany's goal: 15–50 stations by 2015.
- Scandinavia's goal: 15 stations and 30 satellite stations by 2015.
- Finland: published Finnish hydrogen road map.
- Europe's Hydrogen Infrastructure for Transport initiative.
- UK's goal: first 65 refueling stations across the United Kingdom and 1,150 refueling stations by 2030.

A new public-private partnership—H2USA—was initiated in the United States to "coordinate research, conduct technical and market analysis, and identify cost-effective solutions to deploying fueling infrastructure" by convening automakers, government agencies, gas supplies, and the hydrogen and fuel cell industries.

# CHAPTER 3: Advanced Vehicle Deployment Projections

This chapter reviews three recent studies that produced a range of advanced vehicle technology penetration scenarios. The methodologies from these studies are then compared to that for ADOPT—the deployment estimation tool used in this report and planned for use in on-going market impact assessment activities.

## Review of Recently Developed Technology Penetration Scenarios

U.S. EPA[28], NPC[29] and NRC[30] published their assessments on future fuel and vehicle technologies and analyzed potential options to reduce petroleum use and GHG emissions. Table 15 summarizes these studies in terms of studied time period, vehicle types, fuel types, assumptions, methodology, models used, major results, and conclusions. Additional relevant studies have been completed recently[31]. These three studies are distinct in synthesizing a broad range of information and having been developed and vetted by relatively large groups of experts. This chapter reviews each of these three studies and compares projections of future technology and market trends.

**Table 15: Comparison of U.S. EPA, NPC and NRC Studies**

| Study | U.S. EPA 2010 | NPC 2012 | NRC 2013 |
|---|---|---|---|
| Studied years | 2017–2025 | 2010–2050 | 2010–2050 |
| Vehicle type | LDV including ICEV, HEV, PHEV, BEV, FCEV* | LDV, MD & HD truck (class 3-6 and 7&8), rail, water and air;<br>ICEV, HEV, PHEV, BEV, NGV, FCEV | LDV (car and light truck): much more efficient ICEV, HEV, PHEV, BEV, FCEV, and CNGV |
| Fuel type | Gasoline, diesel, electricity, hydrogen* | Gasoline, diesel, biofuels, NG, electricity, hydrogen | Gasoline, diesel, biofuels, NG, electricity, hydrogen, |

[28] U.S. EPA, National Highway Traffic Safety Administration, and ARB, Interim Joint Technical Assessment Report: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2017–2025, September 2010._https://www.epa.gov/regulations-emissions-vehicles-and-engines/interim-joint-technical-assessment-report-light-duty

[29] National Petroleum Council, Advancing Technology for America's Transportation Future – Summary Report, 2012. http://www.npc.org/reports/trans-future_fuels_summary-2012.pdf

[30] National Research Council of the National Academies. (2013). "Transitions to Alternative Vehicles and Fuels." Committee on Transitions to Alternative Vehicles and Fuels, Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences.

[31] David L. Greene, Sangsoo Park, Changzheng Liu, Analyzing the Transition to Electric Drive in California, White Paper 4.13, The Howard H. Baker JR Center for Public Policy, 2013.
Amgad Elgowainy, Aymeric Rousseau, Michael Wang, Mark Ruth, et al., Cost of ownership and well-to-wheels carbon emissions/oil use of alternative fuels and advanced light-duty vehicle technologies, Energy for Sustainable Development 17 (2013) 626-641.

| Study | U.S. EPA 2010 | NPC 2012 | NRC 2013 |
|---|---|---|---|
| | | | and liquid fuels from NG or coal |
| Assumptions | Annual Energy Outlook 2010 reference case energy prices, 3 percent discount rate | Annual Energy Outlook 2010 projections, extrapolated to 2050; Aggressive, but not disruptive, improvements in advanced fuel-vehicle systems and no substantial transition hurdles. | Two sets of assumptions for cost and performance: midrange and optimistic; Conventional and low-GHG- emission scenarios for electricity generation. |
| Methodology | Technical input from stakeholders; Cost, effectiveness and lead-time from the 2012–2016 LD CAFE and GHG final rule with some exceptions.<br>Optimization on technologies added to vehicles | Cost and performance from publicly available literature;<br>Fuel-vehicle systems assessment based on fuel and vehicle costs. Simulation for fuel/vehicle shares, fleet emissions and cost of driving | Based on earlier NRC studies and other studies; scenarios analysis with the business-as- usual case from Annual Energy Outlook 2011 reference, the Committee reference case, and specific technology-focused cases.<br>Simulation for various scenarios with midrange and optimistic cost and performance levels |
| Models used | U.S. EPA's OMEGA model; agencies' mass reduction cost model; ANL's battery cost model. | Vehicle Attribute, Vehicle Choice, TRUCK, VISION, and GREET models | VISION model, LAVE-Trans (nested, multinomial logit model with nine variables considered) |
| Major results | Per-vehicle cost increase, net lifetime vehicle owner savings, payback period to consumer, net reduction in GHG emission, net reduction in fuel consumption, | Ranges of fleet fuel economy and fleet shares; Impact of transportation demand, fuel efficiency improvements and alternative fuel-vehicle systems on GHG | Estimates of U.S. LDV petroleum use and GHG emissions through 2050 under different policies that emphasized specific technologies |

| Study | U.S. EPA 2010 | NPC 2012 | NRC 2013 |
|---|---|---|---|
| | and vehicle technology penetration mix | emissions; Cost of driving | |
| Conclusions | Per-vehicle cost increase could be up to $3,500 for a 6 percent/year GHG reduction; Consumer net lifetime savings up to $7,400 from vehicle efficiency increase;<br>Higher vehicle price payback period to consumer would be within 4 years. | A 50 percent reduction in GHG emissions relative to 2005 by 2050 will require additional strategies even with aggressive advances in technology and infrastructure. | The 2030 goal for a 50 percent reduction in petroleum use relative to 2005 can hardly be achieved. Several combinations of technologies could meet the 2050 goal of 80 percent petroleum use reduction. It may be technically achievable for an 80 percent reduction of LDV GHG emissions by 2050, but very difficult. |

***OMEGA runs did not include FCEVs, but this study assessed FCEV cost and hydrogen infrastructure.**

Sources: U.S. EPA Technical Assessment Report, 2010; National Petroleum Council, Advancing Technology for America's Transportation Future – Summary Report, 2012; National Research Council. "Transitions to Alternative Vehicles and Fuels," 2013.

## EPA Technical Assessment Report

In response to the President's May 2010 calls[32] for further efforts towards a new generation of clean vehicles, the U.S. EPA and the National Highway Traffic Safety Administration worked with the California Air Resources Board to regulate fuel economy and GHG emissions from U.S. light-duty vehicles for MY 2017–2025 based on the first phase of standards for MY standards 2012–2016. These agencies issued a joint Technical Assessment Report (TAR) to inform the rulemaking process (U.S. EPA, National Highway Traffic Safety Administration, and the California Air Resources Board, 2010). Through numerous meetings with stakeholders including auto OEMs, auto suppliers, non-governmental organizations, state and local government organizations, infrastructure providers and labor unions, the agencies gathered technical input and perspectives on key issues, including technology development, costs, benefits, lead time, incentives and other flexibilities, infrastructure and impacts on jobs, to conduct an assessment of more than 30 vehicle technologies for MYs 2017–2025. Technologies considered included engine technologies, transmission technologies, vehicle technologies, electrification/accessory technologies, electric drive technologies and mass

[32] Presidential Memorandum https://www.whitehouse.gov/omb/information-for-agencies/memoranda/#memoranda-2011

reduction. Electric drive vehicles include HEVs, BEVs, PHEVs, and hydrogen fuel cell vehicles (FCVs).

Estimates of the costs and effectiveness of each technology for each year (MY 2017–2025) were from the 2012-2016 light-duty CAFE and GHG final rule with some exceptions on cost updates detailed in the TAR. Cooled-exhaust gas recirculation costs and effectiveness values were updated. Also updated were HEV effectiveness values.

Vehicle manufacturer lead time for MYs 2017–2025 was expected to follow the normal automotive business cycle. "Maximum technology penetration rates" (the maximum modeled fleet penetration into the new vehicle fleet in MY 2020 and MY 2025 for each class of technology) were developed for technology pathways analysis. Using the Optimization Model for reducing Emissions of Greenhouse gases from Automobiles (OMEGA) model (U.S. EPA's vehicle GHG cost and compliance model), the TAR analyzed four tailpipe carbon dioxide reduction target trajectories: 3 percent, 4 percent, 5 percent and 6 percent reductions in tailpipe carbon dioxide emissions per year. Each scenario started at a 250-gram/mile estimated fleet level in MY 2016, and fleet emissions were estimated for MYs 2020 and 2025. Four potential technology pathways, "A," "B," "C," and "D," were developed to meet each target trajectory. The following quotes from the report describe each pathway (TAR 2010, page 6-9):

- "Pathway A is intended to portray a technology path focused on HEVs, with less reliance on advanced gasoline vehicles and mass reduction, relative to Pathways B and C,"
- "Pathway B represents an approach where advanced gasoline vehicles and mass reduction are utilized at a more moderate level, higher than in Pathway A but less than Pathway C,"
- "Pathway C represents an approach where the industry focuses most on advanced gasoline vehicles and mass reduction, and to a lesser extent on HEVs,"
- "Pathway D represents an approach focused on the use of PHEV, EV and HEV technology, and less reliance on advanced gasoline vehicles, mass reduction."

Table 16 and Table 17 present the results of the scenario analysis, including per-vehicle cost increase, net lifetime vehicle owner savings, payback period to the consumer, net reduction in GHG emission, net reduction in fuel consumption, and vehicle technology penetration mix.

Tables 16 and 17 indicate that greater benefits come at greater per-vehicle cost increase ranging from $770 to $3,500 among the four scenarios and four technology pathways. The net lifetime consumer savings are up to $7,400 (tech path C under the 6 percent/yr scenario).

**Table 16: Projections for MY 2025**

| Scenario | New fleet CO2 target g/mile (MPGe) | Lifetime CO2e reduction (million metric tons) | Lifetime fuel reduction (billion barrels) | Tech Path | Per-vehicle cost increase | Payback period (years) | Net lifetime owner savings ($) |
|---|---|---|---|---|---|---|---|
| 3 percent/yr | 190 (47) | 340 | 0.7 | A | $930 | 1.6 | $5,000 |
| | | | | B | $850 | 1.5 | $5,100 |
| | | | | C | $770 | 1.4 | $5,200 |
| | | | | D | $1,050 | 1.9 | $4,900 |
| 4 percent/yr | 193 (51) | 410-440 | 0.9 | A | $1,700 | 2.5 | $5,900 |
| | | | | B | $1,500 | 2.2 | $6,000 |
| | | | | C | $1,400 | 1.9 | $6,200 |
| | | | | D | $1,900 | 2.9 | $5,300 |
| 5 percent/yr | 158 (56) | 440-530 | 1.1 | A | $2,500 | 3.1 | $6,500 |
| | | | | B | $2,300 | 2.8 | $6,700 |
| | | | | C | $2,100 | 2.5 | $7,000 |
| | | | | D | $2,600 | 3.6 | $5,500 |
| 6 percent/yr | 143 (62) | 470-590 | 1.3 | A | $3,500 | 4.1 | $6,200 |
| | | | | B | $3,200 | 3.7 | $6,600 |
| | | | | C | $2,800 | 3.1 | $7,400 |
| | | | | D | $3,400 | 4.2 | $5,700 |

**Note: Per-vehicle cost (to consumers) increase values are relative to the MY 2016 standards. A 3 percent discount rate and Annual Energy Outlook 2010 reference case energy prices were used for payback period and lifetime owner savings. The gasoline price in 2025 is $3.49/gallon and increases to $4.34/gallon in 2050. "MPGe is the equivalent MPG value if all of the carbon dioxide (CO2) reduction came from fuel economy improvement technologies." CO2e reduction values depend on the penetration of EVs and PHEVs due to an increase in upstream emissions.**

Source: U.S. EPA Technical Assessment Report, 2010

**Table 17: Technology Penetration Estimates for MY 2025 Vehicle Fleet**

| Scenario | Technology Path | New Vehicle Fleet Technology Penetration | | | | |
|---|---|---|---|---|---|---|
| | | Mass Reduction* | Gasoline & diesel vehicles | HEVs | PHEVs** | EVs |
| 3 percent/year | Path A | 15 percent | 89 percent | 11 percent | 0 percent | 0 percent |
| | Path B | 18 percent | 97 percent | 3 percent | 0 percent | 0 percent |
| | Path C | 18 percent | 97 percent | 3 percent | 0 percent | 0 percent |
| | Path D | 15 percent | 75 percent | 25 percent | 0 percent | 0 percent |
| 4 percent/year | Path A | 15 percent | 65 percent | 34 percent | 0 percent | 0 percent |
| | Path B | 20 percent | 82 percent | 18 percent | 0 percent | 0 percent |
| | Path C | 25 percent | 97 percent | 3 percent | 0 percent | 0 percent |
| | Path D | 15 percent | 55 percent | 41 percent | 0 percent | 4 percent |
| 5 percent/year | Path A | 15 percent | 35 percent | 65 percent | 0 percent | 1 percent |
| | Path B | 20 percent | 56 percent | 43 percent | 0 percent | 1 percent |
| | Path C | 25 percent | 74 percent | 25 percent | 0 percent | 0 percent |
| | Path D | 15 percent | 41 percent | 49 percent | 0 percent | 10 percent |
| 6 percent/year | Path A | 14 percent | 23 percent | 68 percent | 2 percent | 7 percent |
| | Path B | 19 percent | 48 percent | 43 percent | 2 percent | 7 percent |
| | Path C | 26 percent | 53 percent | 44 percent | 0 percent | 4 percent |
| | Path D | 14 percent | 29 percent | 55 percent | 2 percent | 14 percent |

*** Mass reduction is the overall net reduction of the 2025 fleet relative to MY 2008 vehicles.**
**** This assessment considered both PHEVs and EVs. These results show a higher relative penetration of EVs compared to PHEVs. The agencies believe PHEVs may be used more broadly by auto firms than indicated in this technical assessment.**

Source: U.S. EPA Technical Assessment Report, 2010

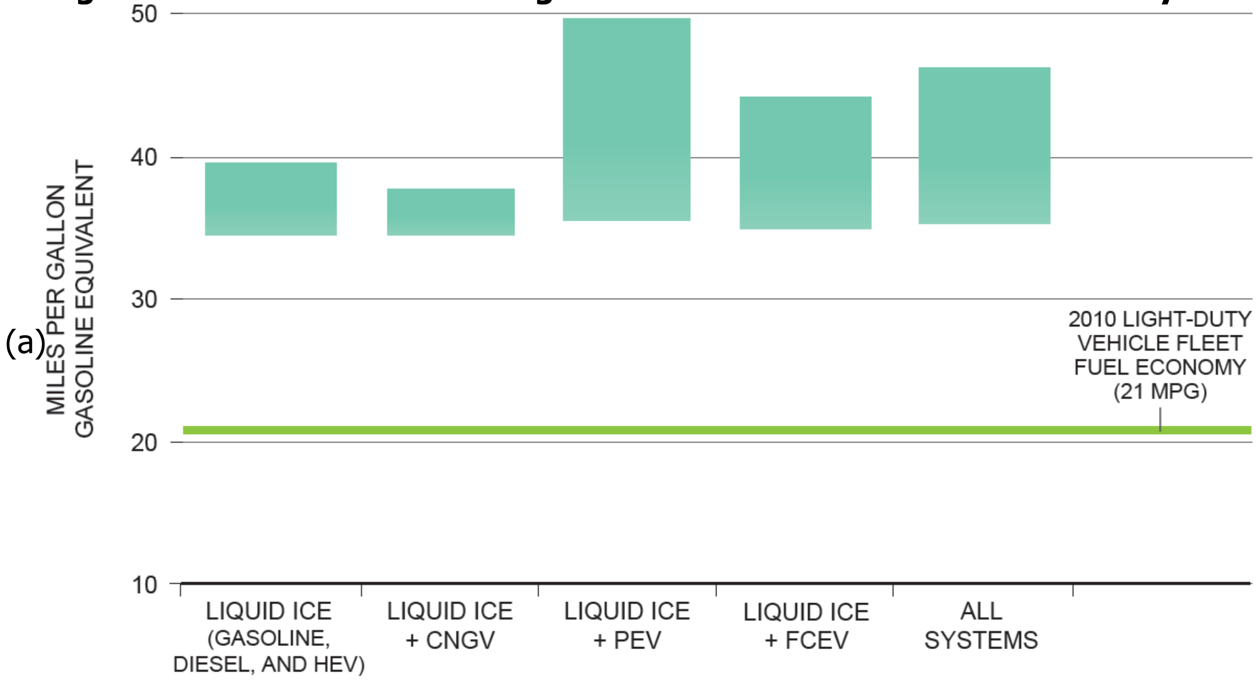
## National Petroleum Council

As a response to the Secretary of DOE's request in September 2009 for NPC's advice on future transportation fuels, a committee was established to conduct an analysis on this topic by the NPC with participants from vehicle manufacturers, transportation services end-users, non-governmental organizations, financial institutions, consultancies, academia and research groups as well as NPC members' organizations. Three task groups focused on demand, supply and infrastructure, and technology. The Demand group worked on national transportation (light- duty and heavy-duty vehicles) demand through 2050. The Supply and Infrastructure group assessed possible fuel-vehicle supply chain pathways including hydrocarbon liquids, biofuels, electric, natural gas, and hydrogen. The Technology group provided technical assistance and peer review. Instead of a direct evaluation of commodity or fuel prices, the NPC study (NPC, 2012) adopted the projections in Annual Energy Outlook 2010 and extrapolated out to 2050 with consistent assumptions.

Based on reviews of published studies on fuel and vehicle system analyses, the NPC study estimated potential future supply of each fuel-vehicle type, which was used as input for integrated analyses. Key assumptions included aggressive but not disruptive improvements in advanced fuel-vehicle systems, no substantial transition hurdles and no impact on fuel prices from changes in projected supply and demand. Four vehicle platforms (liquid fuel internal combustion engines [ICE] including hybrids, compressed natural gas vehicles [CNGVs], PEVs, and FCVs) and six fuel types (gasoline, diesel, biofuels, natural gas, electricity, and hydrogen) were considered for light-duty vehicles (LDVs). Medium- and heavy-duty vehicles considered were ICE vehicles (ICEVS), including hybrids with four fuel types (gasoline, diesel, biofuels and natural gas). The EIA Annual Energy Outlook 2010 reference case was chosen as the NPC reference case (http://www.npc.org/reports/trans.html) and Vehicle Attribute, Vehicle Choice, TRUCK, and VISION Models were used to consider potential scenarios to 2050 with accelerating commercialization of alternative fuels and vehicles. The comparison of fuel-vehicle systems was based on their fuel and vehicle costs. The results of this analysis were presented as a wide array of possible outcomes, including fuel shares, fuel economy, vehicle shares, fleet GHG emissions and fleet cost of driving in cents per mile, from simulations with ranges of input variables.

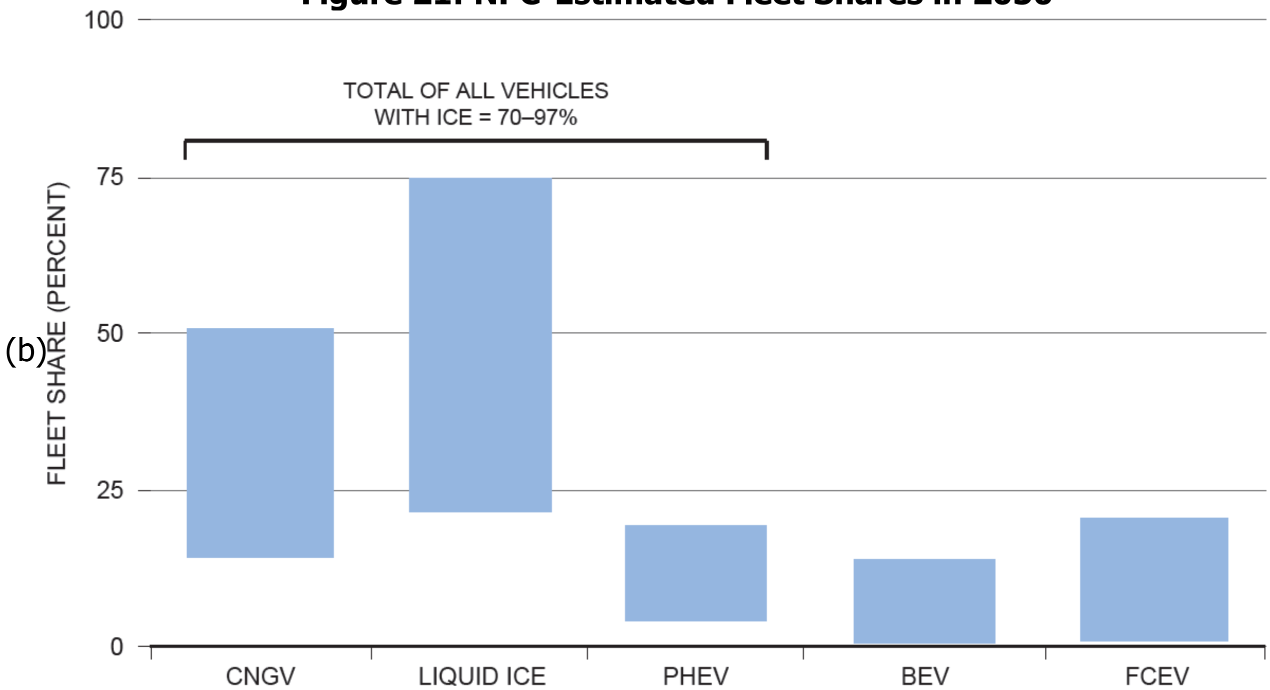
Figure 20 shows the LDV on-road fleet fuel economy and shares in 2050 under reference, high, and low oil price cases with vehicles designed to achieve the minimum cost of driving (vehicle price plus fuel costs) given three-year economics. Compared to the 2010 LDV fleet average fuel economy, liquid ICEV vehicle fleet fuel economy increases by 60 percent to 90 percent resulting from fuel economy improvements of new vehicles and increasing shares of HEVs in the fleet. More PEVs and FCVs could increase the overall fleet fuel economy up to 140 percent. The upper range of possible market share results by 2050 is highest for liquid ICEVs and CNGVs, up to 75 percent and 50 percent respectively, and relatively moderate for PHEVs, BEVs, and FCEVs, each achieving less than 20 percent–25 percent maximum market share (Figure 21). The study results suggest that PHEVs have a market share floor of about 5 percent, while BEVs and FCEVs could have minimal or essentially zero market share by 2050 under certain conditions.

**Figure 20: NPC-Estimated Ranges of LDV On-Road Fleet Fuel Economy in 2050**




Source: National Petroleum Council, Advancing Technology for America's Transportation Future – Summary Report, 2012

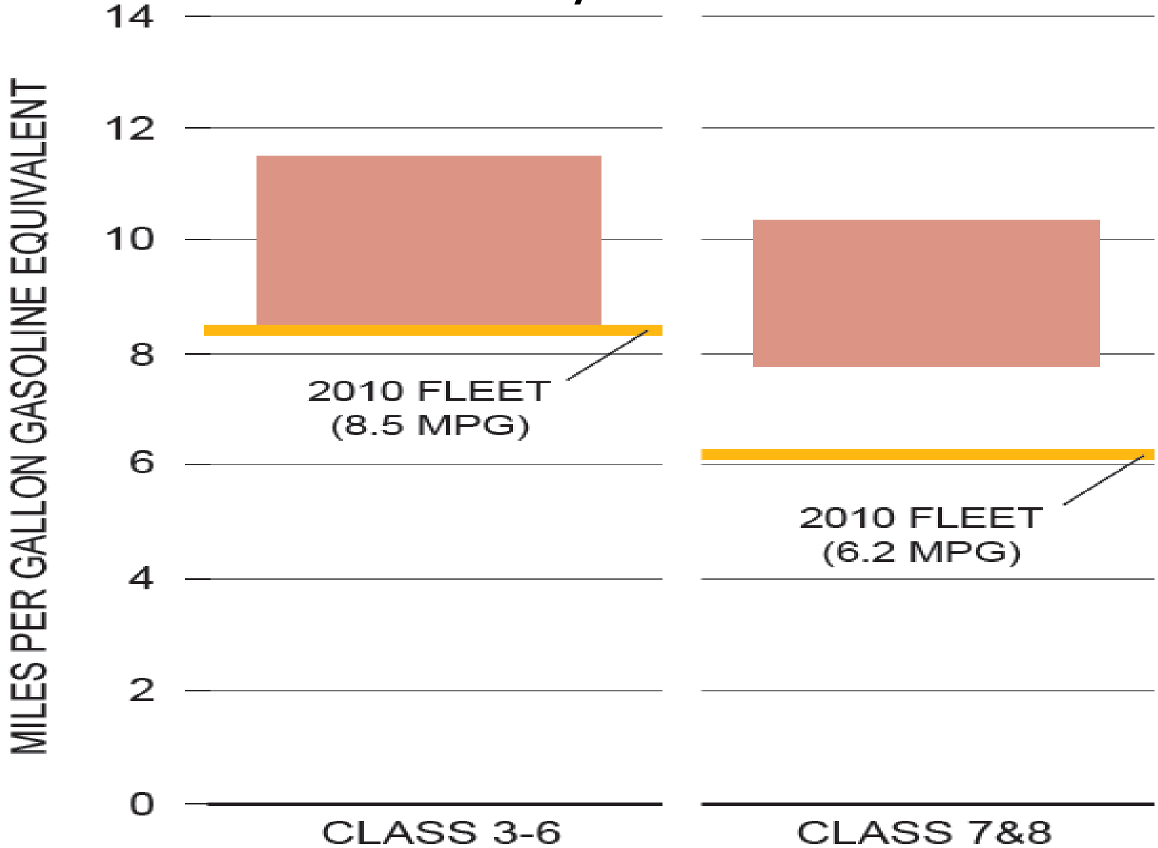
**Figure 21: NPC-Estimated Fleet Shares in 2050**



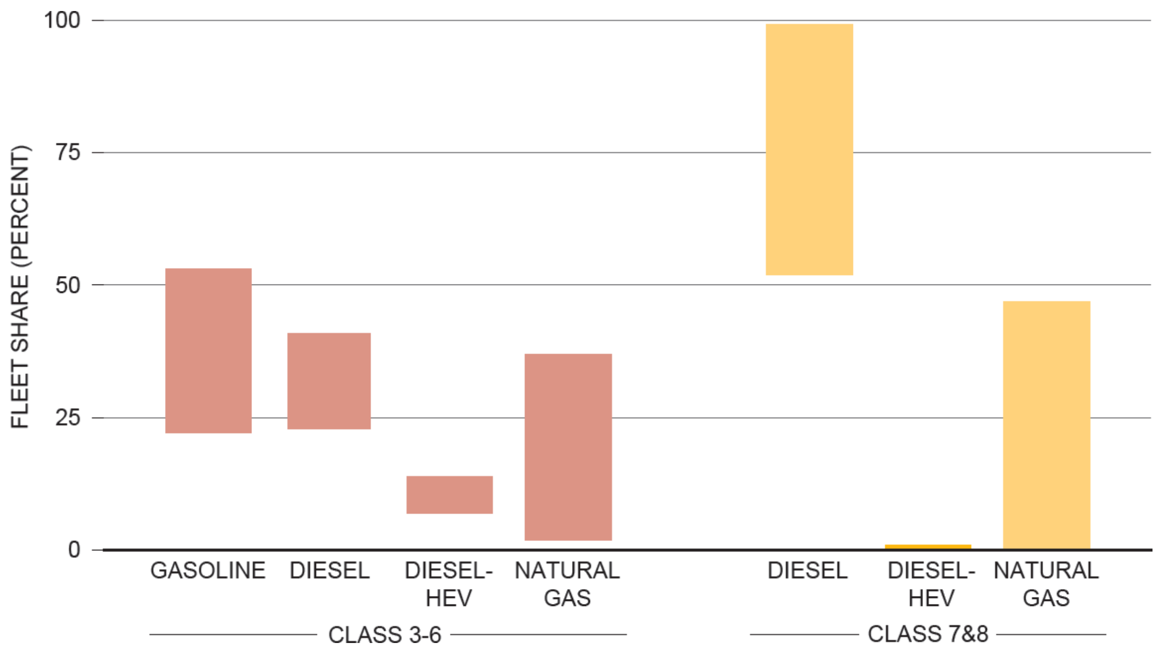

Source: National Petroleum Council, Advancing Technology for America's Transportation Future – Summary Report, 2012

Figure 22 shows comparable results for medium- and heavy-duty vehicle fleets under all oil prices. Fuel economy increase for new heavy-duty trucks could be up to 100 percent primarily due to advances in engine and vehicle design.

**Figure 22: NPC-Estimated Ranges of Medium- and Heavy-Duty Vehicle Fleet Fuel Economy in 2050**



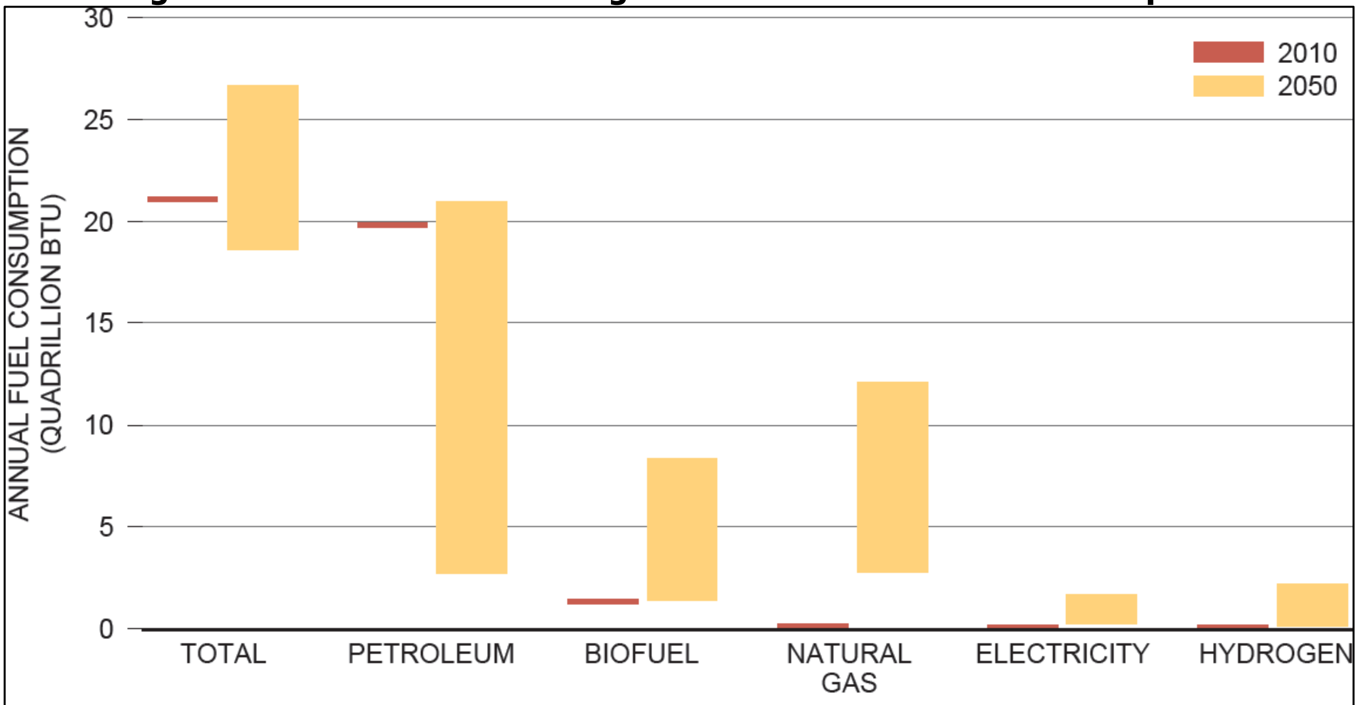

Source: National Petroleum Council, Advancing Technology for America's Transportation Future – Summary Report, 2012Figure 23: NPC-Estimated Fleet Shares in 2050




Source: National Petroleum Council, Advancing Technology for America's Transportation Future – Summary Report, 2012

The range of fuel demand in 2050 is shown in Figure 24 as compared to the 2010 values for each fuel type. The study concluded that "projected efficiency gains can potentially offset all of the growth in LD demand and most of the growth in MD and HD demand."

**Figure 24: NPC-Estimated Range of 2050 On-Road Fuel Consumption**

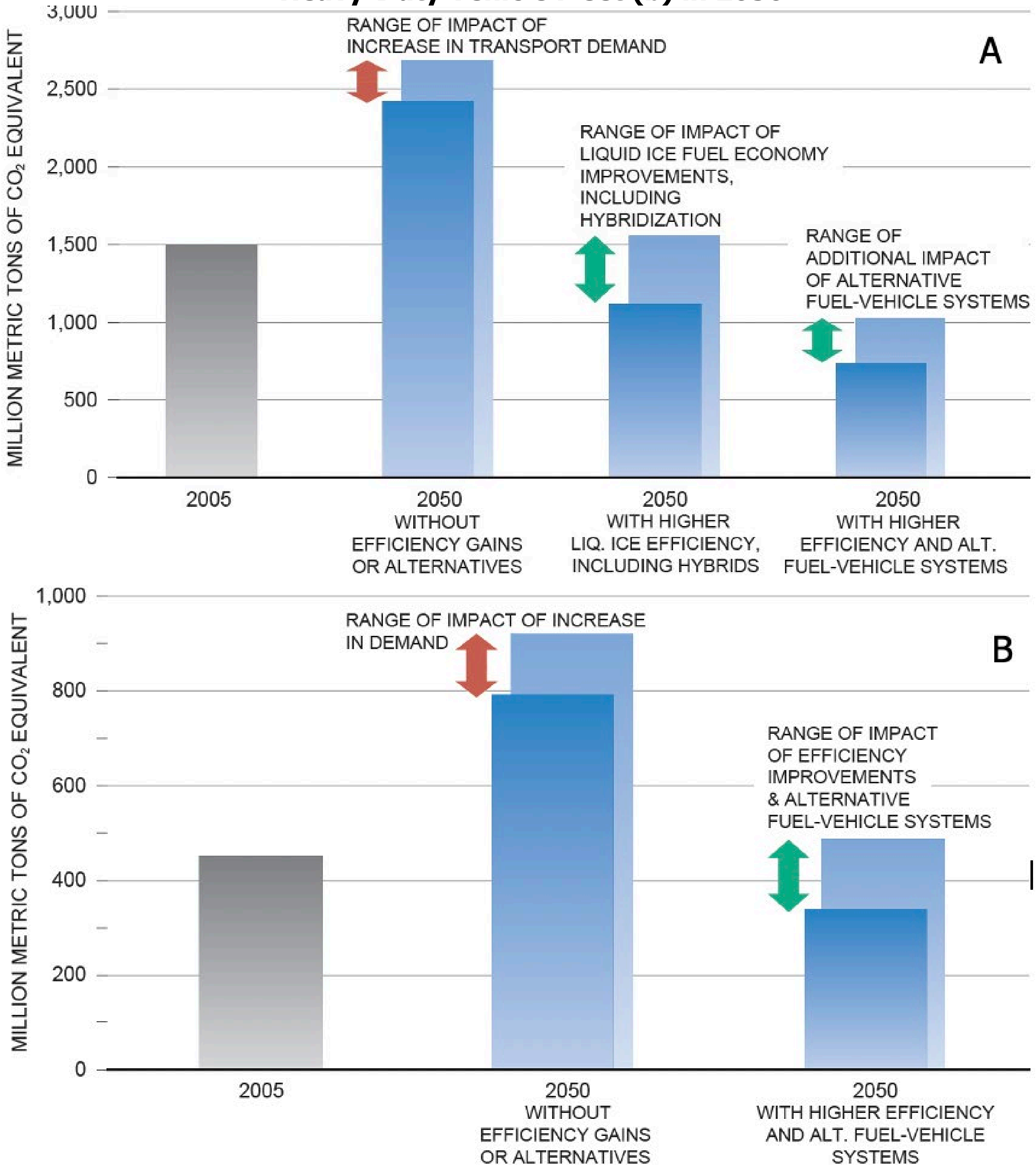



Notes: On-road includes light-, medium-, and heavy-duty sectors.
Figure does not include additional energy consumption associated with fuel production.
At equivalent fuel consumption (by energy), alternatives such as hydrogen fuel cell electric vehicles and other electric vehicles can support two to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

Source: National Petroleum Council, Advancing Technology for America's Transportation Future – Summary Report, 2012

The total well-to-wheels GHG emissions were calculated with the GREET model developed by Argonne National Laboratory, accounting for some uncertainties in measurement variability, transportation demand, indirect land use change and GHG emissions intensity of electricity generation. Figure 25 shows the projected range of impact of demand, fuel efficiency improvements, and alternative fuel-vehicle systems on 2050 vehicle fleet GHG emissions. For the light duty fleet, the combination of high-efficiency liquid ICE and advanced fuel-vehicle systems would decrease total CO2e emissions by 500-800 million metric tons relative to the 2005 level (about 1,500 million metric tons). For the medium duty/heavy duty fleet, the total CO2e emissions would be 350-500 million metric tons (about 500 million metric tons in 2005).

**Figure 25: NPC-Estimated GHG Emissions for LDV Fleet (a) and Medium- and Heavy-Duty Vehicle Fleet (b) in 2050**




Source: National Petroleum Council, Advancing Technology for America's Transportation Future – Summary Report, 2012

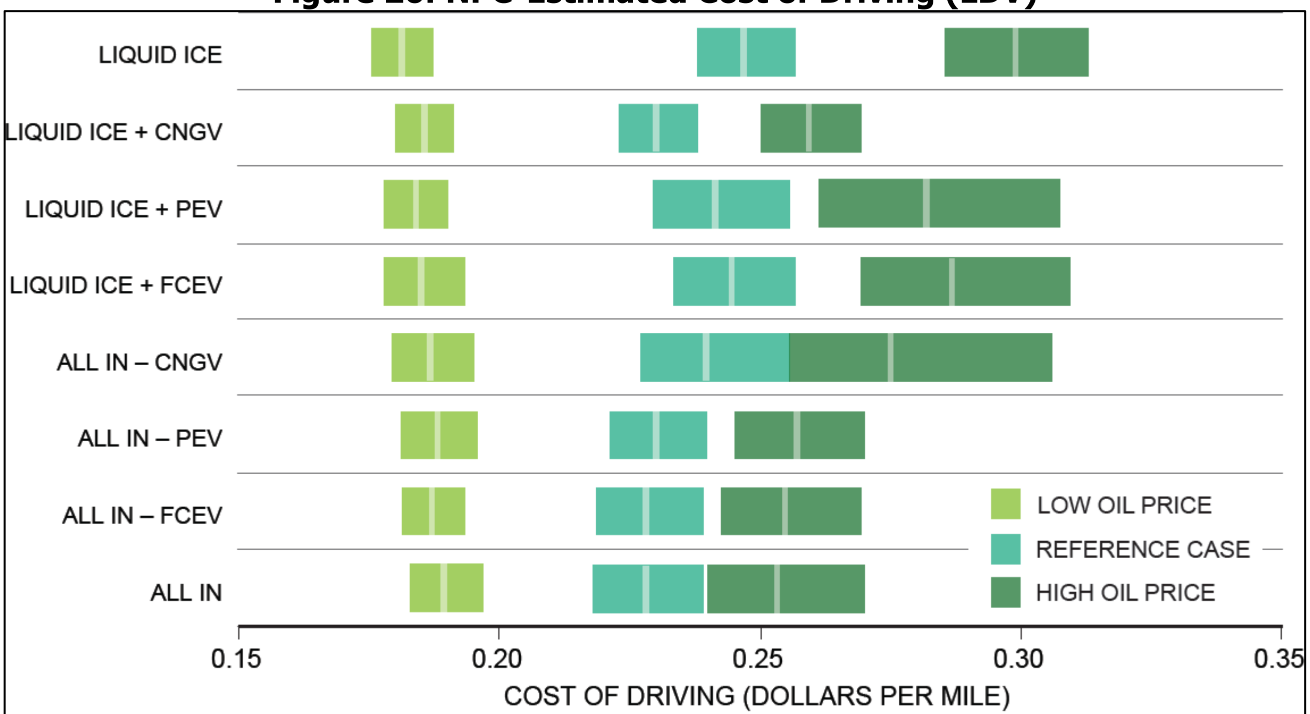
Assumptions:

- Based on Annual Energy Outlook 2010 Reference Case conditions with 3-year and 17-year fuel expenditure considerations
- VMT range based on Annual Energy Outlook 2010 Reference Case and Annual Energy Outlook 2012 Early Release, extrapolated to 2050
- Carbon intensity (grams CO2e/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. Source: NPC 2012

The cost of driving in dollars per mile was computed for each year as the sum of total fuel expenditures and amortized on-road vehicle costs divided by total VMT. Figure 26 shows the LDV results for 2050 under the three distinct Annual Energy Outlook oil price projections (low, reference, and high) and various combinations of vehicle technologies. When only liquid ICE technologies are considered, the range in cost of driving results shows an average of 18 cents per mile for the low oil price projection and 28 cents per mile for the high oil price projection. The next three rows in the figure show results for the liquid ICE technology plus only CNGVs, only PEVs, and only FCEVs. The final row in the figure indicates "All In" results with all technology types included, and rows 5–7 indicate results for "All In" minus only CNGVs, only PEVs, and only FCEVs. These comparisons highlight that the majority of the reductions in the range of high and low cost of driving results is due to the CNGVs, while inclusion of PEV and FCEV technologies results in only a modest reduction in the high-low range by 2050.

**Figure 26: NPC-Estimated Cost of Driving (LDV)**




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

**Liquid ICE = Conventional ICE vehicle, HEV and diesel vehicle Liquid ICE + CNGV = Liquid ICE vehicle and CNGV**

**Liquid ICE + PEV = Liquid ICE vehicle and PHEV (PHEV10 and PHEV40) Liquid ICE + FCEV = Liquid ICE vehicle and FCEV**

**All in – CNGV = Liquid ICE vehicle, PHEV, BEV100 and FCEV All in – PEV = Liquid ICE vehicle, CNGV and FCEV**

**All in – FCEV = Liquid ICE vehicle, CNGV, PHEV and BEV All in = all fuel-vehicle systems**

Source: National Petroleum Council, Advancing Technology for America's Transportation Future – Summary Report, 2012

## National Research Council

The U.S. DOE's Office of Energy Efficiency and Renewable Energy responded to a congressional mandate in the Senate's fiscal year 2010 report 111-45[33] by contracting with the National Academy of Sciences to conduct a comprehensive analysis of energy use by LDVs. The Committee on Transitions to Alternative Vehicles and Fuels, convened by the NRC, conducted an assessment (NRC, 2013) on the potential for fuel-vehicle options to achieve on-road LDV petroleum use reduction by 50 percent by 2030 and 80 percent by 2050, and GHG emissions by 80 percent by 2050, relative to 2005. Six types of LDV technologies were considered in the study (ICEVs, HEVs, PHEVs, BEVs, FCEVs, and CNGVs), and five non-petroleum-based fuel technologies were considered (hydrogen, electricity, biofuels, natural gas, and liquid fuels made from natural gas or coal). Building on earlier NRC studies (NRC 2008, 2009, 2010) and other studies by organizations such as the U.S. Department of Transportation[34], the Transportation Research Board, Argonne National Laboratory, and the Electric Power Research Institute, the committee determined the current status for each fuel and vehicle type and then estimated future performance and costs to 2050. Barriers to implementation were also discussed. The committee developed a range of estimates to address the great uncertainties in performance and cost projections out to 2050. There were two sets of assumptions for vehicle cost and performance: midrange (ambitious but reasonable) and optimistic (*potentially* attainable). Both sets of assumptions resulted from strong and effective policies having been put in place. Some important effects were considered in the analysis. For example, economies of scale and learning from experience for costs; resource demands; technical readiness; time and capital investments for new fuel and vehicle technology infrastructure; potential projected performance characteristics of specific vehicles and fuel systems. Crosscutting technologies were also considered, including vehicle weight reduction and improvements in rolling and aerodynamic resistance, and carbon capture and storage for fuels. Consumer preferences and potential reductions in VMT were also taken into account.

The committee and its consultants developed a model to project vehicle performance, and estimated fully mature, high-volume production vehicle costs relative to a 2010 base vehicle by examining existing cost assessments. Table 18 presents estimated fuel economy in miles per gallon gasoline equivalent for ICEV, HEV, BEV, and FCEV. Figure 27 and Figure 28 show estimated incremental cost for each vehicle technology under midrange and optimistic cases.

All vehicle options were analyzed consistently for efficiencies, costs and performance. Each fuel technology was analyzed with consistent assumptions and cost data. Then the VISION (technology pathways assessment) and LAVE-Trans models were used to project future LDV fleet energy use and GHG emissions. Nine variables were considered in the LAVE-Trans model for consumer choices, including retail price equivalent, energy cost per kilometer, range, maintenance cost, fuel availability, range limitation for BEVs, public recharging availability, risk aversion, and diversity of make and model options available. Assumptions on technological progress over time, people's behavior, cost, and value were used in the LAVE-Trans model to

[33] Senate Report 111-45 http://www.gpo.gov/fdsys/pkg/CRPT-111srpt45/html/CRPT-111srpt45.htm

[34] U.S. Department of Transportation (n.d.). Bureau of Transportation Statistics Retrieved from https://www.bts.gov/browse-statistical-products-and-data/bts-publications/z-index

predict the evolution of vehicle fleet composition and impact on petroleum use and GHG emissions.

**Table 18: NRC-Estimated Vehicle Fuel Efficiency on U.S. EPA 2 Cycle Tests***

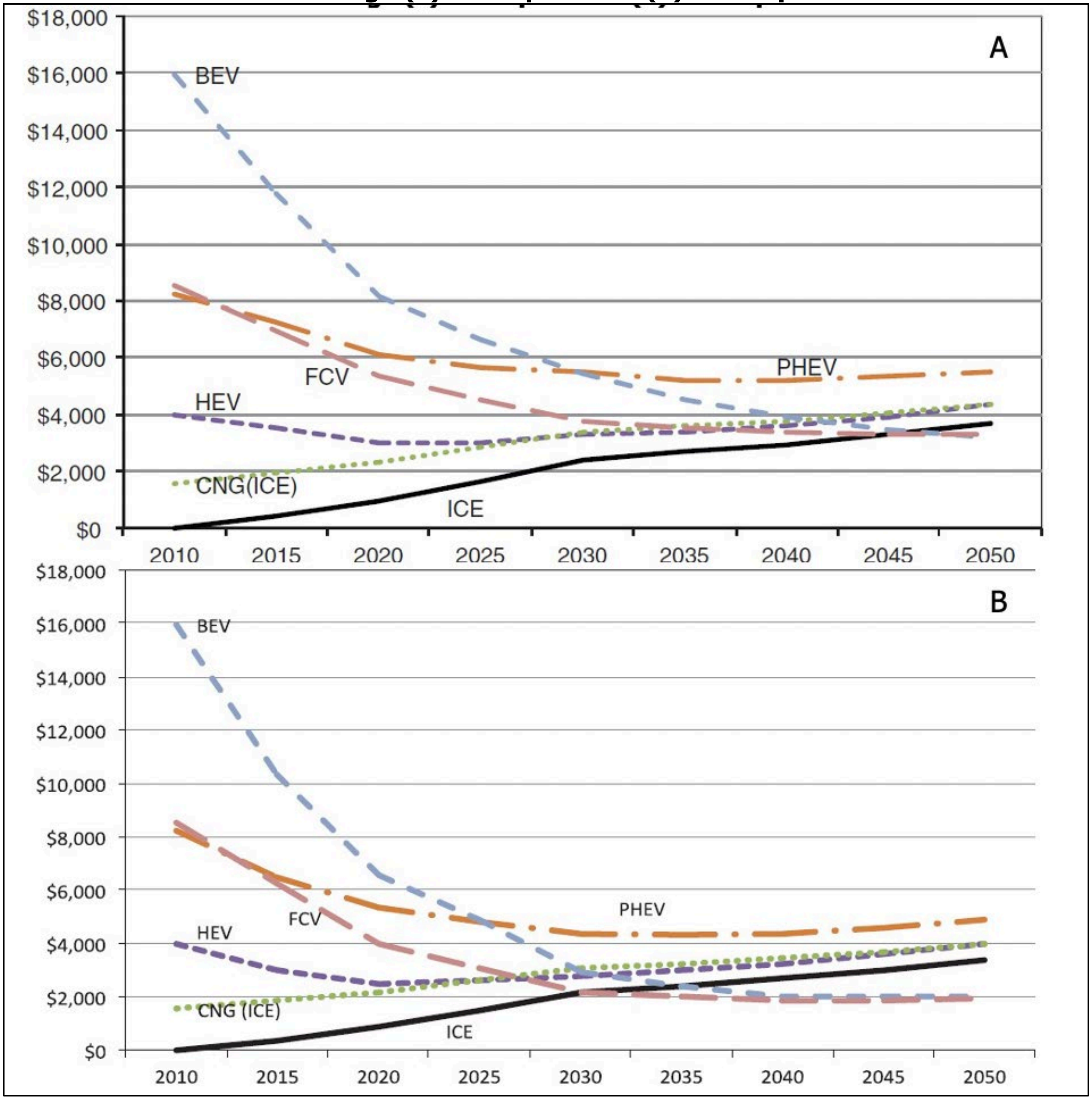
| | ICEV | | HEV | | BEV | | FCEV | |
|---|---|---|---|---|---|---|---|---|
| | Cars | LT | Cars | LT | Cars | LT | Cars | LT |
| 2010 Baseline (mpgge) | 31 | 24 | 43 | 32 | 144 | 106 | 89 | 65 |
| 2030 Midrange (mpgge) | 64 | 46 | 78 | 54 | 190 | 133 | 122 | 86 |
| 2050 Midrange (mpgge) | 87 | 61 | 112 | 77 | 243 | 169 | 166 | 115 |
| 2030 Optimistic (mpgge) | 74 | 52 | 92 | 64 | 219 | 154 | 145 | 102 |
| 2050 Optimistic (mpgge) | 110 | 77 | 146 | 100 | 296 | 205 | 206 | 143 |

***Only two cycles were used for vehicle fuel efficiency test before 2008: Federal Test Procedure (FTP) and Highway Fuel Economy Driving Schedule (HWFET). The two-cycle numbers were unadjusted fuel economy numbers that the CAFE standards use. Compared to the U.S. EPA five-cycle test used after 2008, a multiplier of about 0.7 is used to get the fuel efficiency numbers for the five-cycle mpg values.**

**Tesla Motors Club EPA Range Community Discussion (http://www.teslamotorsclub.com/showthread.php/8252-U.S. EPA-range/page2)**

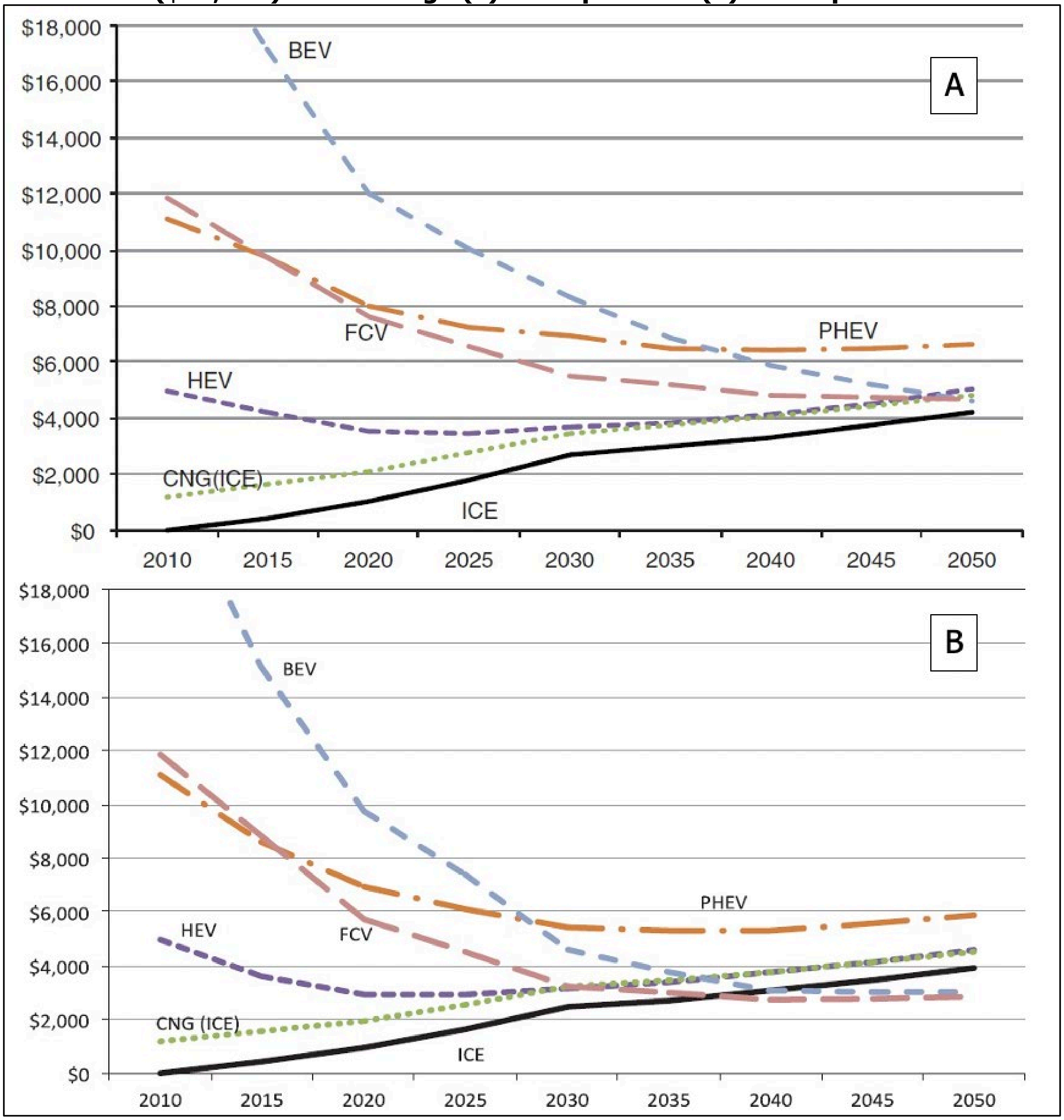
Source: National Research Council. "Transitions to Alternative Vehicles and Fuels," 2013.

**Figure 27: NRC-Estimated Car Incremental Cost Versus 2010 Baseline ($26,341) for Midrange (a) and Optimistic (b) Assumptions**




Source: National Research Council. "Transitions to Alternative Vehicles and Fuels," 2013.

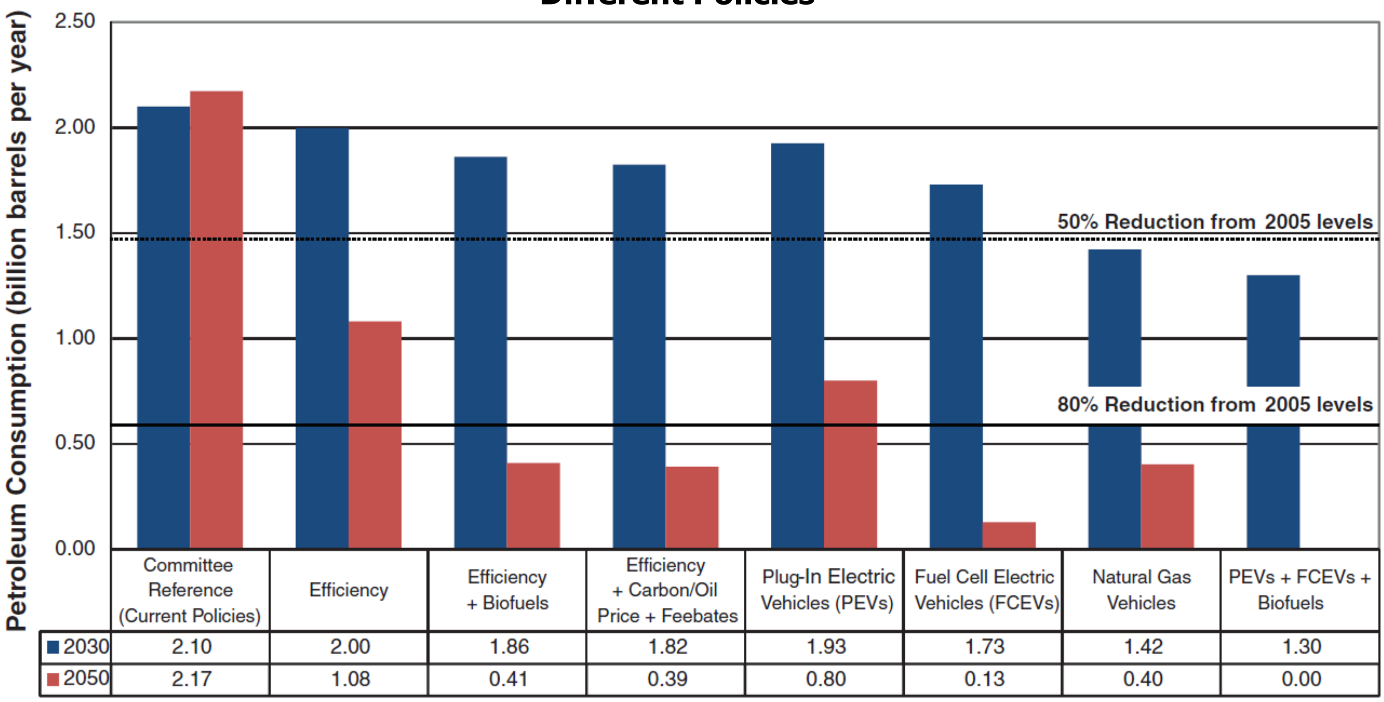
**Figure 28: NRC-Estimated Light Truck Incremental Cost Versus 2010 Baseline ($32,413) for Midrange (a) and Optimistic (b) Assumptions**




Source: National Research Council. "Transitions to Alternative Vehicles and Fuels," 2013.

Two main results from the NRC study are presented in Figure 29 and Figure 30. Projected potential petroleum use for technology-specific scenarios is shown in Figure 29. Among all scenarios, only two scenarios could achieve the 50 percent reduction in petroleum use by 2030 relative to 2005. These scenarios had relatively high market penetration of natural gas vehicles, PEVs, FCEVs, and biofuels. However, the committee concluded that these were unlikely to happen due to time lag to reach such substantial market penetration of new vehicle and fuel technologies. The 80 percent petroleum reduction goal by 2050 could be met if several combinations of technologies achieved the midrange level of success. Vehicle efficiency improvements beyond the 2025 CAFE standards are important to each successful combination. Major expansion of biofuels production capacity or high market penetration rates of CNGVs, BEVs, and/or FCEVs would also be required. For LDV GHG emissions, Figure 29 presents the committee's estimates in 2050 under different scenarios that assume midrange efficiency improvements. These alternative scenarios assume fuel production is constrained by GHG emissions control policies (low GHG production for electricity and hydrogen). The results show that each of the four general pathways (highly efficient ICE vehicles, biofuel, electric, and hydrogen vehicles) would not achieve the 2050 LDV GHG emissions goal even with low GHG fuel production. Noted uncertainties include cost, potential implementation rate, and response of consumers and manufacturers to policies.

**Figure 29: NRC-Estimated U.S. LDV Petroleum Use in 2030 and 2050 Under Different Policies**

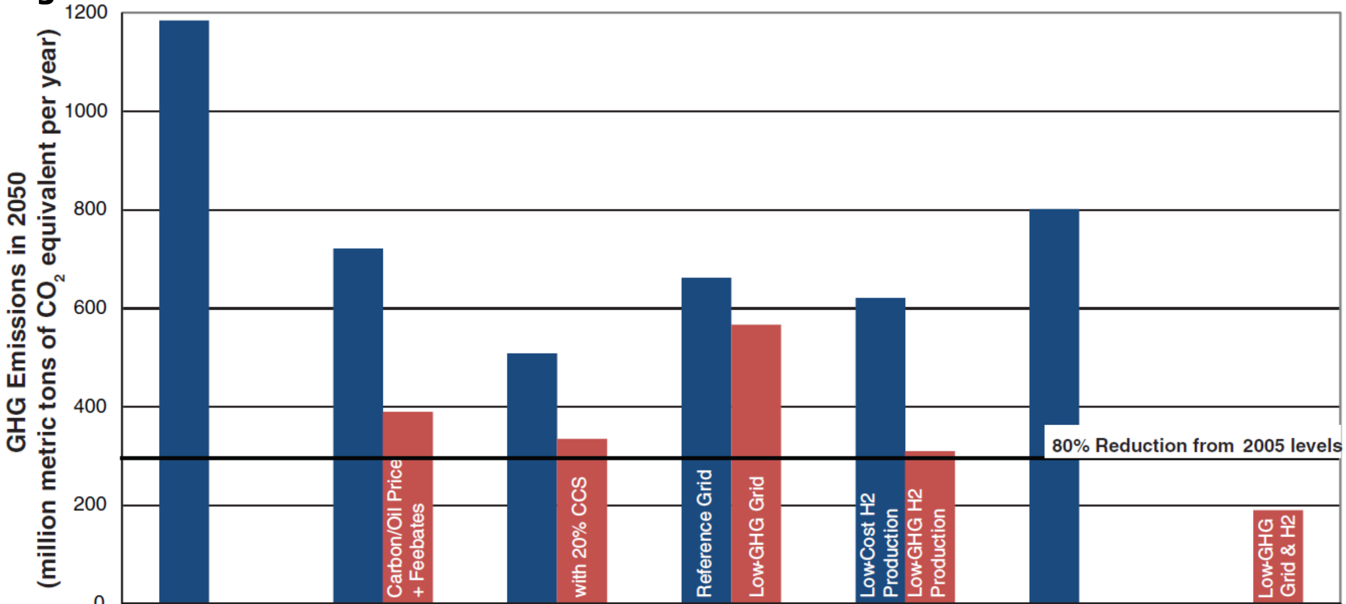



| | Committee Reference (Current Policies) | Efficiency | Efficiency + Biofuels | Efficiency + Carbon/Oil Price + Feebates | Plug-In Electric Vehicles (PEVs) | Fuel Cell Electric Vehicles (FCEVs) | Natural Gas Vehicles | PEVs + FCEVs + Biofuels |
|---|---|---|---|---|---|---|---|---|
| 2030 | 2.10 | 2.00 | 1.86 | 1.82 | 1.93 | 1.73 | 1.42 | 1.30 |
| 2050 | 2.17 | 1.08 | 0.41 | 0.39 | 0.80 | 0.13 | 0.40 | 0.00 |

**Note: The Committee Reference case includes current policies (2025 CAFE and final Renewable Fuel Standard for biofuels)**

Source: National Research Council. "Transitions to Alternative Vehicles and Fuels," 2013.

**Figure 30: NRC-Estimated U.S. LDV GHG Emissions in 2050 under Different Policies**

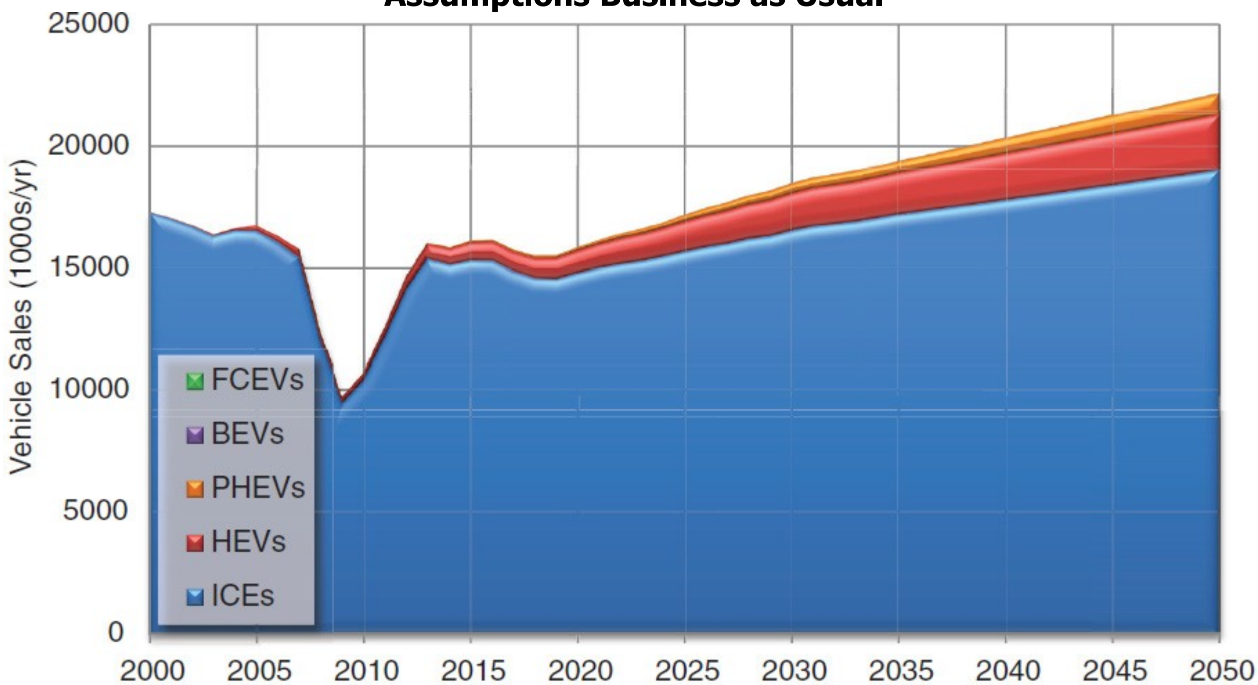



| | Committee Reference (Current Policies) | Efficiency | Efficiency + Biofuels | Plug-In Electric Vehicles (PEVs) | Fuel Cell Electric Vehicles (FCEVs) | Natural Gas Vehicles | PEVs + FCEVs + Biofuels |
|---|---|---|---|---|---|---|---|
| Reference Production | 1184 | 721 | 508 | 662 | 621 | 801 | |
| Low-GHG Production | | 389 | 335 | 567 | 310 | | 190 |

Source: National Research Council. "Transitions to Alternative Vehicles and Fuels," 2013.

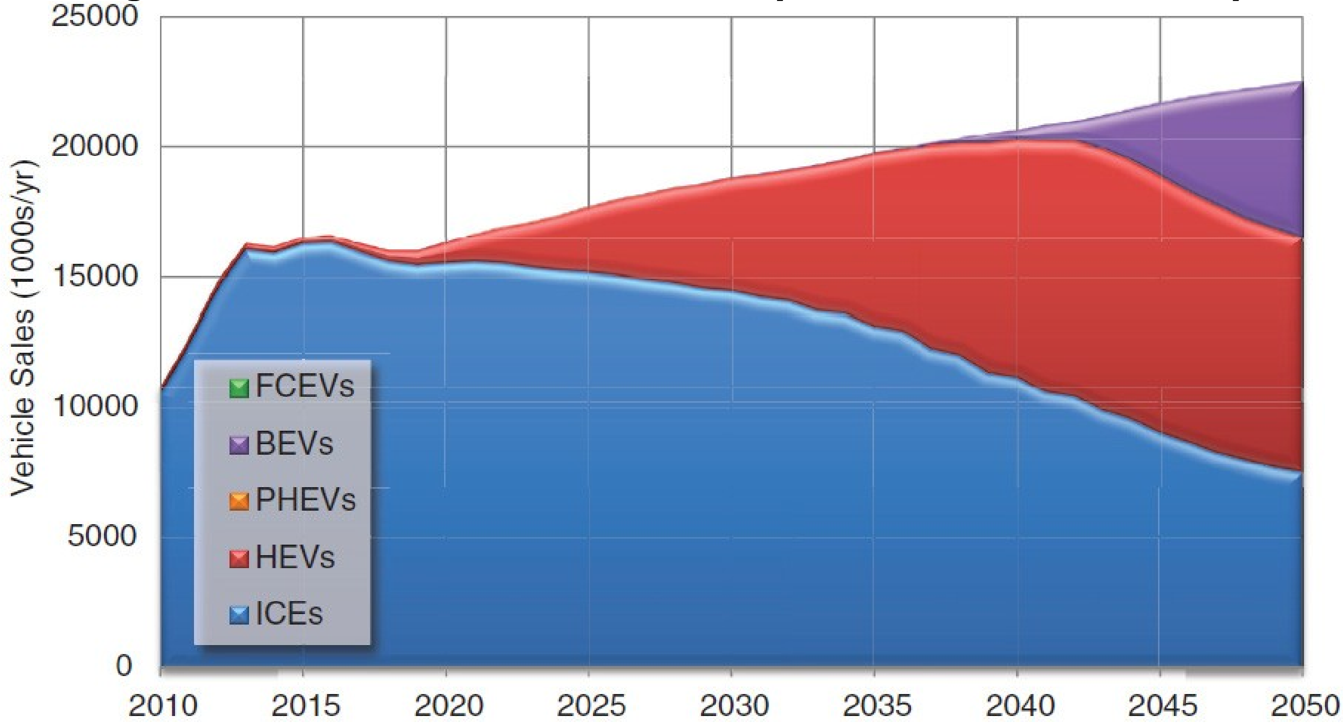
Figures 32-36 shows vehicle sales by powertrain under each midrange technology scenario, as compared to the business-as-usual case (Figure 31) using EIA Annual Energy Outlook 2011 reference assumptions.

**Figure 31: NRC-Estimated Vehicle Sales by Powertrain with Midrange Technology Assumptions Business as Usual**



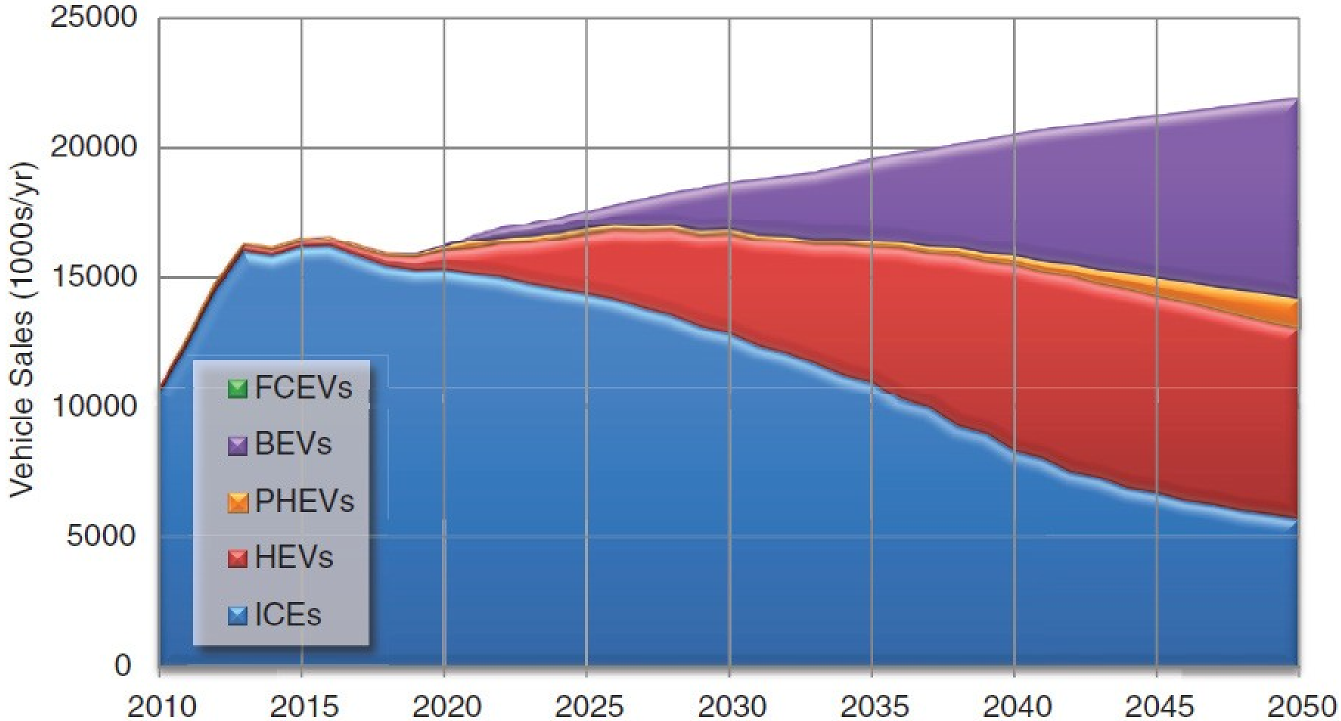

Source: National Research Council. "Transitions to Alternative Vehicles and Fuels," 2013.

**Figure 32: NRC- Estimated Vehicle Sales by Powertrain under Efficiency**



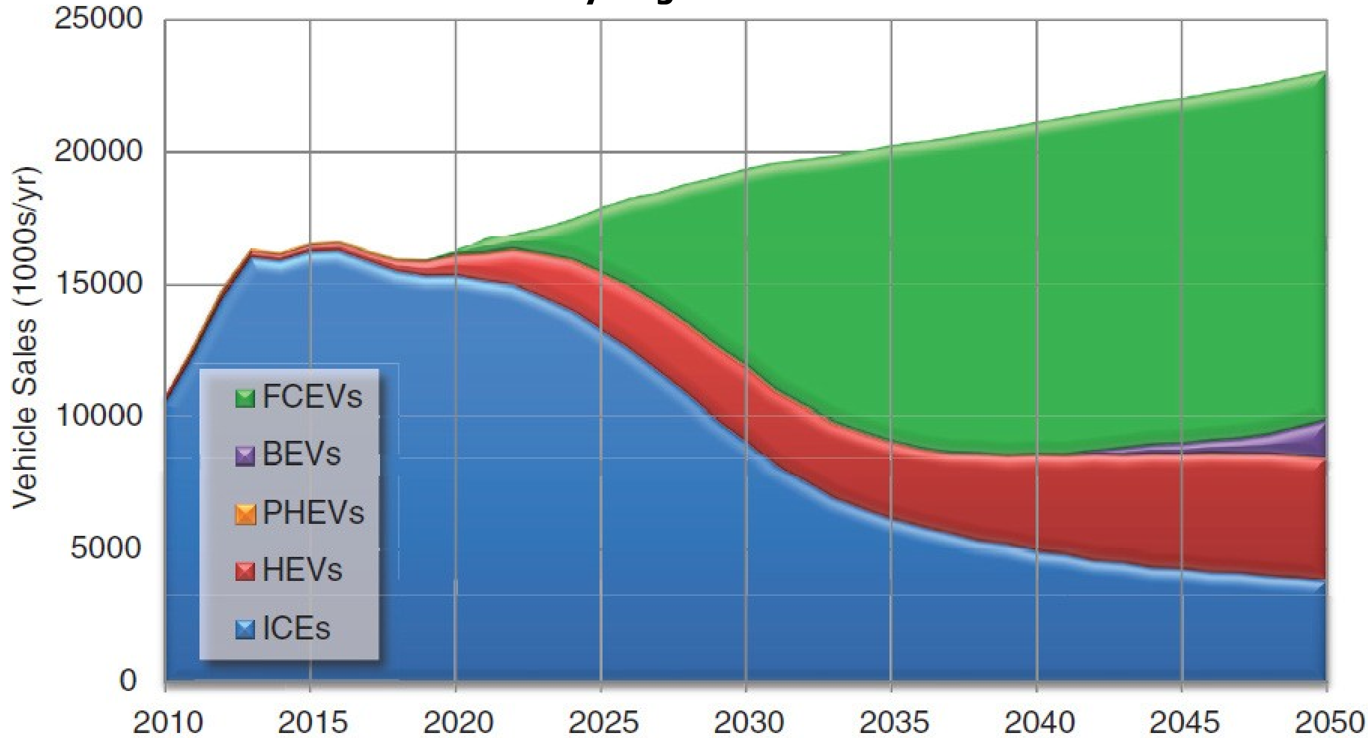

Source: National Research Council. "Transitions to Alternative Vehicles and Fuels," 2013.

**Figure 33: NRC-Estimated Vehicle Sales by Powertrain under PHEVs**



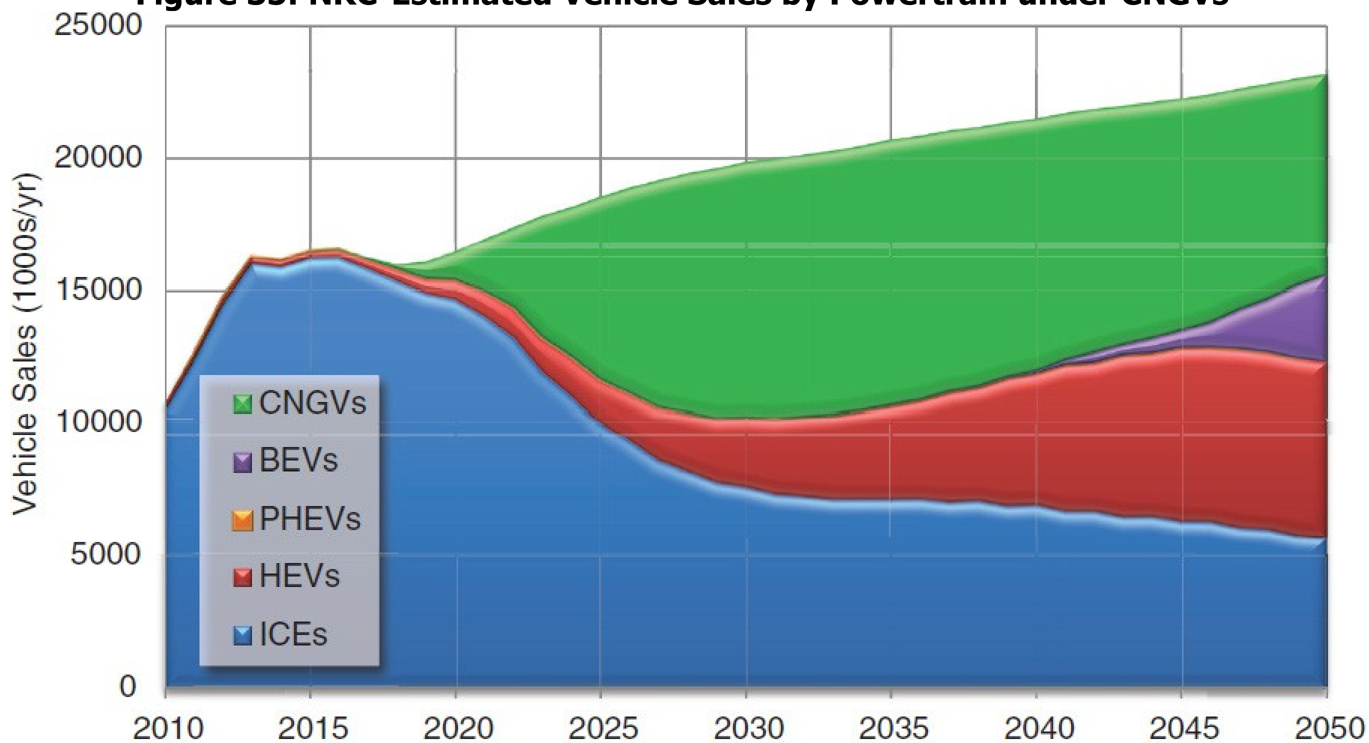

Source: National Research Council. "Transitions to Alternative Vehicles and Fuels," 2013.

**Figure 34: NRC-Estimated Vehicle Sales by Powertrain under Low-Carbon Hydrogen FCEV**



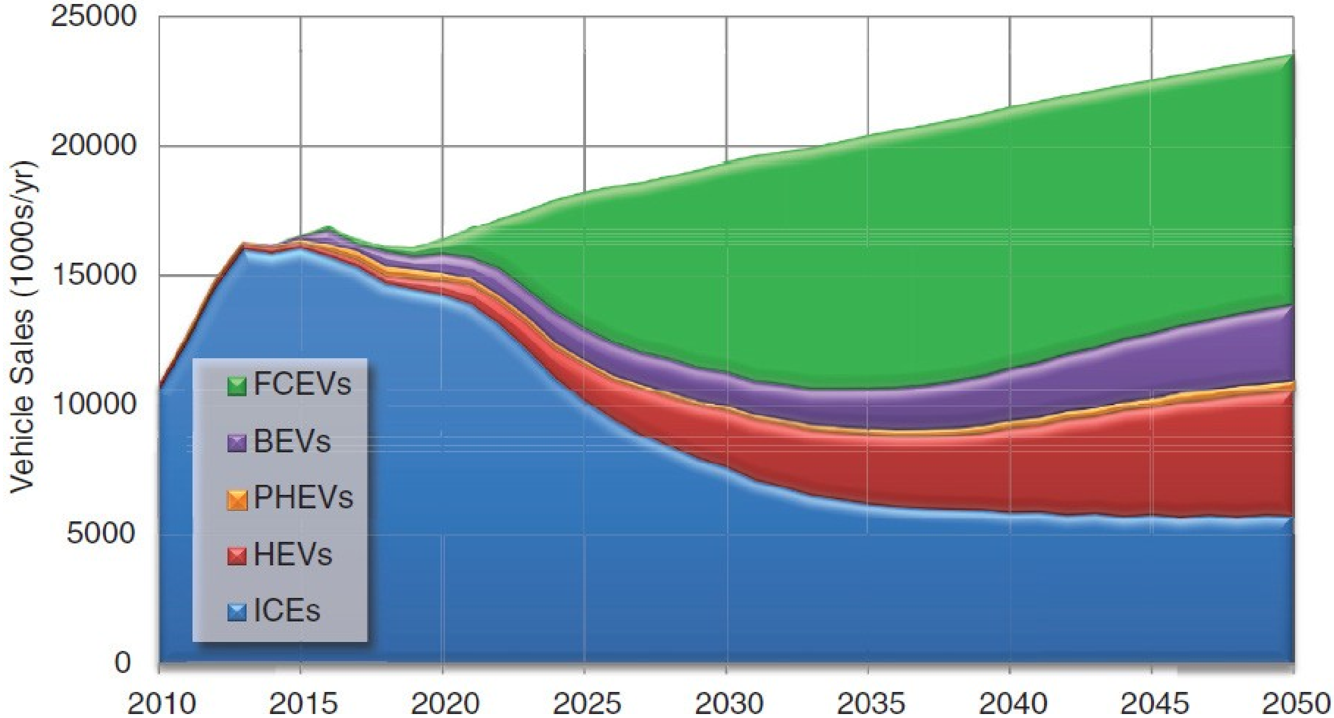

Source: National Research Council. "Transitions to Alternative Vehicles and Fuels," 2013.

**Figure 35: NRC-Estimated Vehicle Sales by Powertrain under CNGVs**




Source: National Research Council. "Transitions to Alternative Vehicles and Fuels," 2013.

**Figure 36: NRC-Estimated Vehicle Sales by Powertrain under PHEV, FCEV, and Biofuels**




Source: National Research Council. "Transitions to Alternative Vehicles and Fuels," 2013.

### Vehicle Choice Modeling Comparison

As mentioned previously, ADOPT supported the advanced vehicle deployment estimates from Chapter 2 of this report and is supporting the ongoing market impact assessment activity.

ADOPT has undergone extensive validation to historical vehicle sales data and has varying levels of overlap with the assumptions and modeling techniques of the U.S. EPA, NPC, and NRC studies.

The ADOPT approach is very different from U.S. EPA's Technical Assessment Report, but the end results nevertheless fall within the same range. The primary difference lies in the process used to generate market share estimates. The Technical Assessment Report used U.S. EPA's OMEGA model. OMEGA is primarily an accounting model.[35] It does not adjust vehicle sales in response to the cost of the technology added to each vehicle. Instead, it assumes different levels of market share for various advanced powertrains as different example GHG reduction pathways. In contrast, ADOPT estimates market share based on consumer and vehicle attributes. There are other, smaller differences too. The Technical Assessment Report relied on Annual Energy Outlook 2010 reference case energy prices whereas ADOPT uses the Annual Energy Outlook 2013 energy prices. The ADOPT model considers all the Technical Assessment Report vehicle and fuel types, but also includes a currently available CNG vehicle model.[36] ADOPT has also been calibrated to have a 14 percent to 46 percent discount rate that varies by income level, compared to the Technical Assessment Report's 3 percent. Despite these

---

[35] U.S. EPA Vehicles and Engines http://www.epa.gov/otaq/climate/documents/420r12024.pdf

[36] U.S. EPA TAR Study https://www.epa.gov/regulations-emissions-vehicles-and-engines/midterm-evaluation-light-duty-vehicle-greenhouse-gas

differences, both approaches estimate that HEVs will have the largest advanced vehicle market penetration while PHEVs and EVs have a significantly smaller share. Preliminary, ADOPT runs estimate 7 percent of the fleet to be HEVs in 2025, which falls within the Technical Assessment Report's 3 percent to 68 percent range. The ADOPT model's preliminary assumptions and approach will be finalized for application in the ongoing market impact assessment activity.

The ADOPT approach is more similar to the NPC 2012 study. They both use vehicle choice models to estimate sales, share the same powertrains and fuel types, and capture technology improvements over time. The NPC study used the Consumer Vehicle Choice Model. Like ADOPT, Consumer Vehicle Choice Model uses a Multinomial Logit model. A Multinomial Logit model is basically a weighting function that estimates sales based on the estimated value of vehicle attributes to consumers. A challenge with using a simple Multinomial Logit model is capturing the correct substitution pattern. For example, if an advanced powertrain car enters the market, a Multinomial Logit model may suggest that a similar proportion of trucks and cars are substituted with the new car. Some argue that the new car should capture a greater portion of its sales from similar vehicles, such as other cars. Two modifications to the Multinomial Logit model, mixing and nesting, have been devised to improve the substitution pattern. Mixing involves adding heterogeneity to the preferences by using a random distribution of preferences for each vehicle attribute. This approach improves the substitution pattern by reflecting variations in consumer preference.

Nesting involves creating subsets of similar vehicles with greater levels of substitution. ADOPT is a Mixed Multinomial Logit model whereas the Consumer Vehicle Choice Model is a Nested Multinomial Logit model. Both approaches add variables that are hard to substantiate given a lack of empirical data. The mixed approach was chosen for ADOPT to minimize the number of additional variables to five and to focus on capturing variations in consumer preference. Those five variables represent the amount of variation around each preference weighting. A nested approach requires deciding how vehicles should be grouped and how important each grouping is. The Consumer Vehicle Choice Model has 28 nesting involves creating subsets (Consumer Vehicle Choice Model Documentation, 2012) to define and calibrate.

While the ADOPT and NPC study frameworks have significant overlap in their approach, they have been run with different approaches to their inputs. The NPC study assumes specific cost increments for different levels of fuel economy improvement for HEVs and conventional vehicles.[37] ADOPT assumes these vehicles experience steady technology improvements over time, such as mass reduction, engine efficiency improvements, and battery cost reductions.

While some assumptions are difficult to compare, preliminary ADOPT runs were completed with some significant assumptions, such as battery cost reductions over time, being similar. Similar to the NPC study, the ADOPT runs estimated that HEVs and conventional vehicles make up the majority of the fleet by 2050. The primary reason for the outcome in ADOPT was that the conventional vehicles achieved significant fuel cost reductions from lightweighting, and despite some engine downsizing, still achieved better acceleration than the best-selling

[37] NPC Light Duty Vehicles Study http://www.npc.org/reports/FTF-report-080112/Chapter_2-Light-Duty_Vehicles.pdf

alternative fuel vehicles. The ADOPT runs did not have as significant penetration of CNGVs or FCVs compared to the NPC study due to much more limited infrastructure assumptions.

The ADOPT model is also similar to the Nested Multinomial Logit LAVE-Trans model used in the NRC study. Both models include vehicle price, fuel cost, range, fuel availability, and the diversity of make and model options available in their weighting function. Baseline runs for both models match powertrain sales within a few percent. Similarly, the NRC study's high efficiency case has similar assumptions and results as one of the preliminary ADOPT runs. They both result in similar fuel economies of conventional vehicles and HEVs. However, other scenario assumptions and results differ greatly. In some scenarios, the NRC study assumes conventional gasoline and CNG cars achieve over 90 MPG by 2050. HEVs are assumed to exceed 120 mpg. Preliminary ADOPT runs assume the fleet must meet CAFE by technology improvements, plus engine downsizing if necessary. This results in a maximum 60 mpg conventional vehicle and an average 41 mpg for conventional cars. In several cases, the NRC study also estimates BEV and FCEV prices to fall below conventional vehicles. The ADOPT model estimates the lowest BEV prices to still remain higher than the lowest conventional vehicle cost in 2050. Where the models used very different assumptions, the results also differed significantly.

# CHAPTER 4: Technologies for Potential Future Consideration

This chapter summarizes two advanced technologies that are not currently included in the CEC's portfolio, but that may be worth considering in the future as having a potential to displace petroleum consumption and GHG emissions.

## Electric Roadway

Significant advances in wireless power transfer technology in recent years has led to the development of many prototype and even some commercial products for stationary charging of PEVs without needing to handle a physical cord and plug. This technology may increase the convenience of stationary PEV charging in the near to medium term and minimize missed charging opportunities. In the longer term, the concept of in-motion power transfer along an electric roadway offers a transformative opportunity for electrified transportation.

Transportation electrification has been growing in recent years with the introduction of many new BEV and PHEV models. However, the total amount of electrified miles remains modest as the sales of vehicles such as the Nissan Leaf and Chevrolet Volt have remained below initially publicized expectations (http://www.thedetroitbureau.com/2012/11/nissan-will-miss-leaf-sales-targets-says-ghosn/ and https://www.hybridcars.com/chevy-volts-1788-sales-in-july-means-trading-places-with-nissan-again-sort-of/). Likely barriers to broader market penetration include limited range, higher cost, and longer time needed to refuel (charge) relative to a conventional vehicle.

A small amount of infrastructure that can supply electricity directly to the vehicle while traveling can resolve several vehicle electrification barriers. The Interstate Highway System makes up 1 percent of the roadway miles in the United States, carries about 20 percent of the miles traveled, and connects all major urban areas. Roughly 80 percent of people and businesses are in urban areas and within 10 miles of the interstate highway. Interstate electrification could therefore reduce the battery size needed by BEVs. A small, lower cost battery would be sufficient even for long cross-country trips. If electric roadway capable, PHEVs and even HEVs could replace gasoline consumption on long interstate trips with lower cost electricity and make the vehicles more financially attractive.

Several companies are currently developing electric roadway infrastructure. Volvo is developing an inroad conductive approach using Alstom rail technology to electrify the portion of road under the vehicle.[38] Electrifying class 8 long-haul trucks appears particularly attractive because fuel accounts for their greatest cost,[39] they travel primarily on the interstate, they use more petroleum than all the other heavy vehicles combined and their long constant-speed drive cycles do not generally work well with BEV, PHEV, or HEV powertrains. In addition to Volvo, Siemens has been working on conductive power transfer to heavy trucks through

[38] Volvo, The Road of Tomorrow is Electric https://www.volvogroup.com/en-en/news/2018/sep/volvo-plans-to-build-electric-roads.html

[39] U.S. DOE Research and Development Opportunities for Heavy Trucks https://www1.eere.energy.gov/vehiclesandfuels/pdfs/truck_efficiency_paper_v2.pdf

overhead catenary lines, and the Korea Advanced Institute of Science and Technology together with On-Line Electric Vehicle have implemented inductive power transfer to buses. Other organizations working on inductive power transfer for vehicles include Oak Ridge National Laboratory, WiTricity, Evatran, Mojo Mobility, Qualcomm, Utah State University, and Wireless Advanced Vehicle Electrification.

While electric roadways may help resolve traditional vehicle electrification barriers, the concept has challenges of its own. These include the further work needed to develop a system that can be realistically, reliably, and safely implemented on a large scale, and the significant road infrastructure and electric grid investments that would be required to install such a system on even a small fraction of roadways.

## Dimethyl Ether Engines

Dimethyl ether (DME) is a synthetically generated fuel produced from methanol. It can be derived from a number of feedstocks including coal, natural gas, biogas, and biomass via gasification into syngas. It has historically been used as a household cooking fuel and an aerosol propellant. However, DME exhibits a number of properties that makes it a good candidate as an alternative fuel. DME with a cetane number of ~55 can be readily burned in a diesel engine with only moderate modifications to the fueling system. DME combustion produces no soot (although it can produce nano-particles). With proper engine calibration and optimization, oxides of nitrogen emissions can be significantly lower than for diesel (Robert Bosch GmbH, 2007). These features of DME combustion allow substantial simplification of the aftertreatment system required to meet on-road emissions standards for heavy-duty diesel vehicles, reducing cost, size, and weight.

DME is a colorless gas at room temperature and pressure, but under modest pressures of around 75 pounds per square inch at room temperature, it can be compressed to a liquid. Unlike CNG, which is stored at pressures up to 3,600 pounds per square inch, or LNG, which is stored at -162°C, DME does not require high-pressure or cryogenic storage. DME storage is very similar to storage of propane. This greatly simplifies the on-board storage tank and refueling infrastructure requirements.

Nevertheless, the lack of fuel distribution, storage, and dispensing infrastructure for DME are a major barrier to market penetration.

Figure 19 shows that under typical storage conditions on-board a vehicle, DME has a volumetric energy density similar to LNG and falls just below propane. However, typical specific fuel consumption in turbo-charged compression ignition engines is 30 percent–40 percent lower than in spark-ignited engines for commercial vehicles (Robert Bosch GmbH, 2007). Because DME is suitable for compression ignition due to its high cetane number, and propane and natural gas are typically used in spark-ignition engines, the increased thermal efficiency more than makes up the difference.

Volvo has announced plans to begin limited production of DME heavy-duty commercial vehicles starting in 2015 and is already conducting field testing in the United States with Safeway Inc. and Martin Transportation. Together with Oberon Fuels, which has developed small-scale production units to convert natural gas and biogas into DME on a regional scale, this demonstration project has been recognized and received $500,000 in funding from

California's San Joaquin Valley Air Pollution Control District[40]. However, this is just the beginning, and a substantial investment will be required if DME is going to be commercialized on a large scale.

[40] Borgna, B. (2013, June 6). *Volvo Trucks to Commercialize DME-Powered Vehicles for North America.* Retrieved December 2013, from Volvo Group Global: https://www.volvogroup.com/en-en/news/2013/jun/news-143286.html

# CHAPTER 5: Government and Corporate Incentives Impacting Advanced Vehicle Technologies

Regulations, policies, and incentives have the potential to influence market growth of advanced vehicle technologies, which are ultimately adopted by consumers and fleets operated by public and private institutions, as well as consumers. This section reviews government requirements and incentives. Requirements can set minimum standards, while incentives help industry achieve the established standards; the two approaches can complement each other to achieve similar goals.

## An Assessment of the Range of Public Incentives Available to Advanced Technology Vehicle Producers and Consumers

In California, public incentives are available at the local, state, and federal level for advanced technology vehicles. Incentives available in all other states for HEVs and EVs are summarized by the National Council of State Legislatures. Common incentive types include: tax credits, rebates, grants, and infrastructure incentives. The types and ranges of incentives are presented in Table 19 and Table 20, for consumers and developers, respectively. The incentives captured here are in addition to the Alternative and Renewable Fuel and Vehicle Technology Program and are sourced from the Alternative Fuels Data Center laws and incentives database (www.afdc.energy.gov).

**Table 19: Consumer Incentives to Purchase an Advanced Technology Vehicle**

| Type | Program name | Funding amount | Technology |
|---|---|---|---|
| Federal | | | |
| Tax Credit | Qualified Plug-In Electric Drive Motor Vehicle Tax Credit | \$2,500-\$7,500, based on vehicle's traction battery capacity and the gross vehicle weight rating | Electric vehicles |
| Infrastructure Incentives | Airport ZEV and Infrastructure Incentives | 50 percent of cost of ZEVs used exclusively for airport purposes; funding to install infrastructure to support ZEVs. | ZEVs and associated infrastructure |
| State (California) | | | |
| Rebate (funding exhausted as | Hybrid Truck and Bus Voucher Incentive Project | Vouchers to eligible fleets of \$6,000-\$45,000. | HEVs and ZEVs |

| Type | Program name | Funding amount | Technology |
|---|---|---|---|
| of October 2013) | | | |
| Rebate | Clean Vehicle Rebate Project | Up to $2,500 for light-duty ZEVs and PHEVs approved or certified by the California Air Resources Board. | Light-duty \ ZEVs and PHEVs |
| HOV and HOT Lane Exemption | High Occupancy Vehicle (HOV) and High Occupancy Toll (HOT) Lane Exemption | Can use HOV lanes regardless of the number of occupants in vehicle; exempt from toll charges imposed on HOT lanes | CNG, hydrogen, electric, and PHEVs |
| Grant | Motor Vehicle Registration Fee Program | Funding for projects that reduce air pollution from on- and off-road vehicles | Unspecified |
| Grant | Carl Moyer Memorial Air Quality Standards Attainment Program | Incentives to cover the incremental cost of purchasing engines and equipment that are cleaner than required by law | Heavy-duty fleet modernization, LDV replacements and retrofits, idle reduction technology, and off-road vehicle and equipment purchases. |
| Grant | Goods Movement Emission Reduction Program | Funding for projects that reduce emissions from freight movement, including heavy-duty truck replacement, repower, or retrofit; and truck stop electrification infrastructure development | Heavy-duty trucks, truck stop electrification |
| Grants | Lower-Emission School Bus Program | Grant funding for replacement of older school buses | Alternative fuel buses, hybrid electric school buses (partial funding) |
| Local | | | |

| Type | Program name | Funding amount | Technology |
|---|---|---|---|
| Rebate (Riverside, CA) | Alternative Fuel Vehicle Rebate Program | Up to $2,500 for a qualified PEV or $1,500 for a qualified CNG vehicle or HEV purchased from a City of Riverside auto dealership. | Qualified PEV, CNGV, or HEV |
| Rebate (San Joaquin Valley) | California Hybrid and Zero- Emission Truck and Bus Voucher Incentive Project | $12,000-$30,000 in addition to the Hybrid Voucher Incentive Program rebate | See above |
| Rebate (San Joaquin Valley) | Drive Clean! Rebate Program | Up to $3,000 per vehicle | Qualified natural gas, propane, and PEVs |
| Rebate (San Joaquin Valley) | Public Benefit Grant Program | Maximum of $20,000 per vehicle and limit of $100,000 per agency per year. Funding goes to cities, counties, special districts, and public educational institutions. | Electric, natural gas, and propane vehicles, as well as HEVs |
| Rebate (San Joaquin Valley) | Voucher Incentive Program Truck Voucher Program | Unspecified | Heavy-duty diesel truck replacements that achieve emissions reductions beyond those required by law or regulation |

Source: Alternative Fuels Data Center laws and incentives database (www.afdc.energy.gov)

**Table 20: Public Incentives Targeting Developers of Advanced Technology Vehicles**

| Type | Program name | Funding amount | Technology |
|---|---|---|---|
| Federal | | | |
| Manufacturing Incentives | Advanced Technology Vehicles Manufacturing Loan Program | Component manufacturers eligible for up to 30 percent of the cost of re-equipping, expanding, or establishing manufacturing facilities | Advanced technology vehicles are LDVs or ultra-efficient vehicles that meet specified federal emission standards and fuel economy requirements |
| State (California) | | | |
| Manufacturing Incentive | California Alternative Energy and Advanced Transportation Financing Authority Advanced Transportation Tax Exclusion | Sales and Use Tax exclusion for qualified manufacturers | Advanced transportation produces, components, or systems that reduce pollution and energy use and promote economic development |
| Local | | | |
| Technology Advancement Funding (South Coast) | South Coast Air Quality Management District's Clean Fuels Program | Funding (~$1 million annually, with cost-share requirement) for research, development, demonstration, and deployment of projects expected to accelerate commercialization of advanced low emission transportation technologies | Powertrains and energy storage/conversion devices (e.g., fuel cells and batteries), and implementation of clean fuels (e.g., natural gas, propane, and hydrogen) |

Source: Alternative Fuels Data Center Laws and Incentives Database (www.afdc.energy.gov)

## An Assessment of Government or Corporate Sustainability Policies That Influence Advanced Vehicle Procurement Decisions

Although there are no comprehensive data on the number of advanced vehicles that are being purchased due to corporate or government sustainability policies, qualitative indicators suggest that such policies are impacting the level of alternative vehicle procurement in the United States. Sustainability policies can include commitments to procure alternative fuel vehicles, for example, AT&T in investing more than $500 million to deploy 15,000 alternative fuel vehicles over 10 years.

The U.S. DOE's National Clean Fleets Partnership works with 22 partners to reduce petroleum consumption; partners may be motivated by a number of factors, including sustainability and lowering operation cost. The partners must own or have contractual control over at least 50 percent of their vehicles and operate in multiple states. Partner companies and their advanced vehicle procurements are highlighted in Table 21.

**Table 21: Alternative Vehicle Procurement by Clean Fleets Partners**

| Company | Highlight |
|---|---|
| **Advanced Disposal Services** | 6 CNG fueling stations and more than 140 CNG refuse-collection and support vehicles, out of more than 3,200 vehicles |
| **AMP Americas** | 42 milk-transport trucks powered by compressed natural gas |
| **ARAMARK** | 78 HEVs |
| **AT&T** | 7,500 alternative fuel vehicles, out of more than 74,000 vehicles and 24,800 wheeled equipment units |
| **Best Buy** | Testing both electric and propane vehicles |
| **Coca-Cola** | Alternative fuel vehicles make up close to 10 percent of heavy-duty truck holdings; has the largest heavy-duty, diesel-electric hybrid truck fleet in North America, resulting in significant fuel savings and emissions reductions. |
| **Enterprise Holdings** | More than 70 percent of its shuttle buses run on biodiesel, with approximately 50 percent using 5 percent biodiesel (B5), and more than 20 percent using 20 percent biodiesel (B20). |
| **FedEx** | More than 400 advanced EVs and HEVs; vehicles running on biodiesel, propane, and natural gas |
| **Frito-Lay** | 176 all-electric medium-duty delivery trucks; more than 600 hybrid electric sales cars and rapidly expanding use of propane and natural gas. |
| **GE** | Plans to purchase 25,000 EVs worldwide by 2015 |
| **Johnson Controls, Inc.** | More than 500 hybrids and 20 all-electric vans; also use of compressed natural gas and propane |
| **Kwik Trip** | Driven natural gas fleet more than 1 million miles and displaced 165,195 gallons of diesel fuel |
| **OSRAM SYLVANIA** | Replaced more than one-fifth of its lighting maintenance utility trucks with more efficient trucks that reduce the need for idling |
| **Pacific Gas and Electric Company** | More than 3,100 on-road alternative fuel and high-efficiency vehicles |
| **PepsiCo** | More than 1,300 hybrids in its car fleet |

| Company | Highlight |
|---|---|
| **Ryder** | Opened its first natural gas vehicle maintenance facility in 2011, allowing the company to deploy hundreds of heavy-duty vehicles that run on compressed or liquefied natural gas; also leases electric and hybrid vehicles to its fleet customers |
| **Schwan's Home Service** | Operates the largest propane vehicle fleet in the United States; about 75 percent of the company's trucks run on propane |
| **Staples** | Operates 53 all-electric delivery trucks |
| **ThyssenKrupp Elevator** | Begun expanding its use of propane vehicles; deployed its first electric-drive vehicle |
| **UPS** | Nearly 2,700 compressed natural gas, liquefied natural gas, propane, electric, and HEVs |
| **Veolia Environmental Services** | Operates four compressed natural gas fueling stations and more than 100 CNG refuse-collection and support vehicles |
| **Verizon** | Operates more than 2,500 alternative energy vehicles |
| **Waste Management** | More than 2,000 heavy-duty natural gas trucks; 40 natural gas fueling stations, 15 of which are publicly accessible, and another seven with pre- approved third-party access |

Source: DOE National Clean Fleets Partnership
(http://www1.eere.energy.gov/cleancities/national_partnership.html)

Although partners vary in size and investment in alternative vehicles, companies are motivated by corporate responsibilities well as financial incentives. Federal, state, and local incentives can help push corporate purchasing, thereby creating a larger market, which ultimately drives down cost. For example, the premium for natural gas refuse trucks has declined considerably in recent years.

The federal government also has its own fleet sustainability mandates. Because the federal fleet has more than 600,000 vehicles, changes to its composition have the opportunity to make an impact. In fiscal year 2012, there were 10,304 federal vehicles located in California, of which 46 percent were alternative vehicles. The largest category was E85 flexible-fuel vehicles. Nationally, of the 600,332 federal vehicles, 33 percent were alternative vehicles. Table 22 provides the breakdown of federal vehicle types in California and nationally for FY12. While only 2 percent of federal vehicles are located in California, 15 percent of electric hybrids, 32 percent of dedicated CNGs, 15 percent of gas plug-in hybrids, 7 percent of diesel hybrids, and 25 percent of dedicated hydrogen vehicles are located in California.

**Table 22: Federal Fleet Vehicle Type and Configuration (FY12)**

| Vehicle Type and Configuration | # Total Vehicles (California) | # Total Vehicles (U.S. Total) | Percent CA of U.S. |
|---|---|---|---|
| Gas | 3,996 | 339,843 | 1 percent |
| E85 Flex Fuel | 3,392 | 174,419 | 2 percent |
| Diesel | 1,563 | 64,452 | 2 percent |
| Electric Dedicated | 574 | 3,757 | 15 percent |
| Gas Hybrid | 543 | 15,597 | 3 percent |
| CNG Dedicated | 133 | 421 | 32 percent |
| CNG Bi-Fueled | 56 | 1,245 | 4 percent |
| Gas Plug-In Hybrid | 25 | 166 | 15 percent |
| Diesel Hybrid | 20 | 286 | 7 percent |
| Hydrogen Dedicated | 1 | 4 | 25 percent |
| LPG Bi-Fueled | 1 | 101 | 1 percent |
| LPG Dedicated | 0 | 41 | 0 percent |
| Total | 10,304 | 600,332 | 2 percent |

Source: Adapted from E.O. 13514 Section 12 guidance (https://federalfleets.energy.gov/sites/default/files/static_page_docs/fleetguidance_13514.pdf)

Table 23 lists federal fleet mandates for deployment of alternative fuel and advanced vehicle technologies that have been implemented over the years. State fleets and alternative fuel providers (e.g., utilities) are also regulated under EPAct, with similar requirements to federal fleets.

**Table 23: Federal Government Alternative Fuel Vehicle Purchasing**

| Type | Statute or Executive Order | Requirement |
|---|---|---|
| **GHG reduction** | E.O. 13514 | Sets a percentage reduction target for reductions of scope 1 and scope 2 GHG emissions from fiscal year 2008 to fiscal year 2020 |
| **Petroleum reduction** | E.O. 13514, E.O. 13423, EISA §142 | Annual and total reductions in petroleum use |
| **Alternative fuel use increase** | E.O. 13423, EISA §142 | Requires 10 percent annual increase from fiscal year 2005 through fiscal year 2015; Requires 10 percent total |

| Type | Statute or Executive Order | Requirement |
|---|---|---|
| | | increase from fiscal year 2005 to fiscal year 2015. |
| **Alternative fuel use** | EPAct 2005 §701 | Requires all duel-fueled alternative fuel vehicles to use alternative fuel, unless waivered |
| **Alternative fuel infrastructure** | EISA §246 | Requires every federal fueling center without renewable fuel availability to install a renewable fuel pump |
| **Vehicle acquisition** | EPAct 1992, EISA §141, E.O. 13423 | Requires 75 percent of LDVs acquired in metropolitan statistical areas to be alternative fuel vehicles; prohibits agencies from acquiring vehicles that are not low-GHG- emitting vehicles; requires agencies to use PHEVs when commercially available at a cost reasonably comparable to non-PHEVs |

Source: Adapted from E.O. 13514 Section 12 guidance (https://federalfleets.energy.gov/sites/default/files/static_page_docs/fleetguidance_13514.pdf)

A 2008 Government Accountability Office review found that federal agencies were acquiring alternative fuel vehicles but facing challenges in meeting other fleet objectives (e.g., alternative fuel availability for those vehicles[41]. More recently, the Government Accountability Office found that multiple, sometimes conflicting statutes inhibit federal fleet managers from achieving GHG and petroleum use reduction. For example, Government Accountability Office noted that in 2010, approximately 55 percent of flex-fueled alternative fuel vehicles received a waiver for not operating on E85 because the fuel was not available.[42] Agencies have been procuring alternative fuel vehicles to meet the purchase mandate, but when those vehicles are not running on alternative fuel, they may use more petroleum than a more fuel efficient non-alternative fuel vehicle. As a solution, U.S. DOE and Government Accountability Office propose creating a broader, performance-based approach, which would allow fleet managers to use a variety of options to achieve a target[43].

[41] Government Accountability Office (GAO). (2008). "Federal Energy Management: Agencies Are Acquiring Alternative Fuel Vehicles but Face Challenges in Meeting Other Fleet Objectives". GAO-09-75R. http://www.gao.gov/new.items/d0975r.pdf

[42] Data on the waivered vehicles is published online at Federal Fleet Performance Data http://federalfleets.energy.gov/performance_data/2014_waivers

[43] GAO. (2011). "Energy: Resolving conflicting requirements could more effectively achieve federal fleet energy goals." GAO-11-318SP. https://www.gao.gov/modules/ereport/handler.php?1=1&m=1&path=/ereport/GAO-11-318SP/data_center/Energy/Resolving_conflicting_requirements_could_more_effectively_achieve_federal_fleet_energy_goals

A number of resources have been developed to help federal fleets transition to alternative fuels and alternative vehicles, including the Alternative Fuels Data Center,[44] Alternative Fuel Station Locator, Clean Cities and National Green Fleets Program,[45] FEMP's Sustainable Federal Fleets website,[46] and the Fleet Sustainability Dashboard (FleetDASH).[47]

[44] Alternative Fuels Data Center http://www.afdc.energy.gov/
[45] Alternative Fuel Station Locator http://www1.eere.energy.gov/cleancities/
[46] FEMP's Sustainable Federal Fleets Website https://federalfleets.energy.gov/
[47] Fleet Sustainability Dashboard https://federalfleets.energy.gov/FleetDASH/

# GLOSSARY

ALTERNATING CURRENT (AC)—Flow of electricity that constantly changes direction between positive and negative sides. Almost all power produced by electric utilities in the United States moves in current that shifts direction at a rate of 60 times per second.

AMPERE-HOUR (Ah)—A unit of electric charge, usually used for batteries. This unit combines the amount of current with how long that current can be sustained until the battery completely discharges. Large batteries have several ampere-hours, but cell phones and other small devices have batteries with a total charge measured in milliampere-hours. This measured quantity is called battery capacity.[48]

AUTOMOTIVE DEPLOYMENT OPTIONS PROJECTION TOOL (ADOPT)—The Automotive Deployment Options Projection Tool is a light-duty vehicle consumer choice and stock model. ADOPT estimates vehicle technology improvement impacts on future U.S. light-duty vehicle sales, energy use, and emissions.[49]

BATTERY ELECTRIC VEHICLE (BEV)—Also known as an "All-electric" vehicle (AEV), BEVs utilize energy that is stored in rechargeable battery packs. BEVs sustain their power through the batteries and therefore must be plugged into an external electricity source in order to recharge.

CALIFORNIA ENERGY COMMISSION (CEC)—The state agency established by the Warren-Alquist State Energy Resources Conservation and Development Act in 1974 (Public Resources Code, Sections 25000 et seq.) responsible for energy policy. The CEC's five major areas of responsibilities are:

1. Forecasting future statewide energy needs.
2. Licensing power plants sufficient to meet those needs.
3. Promoting energy conservation and efficiency measures.
4. Developing renewable and alternative energy resources, including providing assistance to develop clean transportation fuels.
5. Planning for and directing state response to energy emergencies.

Funding for the CEC's activities comes from the Energy Resources Program Account, Federal Petroleum Violation Escrow Account, and other sources.

CARBON DIOXIDE (CO2)—A colorless, odorless, nonpoisonous gas that is a normal part of the air. Carbon dioxide is exhaled by humans and animals and is absorbed by green growing things and by the sea. CO2 is the greenhouse gas whose concentration is being most

---

[48] University of Calgary, Energy Education Website (https://energyeducation.ca/encyclopedia/Ampere_hour)

[49] NREL ADOPT Information https://www.nrel.gov/transportation/adopt.html

affected directly by human activities. $CO_2$ also serves as the reference to compare all other greenhouse gases (see carbon dioxide equivalent).

CARBON DIOXIDE EQUIVALENT ($CO_2e$)—A metric used to compare emissions of various greenhouse gases. It is the mass of carbon dioxide that would produce the same estimated radiative forcing as a given mass of another greenhouse gas. Carbon dioxide equivalents are computed by multiplying the mass of the gas emitted by its global warming potential.

COMPRESSED NATURAL GAS (CNG)—Natural gas that has been compressed under high pressure, typically between 2,000 and 3,600 pounds per square inch, held in a container. The gas expands when released for use as a fuel.

DIMETHYL ETHER (DME)—Dimethyl ether is a synthetically produced alternative to diesel for use in specially designed compression ignition diesel engines. Under normal atmospheric conditions, DME is a colorless gas. It is used extensively in the chemical industry and as an aerosol propellant. Dimethyl ether requires about 75 pounds per square inch of pressure to be in liquid form. Because of this, DME's handling requirements are similar to those of propane—both must be kept in pressurized storage tanks at an ambient temperature.[50]

DIRECT CURRENT (DC)—A charge of electricity that flows in one direction and is the type of power that comes from a battery.

E85—E85 motor fuel is defined as an alternative fuel that is a blend of ethanol and hydrocarbon, of which the ethanol portion is 75-85% denatured fuel ethanol by volume and complies with the most current American Society of Testing and Measurements specification D5798.[51]

ELECTRIC VEHICLE (EV)—A broad category that includes all vehicles that are fully powered by electricity or an electric motor.

ELECTRIC VEHICLE MILES TRAVELED (eVMT)—Refers to miles driven using electric power over a given period of time. The more general term, VMT, is a measure of overall miles driven over a period of time.[52]

FUEL CELL ELECTRIC VEHICLE (FCEV)—A zero-emission vehicle that runs on compressed hydrogen fed into a fuel cell "stack" that produces electricity to power the vehicle.

GASOLINE GALLON EQUIVALENT (GGE)—The amount of alternative fuel it takes to equal the energy content of one liquid gallon of gasoline. GGE allows consumers to compare the energy content of competing fuels against a commonly known fuel—gasoline. GGE also compares gasoline to fuels sold as a gas (natural gas, propane, and hydrogen) and electricity.

GREENHOUSE GAS (GHG)—Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($NO_x$), halogenated fluorocarbons (HCFCs), ozone ($O_3$), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).

[50] DME Definition- U.S. DOE https://afdc.energy.gov/fuels/emerging_dme.html
[51] E85 Definition- U.S. DOE https://afdc.energy.gov/laws/6210
[52] U.C. Davis - International EV Policy Council (https://phev.ucdavis.edu/wp-content/uploads/Exploring-the-Role-of-Plug-In-Hybrid-Electric-Vehicles-in-Electrifying-Passenger-Transportation.pdf)

GREENHOUSE GASES, REGULATED EMISSIONS, AND ENERGY USE IN TRANSPORTATION (GREET®)—A full lifecycle model sponsored by the Argonne National Laboratory (U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy). GREET® fully evaluates energy and emission impacts of advanced and new transportation fuels, the fuel cycle from well to wheel, and the vehicle cycle through material recovery and vehicle disposal. It allows researchers and analysts to evaluate various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis.

HYBRID ELECTRIC VEHICLE (HEV)—A vehicle that combines an internal combustion engine with a battery and electric motor. This combination offers the range and refueling capabilities of a conventional vehicle, while providing improved fuel economy and lower emissions.

INTERNAL COMBUSTION ENGINE (ICE)—The ignition and combustion of the fuel occurs within the engine itself. The engine then partially converts the energy from the combustion to work.

KILOWATT (kW)—One thousand watts. A unit of measure of the amount of electricity needed to operate given equipment. On a hot summer afternoon, a typical home—with central air conditioning and other equipment in use—might have a demand of 4 kW each hour.

KILOWATT-HOUR (kWh)—The most commonly used unit of measure telling the amount of electricity consumed over time, means one kilowatt of electricity supplied for one hour. In 1989, a typical California household consumed 534 kWh in an average month.

LIQUEFIED NATURAL GAS (LNG)—Natural gas that has been condensed to a liquid, typically by cryogenically cooling the gas to minus 260 degrees Fahrenheit (below zero).

LIQUEFIED PETROLEUM GAS (LPG)—A group of hydrocarbon gases, primarily propane, normal butane, and isobutane, derived from crude oil refining or natural gas processing. These gases may be marketed individually or mixed. They can be liquefied through pressurization (without requiring cryogenic refrigeration) for convenience of transportation or storage. Excludes ethane and olefins.[53]

MILES PER GALLON (MPG)**—**A measure of vehicle fuel efficiency. Miles per gallon or MPG represents "Fleet Miles per Gallon." For each subgroup or "table cell," MPG is computed as the ratio of the total number of miles traveled by all vehicles in the subgroup to the total number of gallons consumed. MPGs are assigned to each vehicle using the EPA certification files and adjusted for on-road driving.

MILES PER GALLON GASOLINE EQUIVALENT (MPGe)—A measure of the average distance traveled per unit of energy consumed. MPGe is used by the United States Environmental Protection Agency (U.S. EPA) to compare energy consumption of alternative fuel vehicles, plug-in electric vehicles and other advanced technology vehicles with the energy consumption of conventional internal combustion vehicles rated in miles per US gallon.

MODEL YEAR (MY)—The term model year means a manufacturer's annual production period (as determined by the Federal Trade Commission) for motor vehicles or a class of motor

---

[53] Liquefied Petroleum Gas- U.S. Energy Information Administration https://www.eia.gov/tools/glossary/index.php?id=Liquefied%20petroleum%20gases%20%28LPG%29

vehicles. If a manufacturer has no annual production period, the term "model year" means the "calendar year."

NATIONAL PETROLUEM COUNCIL (NPC)—The purpose of the NPC is to advise, inform, and make recommendations to the Secretary of Energy with respect to any matter relating to oil and natural gas or to the oil and gas industries submitted to it or approved by the Secretary.[54]

NATIONAL RENEWABLE ENERGY LABORATORY (NREL)—The United States' primary laboratory for renewable energy and energy efficiency research and development. NREL is the only Federal laboratory dedicated to the research, development, commercialization, and deployment of renewable energy and energy efficiency technologies. Located in Golden, Colorado.

NATIONAL RESEARCH COUNCIL (NRC)—The National Research Council is the operating arm of the National Academies of Sciences, Engineering, and Medicine and is overseen by a governing board that consists councilors from each of the three Academies.[55]

PLUG-IN ELECTRIC VEHICLE (PEV)—A general term for any car that runs at least partially on battery power and is recharged from the electricity grid. There are two different types of PEVs to choose from—pure battery electric and plug-in hybrid vehicles.

PLUG-IN HYBRID ELECTRIC VEHICLE (PHEV)—PHEVs are powered by an internal combustion engine and an electric motor that uses energy stored in a battery. The vehicle can be plugged in to an electric power source to charge the battery. Some can travel nearly 100 miles on electricity alone, and all can operate solely on gasoline (similar to a conventional hybrid).

SOCIETY OF AUTOMOTIVE ENGINEERS (SAE)—A global association of more than 128,000 engineers and related technical experts in the aerospace, automotive, and commercial-vehicle industries. The leader in connecting and educating mobility professionals to enable safe, clean, and accessible mobility solutions.[56]

UNITED STATES DEPARTMENT OF ENERGY (U.S. DOE)—The federal department established by the Department of Energy Organization Act to consolidate the major federal energy functions into one cabinet-level department that would formulate a comprehensive, balanced national energy policy. DOE's main headquarters are in Washington, D.C.

UNITED STATES ENERGY INFORMATION ADMINISTRATION (U.S. EIA)—An independent agency within the U.S. Department of Energy that develops surveys, collects energy data, and does analytical and modeling analyses of energy issues. The Agency must satisfy the requests of Congress, other elements within the Department of Energy, Federal Energy Regulatory Commission, the Executive Branch, its own independent needs, and assist the general public, or other interest groups, without taking a policy position.

---

[54] NPC About Us https://www.npc.org/

[55] The National Academies of Sciences, Engineering, and Medicine About Page https://www.nationalacademies.org/about

[56] Society of Automotive Engineers (https://www.sae.org/about/)

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (U.S. EPA)—A federal agency created in 1970 to permit coordinated governmental action for protection of the environment by systematic abatement and control of pollution through integration or research, monitoring, standards setting, and enforcement activities.

ZERO EMISSION VEHICLE (ZEV)—Vehicles that produce no emissions from the on-board source of power (e.g., an electric vehicle).