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Co-Optimization of Fuels & Engines

History of Significant Vehicle and Fuel Introductions in the United States

John Thomas
Brian West
Teresa Alleman
Margo Melendez
Matthew Shirk

September 2017

OAK RIDGE NATIONAL LABORATORY
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About the Co-Optimization of Fuels & Engines Project

This is one of a series of reports produced as a result of the Co-Optimization of Fuels & Engines (Co-Optima) project, a Department of Energy (DOE)-sponsored multi-agency project initiated to accelerate the introduction of affordable, scalable, and sustainable biofuels and high-efficiency, low-emission vehicle engines. The simultaneous fuels and vehicles research and development is designed to deliver maximum energy savings, emissions reduction, and on-road performance.

Co-Optima brings together two DOE Office of Energy Efficiency & Renewable Energy (EERE) research offices, nine national laboratories, and numerous industry and academic partners to make improvements to the types of fuels and engines found in most vehicles currently on the road, as well as to develop revolutionary engine technologies for a longer-term, higher-impact series of solutions. This first-of-its-kind project will provide industry with the scientific underpinnings required to move new biofuels and advanced engine systems to market faster while identifying and addressing barriers to commercialization.

In addition to the EERE Vehicle Technologies and Bioenergy Technologies Offices, the Co-Optima project team included representatives from the National Renewable Energy Laboratory and Argonne, Idaho, Lawrence Berkeley, Lawrence Livermore, Los Alamos, Oak Ridge, Pacific Northwest, and Sandia National Laboratories. More detail on the project, as well as the full series of reports, can be found at www.energy.gov/fuel-engine-co-optimization.

Availability

This report is available electronically at no cost from http://www.osti.gov/bridge.

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Note

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Abbreviations and Acronyms

AC	alternating current
ACI	advanced compression ignition
AFDC	Alternative Fuels Data Center
AKI	antiknock index
CAFE	corporate average fuel economy
CARB	California Air Resources Board
CNG	compressed natural gas
CR	compression ratio
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
EV	electric vehicle
FE	fuel economy
FFV	flexible fuel vehicle
GCI	gasoline compression ignition
GDI	gasoline direct injection
GHG	greenhouse gas
GM	General Motors Company
HC	hydrocarbon
HEV	hybrid electric vehicle
LD	light-duty
LNG	liquefied natural gas
LPG	liquefied petroleum gas
MPGe	miles per gallon equivalent (for electric power only driving)
MTBE	methyl tertiary-butyl ether
MY	model year
NG	natural gas
NGV	natural gas vehicle
NO_X	nitrogen oxide
OEM	original equipment manufacturer
PEV	plug-in electric vehicle
PHEV	plug-in hybrid vehicle
PNGV	Partnership for a New Generation of Vehicles
PZEV	partial zero emissions vehicle
RCCI	reactivity-controlled compression ignition
RFS	renewable fuel standard
SI	spark ignition
TEL	tetraethyl lead
ULSD	ultra-low-sulfur diesel fuel
ZEV	zero emissions vehicle

Executive Summary

Purpose

The U.S. Department of Energy's (DOE's) Co-Optimization of Fuels & Engines (Co-Optima) initiative is conducting the early-stage research and development needed to accelerate the market introduction of new advanced fuel and engine technologies. Deployment of new fuels in tandem with new engines can be quite complex, depending on interrelated factors (beyond fuel properties) such as international politics and trade relations, consumer confidence, government policy and regulation, environmental impacts, and compatibility with legacy fuels, vehicles, and infrastructure. This report provides a historical look at the introduction of new fuels and vehicles over the past several decades in the United States to inform research considerations as the initiative advances.

The Co-Optima initiative's major goals include significant improvements in vehicle fuel economy (FE), lower-cost pathways to reduce emissions, and leveraging diverse U.S. fuel resources. The research includes both spark-ignition (SI) and compression-ignition (CI) combustion approaches, targeting applications that impact the entire on-road fleet (light-, medium-, and heavy-duty vehicles). It is hoped that the introduction of new fuels and new vehicle technologies developed as a result of the Co-Optima initiative will benefit from this examination of previous deployment strategies.

The light-duty (LD) projects are focused on identifying the fuel properties that maximize efficiency and performance of advanced SI engines to support the growing use of turbocharging and direct fuel injection. As engines are downsized and downsped for improved efficiency, knock mitigation becomes more critical for maintaining efficiency improvements; thus, understanding the effect of fuel properties such as octane number, octane sensitivity, and heat of vaporization are critical. Co-Optima's heavy duty projects are focused on the simultaneous development of advanced compression ignition (ACI) engines and fuels. For both SI and ACI, the implications of introducing new fuels in tandem with new engines depend on the compatibility of the new fuel with existing vehicles and infrastructure or the compatibility of the new vehicles with legacy fuels such as ultra-low-sulfur diesel fuel and regular gasoline containing 10% ethanol (E10).

The authors drew on prior studies, research experience, and reviews of previously published literature to examine the successes and challenges faced in major introductions of new vehicle fuels and engine/powertrain changes in the United States. The findings provide insight for future program decision-making, particularly for understanding the likely barriers and paths to success for new commercial fuels and engines.

Highlights

Although government incentives, laws, mandates, and regulations have historically been very important—and in some cases absolutely essential—to the success of new fuel and vehicle introductions, this Co-Optima study confirms that these measures have proven most successful in stimulating the rollout of new products when working in concert with market forces.

Unleaded Gasoline

One of the most extensive and complex shifts in the U.S. transportation market was the transition from leaded to unleaded gasoline in the 1970s. This changeover required significant investments by the vehicle and fuel producers, as well as fuel retailers. The introduction of unleaded fuel was mandated in mid-1974 in tandem with the introduction of model year (MY) 1975 vehicles that were equipped with exhaust catalytic converters and were required to use this new fuel exclusively. Most fuel retailers were required to immediately offer unleaded gasoline which required new investment. This change was driven by new Environmental Protection Agency (EPA) regulations to lower smog-related exhaust emissions, but was also influenced by widespread concerns over the health effects of lead. This transition was accompanied by a twenty year period of staged EPA-mandated tetraethyl lead additive reductions in fuel for use in vehicles produced prior to 1975. Both the introduction of unleaded gasoline and the lowering of additive in leaded gasoline required fuel industry refinery investment and changes in practice.

Ethanol and Methyl Tertiary-Butyl Ether

Also in the 1970s, gasoline price surges and supply shocks led to the introduction of gasohol (10% ethanol gasoline), mainly in the agricultural ethanol-producing regions. Assisted by various tax breaks, gasohol was a regionally available fuel that persisted even when fuel prices dropped. It was also important that ethanol addition increased octane number, a benefit which has furthered the role of ethanol use in SI fuels.

Another historically important fuel additive introduction began in 1979, with EPA granting a waiver[1] for gasoline containing up to 7 volume % methyl tertiary-butyl ether (MTBE). The additive's low cost and octane number enhancing properties, as well as mandates to use oxygenates to lower vehicle emissions in selected U.S. regions, led to expanded use of MTBE from 1990-2005. Eventually, leaks of MTBE-containing gasoline proved to be environmentally problematic. Due to state government involvement, supplier concerns, and court decisions, ethanol completely displaced MTBE by 2006.

Ethanol use increased substantially following the phasing out of MTBE and the introduction and expansion of renewable fuel mandates in the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007. These laws quickly led virtually all U.S. gasoline grades to be offered as 10% ethanol blends. The acts also influenced the EPA in 2010 to grant a partial waiver for 15% ethanol (E15) in gasoline to be a legal fuel for 2001 and newer light-duty vehicles. The 2010 legalization of E15 for late model vehicles has resulted in many light-duty original equipment manufacturers (OEMs) stating in the owners' manuals that they permit E15 use in new vehicles. As of July 2017, over 900 stations in the U.S. were offering E15.

Diesel Sulfur Levels

The level of sulfur in diesel fuel was uncontrolled up until 1993, and levels as high as 5000 ppm were not uncommon. EPA set a 500-ppm limit to help heavy-duty engines meet the 1994 emissions standards; this became known as low-sulfur diesel fuel. Further reductions were deemed necessary to meet even more stringent pending regulations requiring sophisticated

[1] EPA has the authority to grant waivers from the requirement that fuel be substantially similar to gasoline under CFR 40 part 79

exhaust aftertreatment systems. In 2000, EPA and the California Air Resources Board ruled that 15 ppm sulfur diesel fuel, or ultra-low-sulfur diesel fuel (ULSD), be available starting in 2006. All on-road diesel fuel met this requirement by 2010. Lowering sulfur levels enhances the operations of virtually all diesel emission systems and lowers PM mass levels due to less SO_3 in the emitted particulate.

Biodiesel

The Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 also led to increased use of biodiesel, generally in the form of 5% or 20% biodiesel in petroleum-based diesel fuel. Diesel vehicle manufacturers now allow the use of 5% biodiesel, and some have approved blends up to 20% biodiesel provided the fuel meets proper standards. Federal law prevents vehicle warranties from being invalidated due to biodiesel use unless the fuel is proven to be the cause of the failure in question.

Flexible Fuel Vehicles and Flex Fuel

Under the Alternative Motor Fuels Act of 1988, vehicle manufacturers were offered incentives in the form of credits to build Flexible Fuel Vehicles (FFVs) to help meet federal fuel economy regulations. This led to the introduction of ethanol flex fuel (also referred to as E85) and FFVs that could run on flex fuel, gasoline, or any mixture of these fuels. Although millions of FFVs have been sold, flex fuel use has been comparatively very low. Government FFV incentives have induced manufacturers to produce the vehicles, but limited incentives and unfavorable pricing has minimized industry and consumer interest in flex fuel.

Other Liquid Fuels

A number of other potential fuel blendstocks have been considered during the past several decades, with methanol being one of the most actively studied candidates. However, efforts to introduce these fuel components have stalled due to lack of sufficient incentives or applicable mandates, compatibility concerns, or insufficient backing by interested parties and government.

Gaseous Fuels

Gaseous fuels, particularly natural gas (NG) and to a lesser extent propane, have historically been less expensive than petroleum fuels. However, these price advantages have been offset by higher vehicle costs, greater volume requirements for on-board fuel storage, time consuming or difficult fueling, and lack of infrastructure. NG use in heavy-duty trucks increased in the early years of this decade due to its affordability in comparison to diesel, and new fueling stations were built along several U.S. corridors. A small light-duty NG and propane market also exists, with use generally restricted to fleet vehicles, often supported by government incentives.

Diesel Vehicles

Light-duty diesel vehicle sales in the U.S. have hovered near 1% of the market for decades, primarily due to cost considerations. Diesel powertrain and emission systems have a cost premium and diesel fuel has often been more expensive than gasoline on a volume basis. Efficiency penalties associated with emission control systems for diesel vehicles, together with gasoline powertrain improvements, have eroded the efficiency advantage previously held by diesel powertrains.

Electrified Powertrain Vehicles

Electrified vehicles (including hybrids, plug-in hybrids, and all-electric vehicles) have enjoyed growing sales over the past decade and comprise a generally increasing percentage of the light-duty fleet due to a number of fuel economy and emissions regulations, as well as often-sizable government incentives for the consumer. The electrified powertrain sector is predicted by many to grow significantly beyond the current 3% market share in the U.S. due largely to stringent fuel economy regulations but also anticipated battery and electric drivetrain cost reductions, performance advantages, and charging infrastructure investments.

Key Conclusions

On-road transportation is a heavily regulated sector of the economy. Government legislation and regulations have played a very large part in virtually all major fuel and vehicle introductions. Introducing a new fuel can require significant changes to delivery infrastructure, fuel production, and vehicle technology, all of which require investments and business changes.

This is best exemplified by the introduction of unleaded gasoline in 1974 and of ultra-low sulfur diesel fuel in 2006. Both of these new fuel rollouts were driven by mandates to greatly reduce exhaust emissions and met by changing engine technology and the addition of catalytic exhaust emission controls.

These successful introductions reveal the complexity and enormous scope of factors that must be considered prior to the deployment of new fuels or engine technologies, including the significant investments that producers/manufacturers, distributors, and retailers will be required to make. Further consideration must be given to the consumers, who both receive benefits and bear costs of the changes.

Close collaboration between research, government, and industry stakeholders has enabled successful transitions in the past, and some less successful attempts may have not considered all aspects of the transportation industry sectors. The Department of Energy and its national laboratories can play key roles in convening stakeholders to help ensure that effective pathways are identified. Objective data and analyses from the national laboratories have been cited by regulators in the past, and can help identify and compare options on a comprehensive and consistent basis to allow stakeholders to make the most informed decisions about future fuel and engine solutions.

1 Introduction

1.1 Purpose

The U.S. Department of Energy's (DOE's) Co-Optimization of Fuels & Engines (Co-Optima) initiative is conducting the early-stage research needed to accelerate the market introduction of advanced fuel and engine technologies. The research includes both spark-ignition (SI) and compression-ignition (CI) combustion approaches, targeting applications that impact the entire on-road fleet (light-, medium-, and heavy-duty vehicles). The initiative's major goals include significant improvements in vehicle fuel economy, lower-cost pathways to reduce emissions, and leveraging diverse U.S. fuel resources.

The light-duty projects are focused on identifying the fuel properties that maximize efficiency and performance of advanced SI engines to support the growing use of turbocharging and direct fuel injection. As engines are downsized and downsped for improved efficiency, knock mitigation becomes more critical for maintaining efficiency improvements; thus, understanding the effect of fuel properties such as octane number, octane sensitivity, and heat of vaporization are critical. Co-Optima's heavy duty projects are focused on the simultaneous development of advanced compression ignition (ACI) engines and fuels. For both SI and ACI, the implications of introducing new fuels in tandem with new engines can be quite complex, depending on the compatibility of the new fuel with existing vehicles and infrastructure or the compatibility of the new vehicles with legacy fuels such as ultra-low-sulfur diesel fuel and regular gasoline containing 10% ethanol (E10). This report provides a historical look at the introduction of new fuels and vehicles in the United States over the past several decades to help inform the program's research agenda going forward.

1.2 Background

Vehicle manufacturers along with component developers, suppliers and research institutions are pursuing a wide range of technologies to increase fuel economy and reduce emissions. This pursuit includes engine technologies such as downsped and downsized turbocharged engines, which could benefit from improved antiknock properties of fuel (Jung et al., 2013; Splitter and Szybist, 2014; Leone et al., 2014; Theiss et al., 2016) and novel advanced combustion approaches such as reactivity-controlled compression ignition (RCCI), gasoline compression ignition (GCI), homogeneous-charge compression ignition (HCCI), and several other low temperature combustion approaches (examples include: Chadwell et al., 2011; Ciatti et al., 2013; Dec et al., 2004; Dempsey et al., 2015; Dempsey et al., 2016; Manente et al., 2009; Musculus et al., 2013; Najt and Foster, 1983; Ryan and Callahan, 1996; Suresh et al., 2013; Szybist et al., 2013; Wagner et al., 2003).

Many niche fuels/vehicles have made and continue to make small contributions to fuel diversification in the United States; some have generated significant interest only to decline over time, and others have been introduced and have become pervasive in the marketplace. The available U.S. fuel choices and formulations and other changes in fuels have been driven by market/demand forces and technological advances but were often significantly influenced by regulations. Societal needs, political considerations, and competing interests have also influenced the timing and content of fuel-related regulations. Two recent examples include the Energy Independence and Security Act of 2007 (EISA, 2007), which mandated significant increases in the nation's use of renewable fuels, and the 2012 Fuel Economy rule (FedReg, 2012) which requires significant decreases in CO_2 emissions from vehicles concurrent with dramatic increases in fuel economy. A companion report (Alleman et al., 2017) provides more extensive detail on the historical regulatory landscape with respect to new fuels and new vehicle technologies.

1.3 Approach

Subject matter experts from three National Laboratories utilized prior studies and personal knowledge to examine the important introductions of new road transportation fuels and fuel-related vehicle engine/powertrain changes in the United States. Over 100 references were reviewed. The lessons learned and insights from these past activities will help guide Co-Optima's research program and decision-making, in particular by identifying the likely barriers, technology options to mitigate these barriers, and paths to success for new commercial fuel and engine introductions.

1.4 Overview of Content

This report outlines some of the significant fuel/vehicle introductions that have occurred in the United States during the past several decades. Section 2 describes the more significant fuel changes that have occurred over long time periods, such as the rise and decline of the anti-knock additive tetraethyl lead, the addition of ethanol to the gasoline pool, the introduction of ultra-low sulfur diesel fuel, and the growing use of biodiesel blends. Section 3 describes some of the fuels that have shown promise but achieved limited long term success. Section 4 outlines the recent growth in electrified vehicle technologies, such as hybrids, plug-in hybrids and plug-in electric vehicles. The U.S. experience with niche market vehicle/fuel technologies such as natural gas and propane are described in Section 5. Section 6 provides a brief conclusion, and references may be found in Section 7 and Appendix A.

2 Significant Long-Term Fuel Changes

2.1 Leaded Gasoline

The terms “leaded gasoline” and “unleaded gasoline” stem from about 1923, when the lead-containing compound tetraethyl lead (TEL) was introduced as an octane-boosting antiknock additive. TEL was cheap and effective at boosting fuel octane levels, and within a decade virtually all gasoline sold in the United States contained TEL. In 1973, the U.S. Environmental Protection Agency (EPA) set exhaust emissions regulations that required vehicle exhaust catalysts, and because of catalyst poisoning and lead toxicity concerns, the use of TEL was regulated. Gasoline grades without lead additives, known as unleaded gasoline, were mandated to be widely available for fueling new vehicles starting with MY 1975, with older vehicles permitted to continue using leaded fuel. Regulations simultaneously mandated a lowering of the quantity of lead additive permitted in leaded fuels, and eventually the complete elimination of leaded gasoline (Splitter et al, 2016; Alleman et al., 2017).

2.1.1 *Rise and Decline of Leaded Gasoline*

Gasoline with TEL was introduced in 1923 by the newly formed Ethyl Corporation, a joint venture of General Motors Company (GM), E. I. du Pont de Nemours and Company, and Standard Oil Company of New Jersey (now ExxonMobil Corporation) (Kovarik, 2005). Because of lead’s well-known neurotoxicity in humans, the additive was always somewhat controversial. TEL use varied, but as shown in Figure 2-1 (Splitter et al., 2016; Gibbs, 1990), it was used in concentrations averaging above 1.5 grams of lead per gallon from about 1950 to 1980 (Newell and Rogers, 2003a).

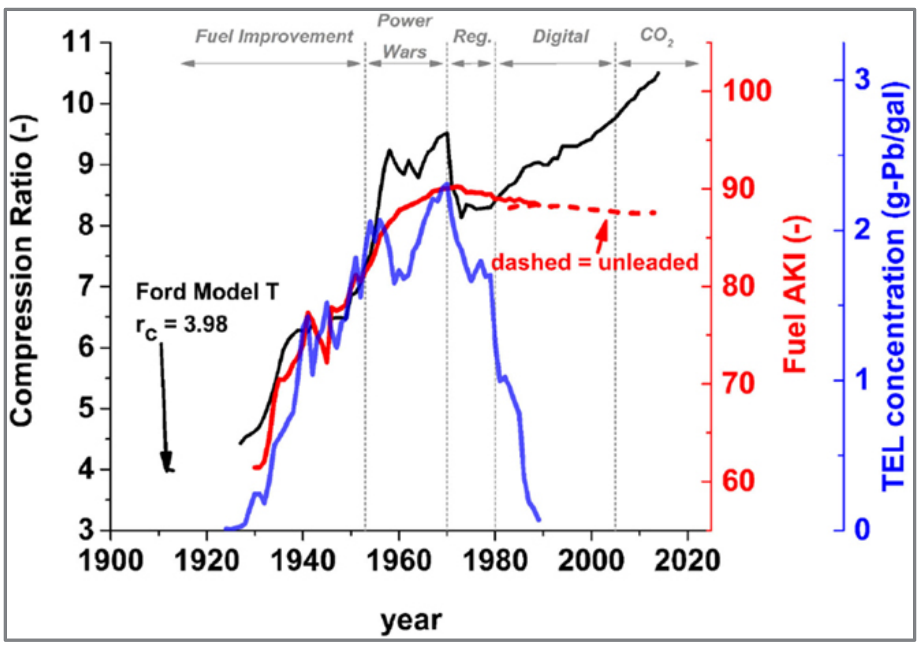

Figure 2-1. Historical change in composite averages for engine compression ratio, gasoline antiknock index, and TEL concentration in gasoline. *(Splitter et al., 2016; Gibbs, 1990) AKI = antiknock index; TEL = tetraethyl lead;* r_c *= compression ratio*

TEL was inexpensive to produce, highly effective at improving the anti-knock quality of gasoline, and popular with motorists. The marketing of TEL was very controversial to some experts and was fiercely opposed by many in the public health community (Kovarik, 2005; Splitter et al., 2016). Early production proved to be dangerous, with manufacturing worker deaths and devastating poisoning of other workers before process controls were improved (Kovarik, 2005). These events, which occurred at the first production facility, forced a temporary shutdown in 1924 and a subsequent grand jury investigation (that ended with no charges filed). Leaded fuel was banned for a time in New York City, Philadelphia and New Jersey. Controversy raged on, studies were done on lead emissions from engines, and arguments were made on the viability of alternative anti-knock fuel additives. Ultimately, TEL was put into widespread use. Interestingly, the product was marketed as "Ethyl gasoline", a term close to ethyl alcohol (ethanol, a competing additive) and without lead in the product name.

Before and during the eventual lead phase-out, the toxicity of lead was very much in the public forum. An EPA press release in 1973 stated "… a significant portion of the urban population, particularly children, are over-exposed to lead through a combination of sources including food, water, air, leaded paint, and dust. Although leaded paint is a primary source of exposure for poisoning in children, leaded gasoline is also a significant source of exposure which can be readily controlled" (EPA, 1973). Then in 1985 another press release stated, "Adverse health effects from elevated levels of lead in blood range from behavior disorders and anemia to mental retardation and permanent nerve damage" (EPA, 1985).

It is not widely recognized that despite the well-documented severe health impacts of lead exposure, the decision to ban lead in gasoline stemmed from air quality rather than health concerns. When EPA was formed in 1970 (from many existing U.S. federal entities), it was given broad power to both regulate and enforce regulations to carry out environmental policy (EPA, 1992). Vehicle exhaust emissions were causing significant air quality problems in various regions, and EPA was considering regulations that would require use of exhaust catalytic converters capable of significantly reducing vehicle emissions. However, these catalytic converters were poisoned and thus rendered ineffective by the lead contained in exhaust from cars burning leaded gas. The solution to enabling cleaner vehicle exhaust was thus "to get the lead out." TEL remained at relatively high levels in gasoline until EPA issued regulations to reduce lead significantly, beginning in 1975 (EPA, 1973). In concert, EPA required the widespread availability of unleaded gasoline by July of 1974. Any station selling more than 200,000 gallons per year (about 111,000 stations) was required to offer unleaded gasoline. The existing fleet would still be fueled by gasoline; however, with lowered lead content. This requirement to develop and market unleaded gasoline was a major step toward the eventual elimination of lead in road-transportation fuel (EPA, 1973; Newell and Rogers, 2003b).

It is instructive to consider the time required to completely remove TEL from on-road gasoline (it is still used in aviation gasoline). Following the initial regulations in 1974, lead continued to decline overall as unleaded fuel was being used in all new vehicles (Gibbs, 1996). In 1985, EPA mandated a steep drop in the lead content of leaded gasoline, requiring reductions from 1.1 grams per leaded gallon to 0.5 grams per leaded gallon by July 1985, and then to 0.1 g/gal starting January 1, 1986 (EPA, 1985). The final phase-out of TEL did not occur until January 1, 1996 (EPA, 1996a), more than 20 years after the initial regulations (California instituted a more accelerated phase out, which lasted from 1977 to 1992).

One of the reasons for the long timeframe is that the phase-out of lead was designed to occur in many steps. The phase-out included provisions for small refiners and/or those that would have more trouble producing quality fuel quickly with less or no lead additive. It was also designed to give all refiners time to make investments and process changes (EPA, 1985). The process included lead credit trading and banking system to promote a more orderly and economically efficient transition (Newell and Rogers, 2003a). The phase-out also allowed for the orderly retirement of legacy vehicles that needed leaded fuel for protection of valve seats (EPA, 1996b). Interestingly, by 1985 it was apparent that consumer non-cooperation was slowing the pace of lead elimination: an estimated 16% of unleaded vehicles were being fueled with leaded gasoline, despite the deleterious effects on the vehicle emissions control systems (EPA, 1985). This likely accelerated the lowering allowed lead-levels in leaded gasoline. The topic of misfueling is an important one when considering the introduction of a new fuel, and a detailed discussion of misfueling mitigation has been provided by Co-Optima researchers. (Sluder et al., 2017).

2.1.2 Antiknock Index, Compression Ratio, and Continuous Engine Improvement

The antiknock quality of gasoline is one of the most important fuel quality properties, and in the U.S. this property has historically been defined in terms of the antiknock index (AKI).[1] A recent review of the coevolution of gasoline AKI and SI engines (Splitter et al., 2016) documents the close coupling between fuel AKI, fuel lead content, and engine compression ratio (CR) from about 1930 to 1973. This coupling is depicted in Figure 2-1. Much of the increase in AKI from 1923 to the mid-1950s was due to increased levels of tetraethyl lead. Gasoline refinery yield and AKI were also improved as a result of the many developments in refinery cracking and reforming from the mid-1920s to the mid-1950s (Gibbs, 1993). CR in engines also rose continuously during this period, allowing significant improvements in engine power and efficiency. Engines were mechanically controlled, open-loop devices, and emissions were unregulated during this time period.

SI engines continued to evolve as a result of advances in engine robustness, metallurgy, cooling, and lubrication. Although engine CR was increased in large part because of the improved AKI of gasoline, engine improvements also brought about part of the CR increase. Continuous engine improvement in areas such as combustion chamber shape, spark plug position, use of turbulence to increase flame speed, and spark timing control also helped to increase the CR, efficiency, and power density of engines (Amann, 1990).

After 1973, the relationship between AKI and CR changed abruptly due to regulations. The effect of EPA exhaust emissions regulations resulted in an immediate sharp drop in CR starting in 1973 (Splitter et al., 2016) as shown in Figure 2-1. Emissions regulations required increasing air–fuel ratio to limit rich combustion and compliance with CO and hydrocarbon (HC) emissions limits. The drop in CR for new cars was not due to using the newly introduced and required unleaded fuel (1975 and beyond). Rather, CR was lowered to reduce in-cylinder peak temperatures and therefore reduce nitrogen oxide (NO_X) production (Splitter et al., 2016). It is

[1] Octane numbers are measured by two engine tests, ASTM D2699, "Standard Test Method for Research Octane Number of Spark-Ignition Engine Fuel," which measures what is known as the "Research Octane Number" or RON, and ASTM D2700, "Standard Test Method for Motor Octane Number of Spark-Ignition Engine Fuel," which measures the "Motor Octane Number" or MON. The antiknock index (AKI) number = (RON + MON)/2. The higher the AKI, the lower the probability of engine knock.

unclear whether there was some drop in AKI as the new unleaded fuels were introduced, but with the necessary steep drop in CR for emissions reasons, slightly lower AKI would not be a detriment at that time. New ways of coping with the unleaded fuels and emissions regulations would soon be developed.

2.2 Unleaded Gasoline and Gasoline Powertrains

The use of unleaded gasoline grew from its EPA-mandated introduction in 1975 until it dominated the market by 1990 (Newell and Rogers, 2003a). All road-vehicle gasoline has been lead-free since the end of 1995. The transition to unleaded fuel allowed for vehicles to use exhaust catalysts starting in 1975 and eventually to use the current generation of long-life three-way catalysts (by requiring gasoline to also have low sulfur content). The introduction of gasohol and the rise of E10 during this time are examined in a later section.

2.2.1 Compression Ratio and Other Engine Improvements

More recent (1980–2014) trends in average fuel AKI and average engine CR are also shown in Figure 2-1 and are quite different from the previous era, when leaded fuel dominated. With engine technology, design, and controls advancing, geometric CR continuously increased from 1980 until the present, despite average gasoline AKI dropping slowly and exhaust emission regulations tightening considerably. A great many technologies contributed to this CR increase, including low-deposit-forming fuels; electronic spark timing; precise control of EGR; 3-, 4-, and 5-valve per cylinder designs; variable valve timing and lift; sequential port fuel injection; direct fuel injection; cylinder, piston, and combustion volume design; and other combustion control techniques. High-speed computer technology and sensors have allowed great progress in precision control of the SI engine, which has contributed to knock avoidance. Overall, engine power density and thermal efficiency continuously improved since 1980, in part due to the increased CR.

Engine design advancements led to continual increases in CR and other combustion related improvements despite average fuel AKI slightly decreasing from 1980 to the present. The reduction in deposits due to fuel formulations and additives assisted this CR trend (Figure 2-1, starting in 1980) because deposits increase the propensity for preignition via surface ignition (Gibbs, 1990). Gasoline may have improved in regard to additives and deposit formation, but in regard to other combustion qualities (such as measured AKI) it was stagnant over this period. The unleaded fuel trend of slightly lower AKI over time has prevented an even steeper increase in CR from 1980 to today, and modern SI engine CR (and thus efficiency) is still limited by fuel antiknock properties provided by current market fuels.

2.2.2 Changes Driven by Regulatory Action

Many of the important changes to gasoline powertrains from 1975 through 2005 have been driven or influenced by regulations concerning emissions and, to a lesser extent, FE standards. However, consumer preferences and demands also played a role. This is certainly true of the large general increase in power to weight ratio that occurred during this period, as well as increases in FE (EPA, 2015a). This was a period of gasoline price spikes and general disruptions in the world oil market. It was not fuel properties driving improvements in powertrain efficiency, but rather fuel insecurity, significant price spikes, and regulations combined with technology advancement.

More recently, regulations to lower sulfur levels in gasoline were implemented to allow the use of long-life three-way exhaust catalysts that could help vehicles meet increasingly strict emissions standards. The annual corporate average sulfur levels were required to reach 120 ppm in 2004, 90 ppm in 2005, and 30 ppm in 2006 (EPA, 1999). The next phase of emissions regulations (Tier 3) requires further decreases in gasoline sulfur, reaching 10 ppm by 2017. The lower sulfur levels will allow better control with the three-way catalyst system for CO, HC, and NO_X emissions. Lower sulfur will also reduce fine particulate matter (PM) emissions by decreasing sulfate emissions, an important component of PM. Unfortunately, the refining technology most effective at reducing sulfur levels in gasoline – hydrotreating – also reduces both unit yields and the AKI of the gasoline blendstocks, leading to an increase in operating and thus fuel costs. Meeting regulations has spurred the development of new and innovative refining technologies.

Since 2005, FE and CO_2 emissions regulations have been driving light-duty FE improvements. The growing number of transmissions with more gears, continuously variable transmissions, improved engine efficiency, and a focus on vehicle drag reduction has brought about significant improvements in FE (EPA, 2015a; Thomas, 2016). Gasoline direct injection (GDI) technology has become widespread as a method to improve engine fuel efficiency, and some antiknock benefit is realized by GDI fueling. This fueling method has increased the demand for gasoline detergents because deposits exacerbate knock and may interfere with the quality of the fuel injection. Some vehicle manuals call for use of “Top Tier” gasoline, which is fuel specified to have a higher level of detergent additives (compared to the EPA regulatory minimum detergent levels) that help mitigate deposits (Top Tier, 2015).

2.2.3 Other Fuel Effects on Powertrains

The elimination of TEL also eliminated lead oxide deposits, which reduced spark plug fouling and generally lowered corrosive combustion products in the engine, lubricating oil, and exhaust system of vehicles (Armstrong et al., 2004). A negative effect of lead removal was on valve seating and sealing because the lead oxides formed a cushioning/lubricating deposit on the valves and valve seat surfaces that reduced wear. Engines designed for unleaded fuel generally required harder, wear-resistant valve seats. This meant valve seat inserts for aluminum engine heads or hardening treatment at the valve seat surfaces for cast iron engine heads. Valve seat recession problems due to the absence of lead additive were more of a concern for engines operated at high load for extended periods of time (Armstrong et al., 2004; Hutcheson, 2000).

Fuel and oil quality improvements over time have resulted in fewer deposit- and corrosion-related problems with the engine systems. Spark plug change intervals have lengthened from every 6,000 miles or 6 months in the 1970s to every 100,000 miles or more—only one or two times in the life of some vehicles. With less corrosive compounds in the exhaust and the use of better materials, items such as exhaust systems and mufflers are now rarely replaced.

2.3 Addition of Oxygenates

Petroleum-based gasoline with no oxygenates was essentially the exclusive fuel from the beginning of the U.S. automotive market until the use of ethanol and other oxygen-containing additives began in the late 1970s (Bechtold, 1987; Bechtold et al., 2007). As early as the 1920s, ethanol was a known effective antiknock fuel component, but TEL and improved oil refining technologies were relied upon as cost effective means to improve antiknock qualities of fuel (Gibbs, 1990).

Interest in alternative fuels intensified in the 1970s as a result of Middle East oil supply disruptions and oil price instability, bringing U.S. energy security to the forefront of politics. Various alliances formed to champion ethanol as a fuel, and many state governments began promoting ethanol, particularly agricultural states that were, or could be, ethanol producers. Federal involvement was also a factor, providing research funding and offering other grants concerning use and production of alternative fuels. These developments spawned conflicts between petroleum fuel interests, which naturally were reluctant to lose petroleum market share to alternative fuels, and entities wanting to reduce petroleum use or provide nonpetroleum fuel components (Bechtold, 1987).

During this time, many types of fuel blends were considered, with constituents including isobutanol, tertiary butanol, isopropanol, methyl tertiary-butyl ether (MTBE), and proprietary chemicals, in addition to ethanol and methanol. Neat methanol and very high levels of ethanol and methanol in gasoline were also under consideration. Engine, vehicle, and fleet tests of such alternative fuels occurred from the late 1970s into the early 1990s (West et al., 1993; Nichols, 1987; Bromberg and Cheng, 2010). Many OEMs produced prototype alternative fuel vehicles and FFVs for testing (Bechtold, 1987), and DOE conducted a demonstration program with dedicated M85[1] vehicles at three national laboratories from 1986 through 1991 (West et al., 1993). Fuel methanol is discussed in more detail in Section 3.1.

2.3.1 Introduction of Gasohol

The term "gasohol" was used to describe the 1970s-era gasoline splash-blend with 10% ethanol (presumably 10% by volume) (Bechtold, 1987). The Nebraska and Iowa legislatures reduced taxes in 1972 and 1973 respectively for 10% ethanol blended with gasoline, which was marketed as gasohol. There is little evidence that this fuel was used in any significant quantities at this time, but it was marketed and used in small amounts by the late 1970s (Bechtold, 1987; Bechtold et al., 2007). Its use was initially limited mainly to certain states in the Corn Belt. In 1974 Nebraska initiated the first fleet testing of gasohol.

Under provisions of the 1977 Clean Air Act, EPA was given direct authority to approve new motor fuels. Because unleaded fuel was mandated to be available for new vehicles in late 1974, octane boosting alcohols and other additives were considered. On November 8, 1977, EPA declared gasohol to not be a legal commercial fuel because it had not been approved under the 1977 Clean Air Act (Bechtold, 1987). In June of 1978, Gas Plus Inc. applied for a waiver for gasohol, but the application contained no data directly applicable to 10% ethanol in gasoline. EPA did not approve the application, presumably due to lack of data, but also took no action to disapprove it. As a result of Clean Air Act provisions at the time, after 6 months it became a legal fuel by default, receiving a waiver from the requirement that it be substantially similar to gasoline (Bechtold, 1987; Bechtold et al., 2007). By 1980 about half of the U.S. states had given tax breaks to encourage gasohol fuel, the executive branch had set fuel alcohol production goals, and federal tax incentives were given for producing fuel alcohol and selling gasohol (Bechtold,

[1] Methanol fuel designations are similar to those for ethanol blends, with the "M" standing for "methanol" and the numeral for the volume percent of methanol mixed with a petroleum-based fuel.

1987). In 1982, EPA issued an interpretation of the waiver to include gasoline blends with 10% ethanol or less by volume. Fuel ethanol consumption has grown steadily since the 1980s, as shown in Figure 2-2. From Figure 2-2 it is inferred that gasohol grew to about 5% of the gasoline market by 1985 and to 10% by 1995.

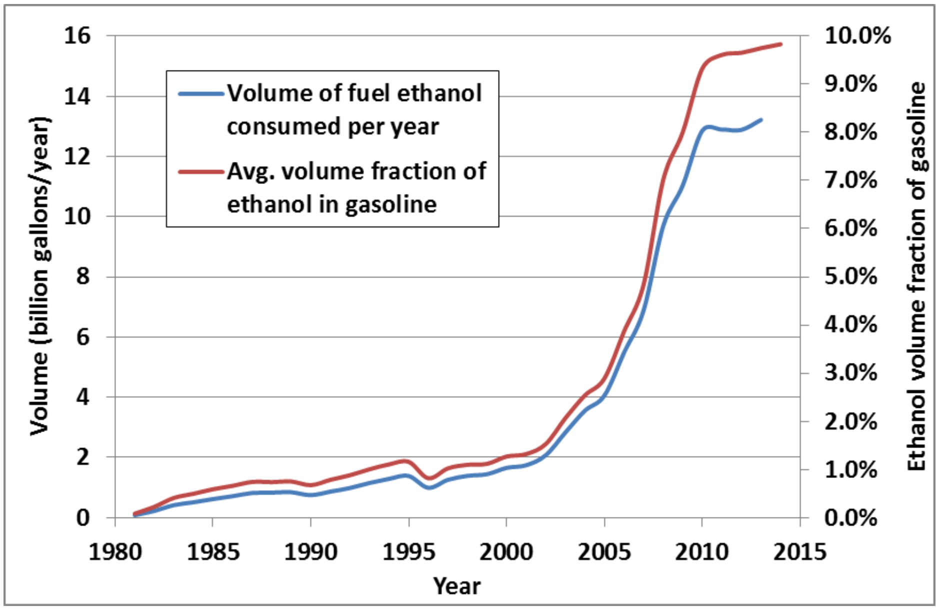

Figure 2-2. Ethanol fuel consumption, 1975–2015. *(EIA, 2016a)*

There was concern with gasohol being a “new solvent” and having different corrosion, swelling, and other effects on materials compared to the current gasoline grades. The automotive manufacturers had not designed vehicles specifically to use gasohol but quickly began to accommodate the new fuel for new car model introductions. The vehicle compatibility of gasohol and other fuels given EPA waivers was studied extensively. Problems cited due to the use of gasohol included clogged fuel filters (due to the solvent effect of the new fuel), possible long-term corrosion if no corrosion inhibitors were added to the fuel, and cold starting becoming more problematic (Mueller, 1988; API, 2001; Bechtold et al., 2007). There was apparently no rigorous study of in-service vehicle problems to quantify the adverse effects caused by the first several years of gasohol use.

2.3.2 Methyl Tertiary-Butyl Ether Use and Replacement with Ethanol

MTBE is an oxygenate additive that received much attention in the 1970s as a potential route to enhance unleaded gasoline octane. In 1979 ARCO (Atlantic Richfield Company) was granted an EPA waiver for blends of up to 7 volume % MTBE in unleaded gasoline. It was inexpensive to produce and distribute by the chemical and oil refining industry and was generally used as a low level additive (EPA, 2016). From 1992 to 2006 MTBE was used at higher concentrations (Alleman et al., 2017) in an effort to lower vehicle emissions in selected U.S. regions mandated to use oxygenates (EPA, 2016), a requirement of the 1990 Clean Air Act Amendments [see Alleman et al., 2017 for more details]. Peak use of MTBE in U.S. gasoline reached about 4 billion gallons per year from 1999 to 2002.

Over time, it became apparent that MTBE was a potential groundwater contaminant through leaks in underground gasoline storage tanks. Because MTBE has high solubility in water and is slow to biodegrade, it spreads much farther and faster through the water table and environment than other gasoline components (Sulfita and Mormile, 1993; Mormile, et al., 1994). It also has an unpleasant taste in drinking water at very low concentrations. Spurred in large part by liability concerns over leaks and groundwater contamination, gasoline providers phased out MTBE from about 2000 to 2006 and began using ethanol as a replacement, resulting in a trend of significant increases in ethanol use each year during that period (Figure 2-2).

Ethanol production in the United States grew moderately or was relatively constant from the early 1980s until about 2002. As more blenders looked to ethanol to supplant MTBE, ethanol production began to grow more rapidly, as shown in Figure 2-2. Federal legislation in 2005 and 2007 led to even more rapid growth in domestic production beyond 2006, as explained in the next section.

2.3.3 E10 and Mandates for Renewable Fuel

The Energy Policy Act of 2005 required use of 7.5 billion gallons of renewable fuel by 2012, and the Energy Independence and Security Act of 2007 established a requirement of 36 billion gallons per year by 2022, of which 16 billion gallons were required to be advanced biofuels (AFDC, 2014). This latter requirement specifically excludes corn starch–based ethanol (the current source of almost all fuel ethanol), but these standards provided a strong incentive for ethanol use to grow. These mandates essentially pushed the market to quickly spread E10 use so that virtually all gasoline sold throughout the United States contained 10% ethanol by 2010. A very steep climb in ethanol use occurred with a leveling off from 2010 at about 13 billion gallons per year, as seen in Figure 2-2. This ceiling is the result of the so-called "blend wall," which reflects the point where virtually all gasoline is 10% ethanol and no more ethanol can be accommodated without exceeding the 10% limit. Solutions to the blend wall include selling greater amounts of higher ethanol containing fuels such as E85. However, as described later (section 3.2), a relatively small percentage of vehicles can use this fuel, and E85 sales have not increased fast enough to allow overall ethanol levels to keep pace with the EISA requirements. Another route is to increase the allowed ethanol levels in gasoline used by the majority of the light duty fleet. In a step towards this, E15 was declared a legal fuel in 2010, and currently a small amount is being sold at over 900 stations (E15 is discussed in more detail in Section 3.3).

2.4 Ultra-Low-Sulfur Diesel Fuel

The level of sulfur in diesel fuel was uncontrolled up until 1993, and levels as high as 5000 ppm were not uncommon. EPA set a 500-ppm limit to help heavy-duty engines meet the 1994 emissions standards; this became known as low-sulfur diesel fuel (EPA, 2015b). Further reductions were deemed necessary to meet even more stringent pending regulations. The DOE, the Engine Manufacturers Association, and several other stakeholders executed a cooperative government/industry effort known as the Diesel Emissions Control Sulfur Effects (DECSE) Program in the late 1990s (Clark, et al., 2000). In 2000, EPA and the California Air Resources Board (CARB) cited data from this program in ruling that 15 ppm sulfur diesel fuel, or ultra-low-sulfur diesel fuel (ULSD), be available starting in 2006. All on-road diesel fuel met this requirement by 2010. Lowering sulfur levels enhances the operations of virtually all diesel emission systems and lowers PM mass levels due to less SO_3 in the emitted particulate. Although

ULSD was initially intended to support the use of lean NO_X traps, which are extremely sensitive to sulfur poisoning, all other catalysts used to control diesel emissions perform better with ULSD (EPA, 2000).

Removal of fuel sulfur led to some challenges and unintended consequences. In particular, severe hydrotreating of crude oil necessary to remove some of the more recalcitrant sulfur compounds lowered lubricity in diesel fuel, and lubricity additives were required to avoid fuel injector failure. Refineries had to adapt and develop new technologies to produce ULSD requiring significant research and capital investments.

2.5 Biodiesel

Biodiesel is produced by transesterification from a wide range of plant oils, animal fats, and recycled greases. This reaction converts the oils and fats into long-chain mono alkyl esters, for example fatty acid methyl esters when the alcohol used in production is methanol. In the United States, the process involves catalytic reaction with methanol, although other short chain alcohols may be used (AFDC, 2016a). To be a legal blendstock, pure biodiesel (B100) must meet the ASTM D6751-15ce1 specification; however, this specification does not ensure that B100 will be fit-for-purpose as a pure fuel. The specification is feedstock and process neutral.

Biodiesel is most often used blended with petroleum diesel fuel and only rarely is used in pure form (B100). Diesel fuel can benefit from biodiesel blending, particularly due to the high lubricity and cetane number of biodiesel. These properties can make biodiesel addition attractive.

Common commercially-available blends are 20%, 5%, and 2% biodiesel (B20, B5, B2). Biodiesel blends of 6% to 20% biodiesel mixed with ULSD must meet ASTM standard D7467-15ce1. Recently, ASTM International updated the specification for diesel fuel, D975, to allow up to 5% biodiesel blends. A special grade of biodiesel (No. 1-B) was recently added to D6751 to address applications that are sensitive to partially reacted glycerides, such as some low temperature applications (AFDC, 2016a).

Use of biodiesel in 2013 through 2015 reached about 2.6%–2.8% volume use compared to petroleum-based diesel (EIA, 2016b). A certain amount of biodiesel use is required as part of the Renewable Fuel Standard Program (Alleman et al., 2017).

2.5.1 Biodiesel and Vehicles

There are a variety of statements about biodiesel use from engine and/or vehicle manufacturers, which refer to the warranty. Engine and vehicle manufacturers provide warranties covering materials and workmanship on their products but do not necessarily cover damage caused by external conditions. Fuels are not covered under these terms. Federal law prohibits the voiding of a warranty just because biodiesel was used. The biodiesel would need to be shown to be the cause of the failure. If an engine experiences a failure caused by biodiesel use (or any other external condition, such as bad diesel fuel), the damage will not necessarily be covered by the OEM’s warranty (NREL, 2009), but fuel-related damage may be covered by the fuel supplier's general liability insurance. Biodiesel users may use biodiesel suppliers that provide liability coverage on the biodiesel and its blends.

All known engine OEMs have approved the use of biodiesel blends up to B5 as long as the biodiesel meets the D6751 specification (or the European biodiesel specification, EN14214). More and more OEMs are recognizing higher blend levels, and several approve up to B100. Approval levels for biodiesel-blended fuels are separate from the warranties (NREL, 2009).

2.5.2 Biodiesel History and Incentives for Production

In the U.S. the biodiesel market grew directly out of soybean production. Soybeans are grown mainly for their protein and meal, for animal feed. The oil is a by-product, some of which is used in cooking applications. But as soybean productivity grew, the oil became a less valuable by-product. In 1990, the Missouri Soybean Board and the University of Missouri began a demonstration project using soybean oil converted into fatty acid methyl esters to replace petroleum diesel fuel.

Momentum slowly grew, and the first biodiesel producers registered with EPA in 1996 (health effects testing was completed in 2000). By 2001 the biodiesel market grew from a small demonstration to an 8.5-million-gallon per year industry. The industry was strongly feedstock and process agnostic, which allowed for biodiesel to be produced from feedstocks other than soybean oil, including canola oil, corn oil, recycled restaurant greases, and animal fats. Today most biodiesel is a complex mixture of multiple feedstocks. Growth was helped by the passage of the Energy Policy Act of 2005 (EPA, 2013), which allowed fleets to gain alternative fuel compliance by using biodiesel (NBB, 2016).

The first version of ASTM D6751 was adopted in 2002, giving producers and users a benchmark for quality. The specification has undergone multiple revisions over the years. Many of these revisions were in response to stakeholder activities at ASTM to ensure that biodiesel was fit-for-purpose and could be used in a wide variety of applications (NBB, 2016).

By 2004 the biodiesel market had grown to nearly 28 million gallons per year. Congress provided a tax credit for biodiesel blending, which resulted in a near exponential increase in production through 2008, as shown in Figure 2-3. Expiration of the credit directly resulted in a market contraction. The biodiesel market shrank again in 2009–10, in part due to uncertainty with the blender's tax credit and RFS. By 2011 the market had recovered and production doubled from 2008 to 2014.

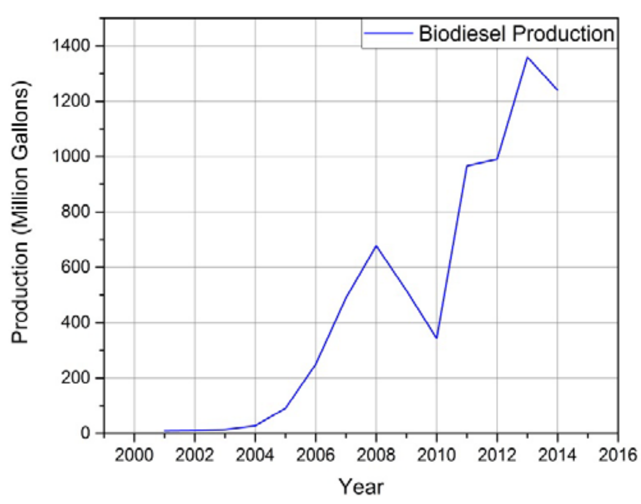

Figure 2-3. U.S. biodiesel production *(AFDC, 2016a)*

3 Fuels With Limited Market Share

3.1 Methanol

Interest in alternative fuels was intensified in the 1970s by Middle East oil supply disruptions and oil price instability, bringing U.S. energy security forward as a driving force. Various companies and entities began to examine methanol and methanol blends as promising fuels, and EPA identified methanol to have potential for low exhaust emissions. Federal and California State involvement provided research funding and grants concerning use and production of alternative fuels (Bechtold, 1987). It is possible to produce methanol from various feedstocks including biomass, natural gas (NG), and coal. Many considered methanol as a long-term replacement for petroleum, but only if it could meet or exceed the performance of legacy fuels, be competitive in price, and be widely available. FFVs were seen as the bridge to solving the availability problem in the near term so that an orderly transition to the new fuel could be made when the need arose (Nichols et al., 1987).

Methanol was tested and scrutinized in parallel with ethanol, other oxygen-containing constituents, proprietary chemicals, and other alternative fuels, generally in the form of gasoline blends. Neat methanol and very high levels of ethanol and methanol in gasoline were also under consideration. Engine, vehicle and fleet tests of such alternative fuels occurred mainly in the late 1970s and into the 1980s. Many OEMs produced prototype alternative fuel vehicles and FFVs for testing (Bechtold, 1987; Nichols, 1987), and DOE conducted a demonstration program with dedicated M85 vehicles at three national laboratories (West et al., 1993). Like many alternatives, the small number of refueling stations led to limited use of M85. Methanol's toxicity, low energy density, and corrosivity, coupled with low oil prices, led to waning interest in methanol. Strong advocacy for ethanol and weak advocacy for methanol allowed ethanol to supplant methanol in the United States as a petroleum alternative (Bromberg and Cheng, 2010).

3.2 Ethanol Flex Fuel

"Ethanol flex fuel" refers to a fuel made from a regular unleaded gasoline or gasoline BOB (blendstock for oxygenate blending) or natural gasoline and denatured fuel ethanol—in the case of E85 and similar designations, the "E" stands for ethanol and the numeral the volume percent of ethanol. The ASTM D5798 specification allows for flex fuel with ethanol content between 51% and 83%. Notably the U.S. alternative or historical name for flex fuel is E85, which is often still used even for lower ethanol volumes. Winter grades of E85 use higher gasoline fractions to facilitate cold start. The fuel is intended for FFVs but is also used as a high octane fuel for niche applications such as amateur racing and for blender pumps that distribute E15, E30, or other custom ethanol blends. Flex fuel has a very high octane number, even when blended with low octane gasoline (Szybist et al., 2013), however OEMs have not been able to take full advantage of the potential efficiency benefits because in FFVs they have to tune the engines so that they can operate safely even with the lowest available octane in the market, which in the U.S. is 85 AKI. Although the fuel is fully legal and available, E85 dispensers can be sparse in some regions. Use of E85 in 2015 was about 342 million gallons, which was 0.25 volume % of the gasoline market or about 0.21% by energy use (EIA, 2016b). While small compared to total ethanol consumption (about 2%), this E85 consumption rate is more than 10 times higher than it was in 2010. There were about 2,800 fueling stations offering E85 and some 17 million FFVs in use in 2015 (AFDC, 2016a). On average, only about 20 gallons of E85 is consumed per FFV per year, so obviously E10 is the dominant fuel used in FFVs. Low E85 use can be attributed to many factors, including limited numbers of FFVs, limited fuel availability, lower FE and/or loss of range, and frequently unfavorable pricing, effectively increasing cost-per-mile for the consumer. It should be noted that the unfavorable pricing is a likely strong factor keeping consumer flex fuel demand very low, discouraging investment in infrastructure for fuel availability, and negating any consumer-driven demand for FFVs.

There has been some interest in using FFVs as a bridge to a new high-octane mid-level ethanol blend such as E25 or E30 (Thomas et al., 2015). Vehicle manufacturers were offered FE incentives to build FFVs under the Alternative Motor Fuels Act of 1988, and production grew steadily over the years, with more than 500,000 FFVs sold in 2000, more than 1 million in 2007, and more than 2 million in 2011 and 2012 (AFDC, 2013). Under the 2012 FE rule (FedReg. 2012), manufacturers will only receive corporate average fuel economy (CAFE) credit for FFVs beyond 2019 if they can prove the vehicles are using E85. Under this scenario it is expected that FFV production will decrease sharply.

3.3 E15

In response to President Bush's 20-in-10 Initiative (January 2007), the DOE Vehicle Technologies Office (VTO) and the Bioenergy Technologies Office (BETO) initiated a set of studies to examine the impact of increasing fuel ethanol from the maximum legal 10% (E10) to up to 15% or 20% (E15 or E20). Later that same year, the Energy Independence and Security Act (EISA) of 2007 set into law the requirement that the nation use 36 billion gallons of renewable fuel per year by 2022. The rapid growth in ethanol production and the EISA law made it clear that the allowable ethanol content in gasoline would potentially need to be increased from the maximum legal 10% to up to 15% or 20% to support the EISA mandate. However, there were potential negative impacts of this new fuel on legacy vehicles, small nonroad engines, and the fueling infrastructure; hence the national ramifications were significant. The numerous DOE research programs were led by Oak Ridge National Laboratory and the National Renewable Energy Laboratory, with substantial subcontractor support and industry cooperation and guidance. An extensive bibliography of publications from these studies is provided in Appendix A (see Appendix A, Mid-Level Ethanol Blends Bibliography). While this test program was underway, in 2009 Growth Energy petitioned EPA to allow E15 use in SI engines. Under 40 CFR Part 79, EPA has the authority to grant or deny approval to such waivers. EPA granted partial approval of the waiver in October 2010 and January 2011, allowing gasoline blends with up to 15% ethanol to be used in 2001 and newer light-duty vehicles provided additional requirements were met (FedReg, 2010; FedReg, 2011). The waiver was denied for E15 use in heavy-duty vehicles, motorcycles, and nonroad applications. The additional requirements were satisfied in June 2012 and included registration by the fuel manufacturers (including submission of a health effects testing data package), and because of the restrictions on the partial waiver, a misfueling mitigation plan was also required.

This waiver approval was not supported by the vehicle manufacturers who did not approve of the use of E15 in "2001 and newer vehicles" with the exception of FFVs available and in use at the time. However, beginning in 2012 GM began permitting (via statements in the owner's manuals) the use of E15. In subsequent years, Ford, Toyota, Honda, Chrysler, and other manufacturers followed suit. As of model year 2017, the Renewable Fuels Association's review of owner's manuals indicates that some 80% of new vehicles are permitted by the manufacturer to use E15. The number of stations offering E15 has grown recently due in part to the USDA Biofuels Infrastructure Partnership Program (USDA, 2015). As of July 2017, over 900 stations in 29 states were offering E15 (Growth, 2017; AFDC, 2016b).

In locations in which the Authority Having Jurisdiction requires a recognized listing agency such as Underwriters Laboratories to list dispensers for the fuels that are dispensed, an E25-compatible dispenser (or flex-fuel dispenser) must be used. The Underwriters Laboratories 87-A listing for dispensers only allows for up to E10; additional listings are available for ethanol in gasoline up to E25 and another for up to E85 (Moriarty et al., 2009; Moriarty and Yanowitz, 2015). In August 2016, Wayne Fueling Systems announced that they would begin offering UL-Listed E25 dispensers as standard equipment (Wayne, 2016).

4 Electrified Vehicles

Vehicles with electrified powertrains can have significant GHG and FE advantages over conventional powertrain vehicles. Under the 2012 FE rule (FedReg. 2012), manufacturers will have increasing incentive to successfully market electrified powertrain vehicles to meet the GHG and FE standards (Pannone et al., 2017).

4.1 Hybrid Electric Vehicles

The hybrid electric vehicle (HEV) drivetrain combines an internal combustion engine (ICE) with one or more electric motors and a battery pack to store electrical energy from regenerative braking or engine charging. HEVs are fueled in the same manner as conventional gasoline vehicles and are not plugged into the grid to charge, as all energy on the vehicle originates from the ICE (INL, 2016). The number of light-duty hybrid models offered has been growing, and market share has generally been increasing, although it has fluctuated with fuel prices. From 2001 to 2007 the hybrid vehicle market share grew from insignificant to 2.2% of light-duty sales. Since 2007 the market share has been in the 2.2% to 3.8% range (EPA, 2015a; AFDC, 2016d). Roughly two-thirds of the market is Toyota and Lexus products (AFDC, 2016d). Most HEVs sold are classified as cars, with very low sales of hybrid trucks. The situation may change as FE standards tighten and many new models are introduced. Through MY 2016, no diesel HEVs had been introduced to the U.S. market.

The first gasoline HEVs were introduced in the United States for MY 2000, and early models were small and offered limited utility compared to class-comparable conventional light-duty vehicles. HEVs evolved to offer comfort, performance, and a driving experience comparable to conventional vehicles. For MY 2015, 46 light-duty HEVs were available with EPA combined fuel efficiency ratings ranging from 20 mpg to 50 mpg (DOE, 2016). The design purpose of hybridization can vary from offering increased performance to offering increased FE over comparable conventional models, though the latter design purpose addresses primary factors limiting the sustainability of automobility: criteria emissions, oil security, and greenhouse gas emissions (Turrentine et al., 2006). The lower fuel consumption and corresponding lower carbon and criteria emissions of HEVs are primarily achieved through brake energy capture, engine efficiency optimization, and idling minimization (Thomas, 2014).

A significant component of consumer choice related to HEV adoption is the financial cost or benefit of fuel-saving technology. However, one study found that, among a limited sample of vehicle owners, no owners had a systematic method to make vehicle purchasing decisions based on vehicle and fuel costs (Turrentine and Kurani, 2007). This lack of consumer calculation is in spite of the tools made publicly available such as EPA's FE ratings and calculators on the DOE-EPA website www.fueleconomy.gov. Determining an HEV's lifetime fuel cost savings relative to a comparable conventional vehicle is complicated by expected maintenance costs and depreciation, how and where the vehicle will be driven, length of ownership, and the variable price of gasoline over the ownership period (INL, 2016a). Despite this mix of factors, the market share of HEVs has tracked with the price of fuel as shown in Figure 4-1, demonstrating that fuel price has had a strong influence on the yearly market share of HEVs. Laws and incentives motivating the adoption of HEVs are addressed in a complementary report specifically investigating laws and incentives for several vehicle and fuel types (Alleman et al., 2017).

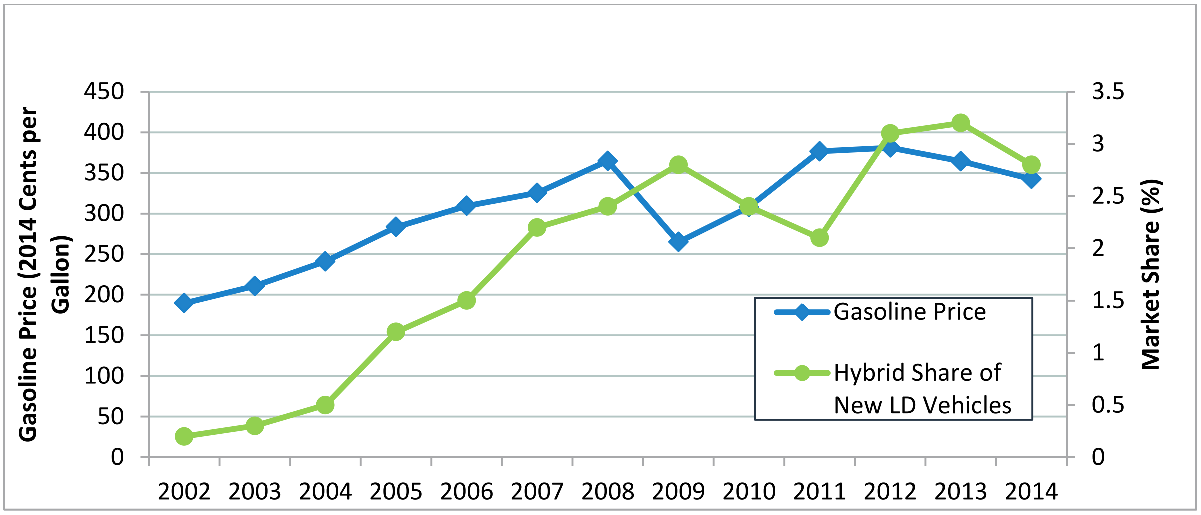

Figure 4-1. Hybrid electric vehicle market share and adjusted fuel price from 2002–2014. *[compiled from ORNL Transportation Energy Data Book (Davis et al., 2015) LD = light-duty]*

While the adoption of HEVs has clearly depended on fuel costs, a complex set of factors is understood to affect consumer choice and may include both financial and intangible considerations such as social desirability and perceptions of quality and reliability. The "neighbor effect," or the effect of market penetration on consumer preference, was investigated by refining behavioral adoption models to include these intangible factors based on survey results that informed stated preference and revealed preference. The consumer survey–based model predicted increasing the new vehicle HEV market penetration to 7% eliminates the negative impact of intangible factors compared to a 3% HEV market share in California in 2006 (Turrentine et al., 2006; Axsen et al., 2009). The model predicts intangible factors will become beneficial and stable at or beyond 10% market share (Axsen et al., 2009; Davis et al., 2015).

While some HEVs have been shown to be financially beneficial under a range of scenarios, many HEVs are more expensive to operate over their lifetimes under recent fuel prices and incremental technology costs. It would be an oversimplification to assume buyers who purchase HEVs despite unlikely payback are misinformed. Traditional modeling of consumer response has focused on the economic model of the rational actor and minimizes consideration of symbolism and expression of values through vehicle ownership, which affects the rationale of HEV and alternative fuel adoption (Heffner et al., 2008). Values commonly expressed were concern for the environment, opposition to war, cost of ownership, reduction of support for oil producers, and adoption of new technology (Heffner et al., 2008). Such consumer ideals likely drive significant HEV sales despite an uncertain financial return on hybrid ownership.

As the number of HEV models has increased, the FE range has broadened widely as performance and luxury hybrids entered the marketplace. Figure 4-2 illustrates the FE range for all HEV car models offered each year. HEV technology can increase performance over a nonhybrid variant rather than decrease fuel consumption, though both can occur simultaneously.

Of the topologies of HEVs that have been studied and proposed, only the gasoline-fueled HEV with battery storage have been marketed in the United States. Diesel-fueled HEVs have been extremely limited worldwide and have not been introduced in the United States, where light-duty diesel vehicles make up about 1% of the market. Some HEV gasoline engines have been further optimized for efficiency (e.g., use of the Atkinson cycle) due to lowered ICE peak power requirements and the ability to maintain ICE operation in more efficient speed-load operating regions. These advantages minimize the additional benefit diesel engine efficiency could bring without the additional cost of the diesel engine and emissions after-treatment systems.

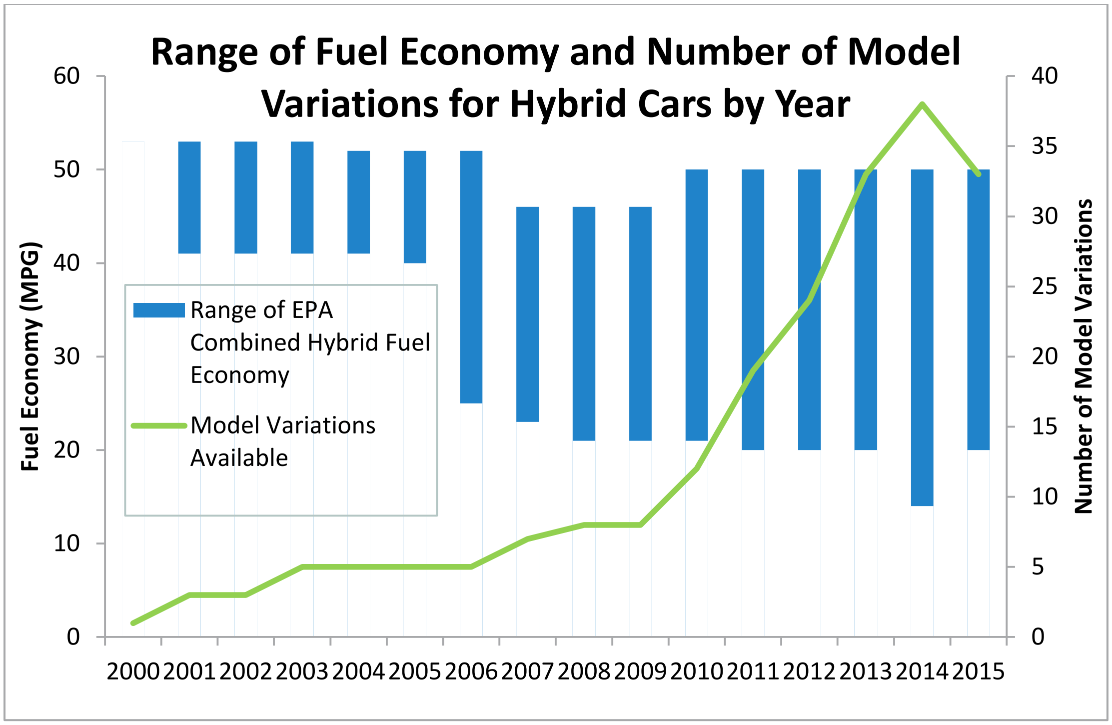

Figure 4-2. The range of U.S. Environmental Protection Agency (EPA)–rated combined FE for each model year, 2000–2015, along with the number of model variations available. *[compiled from www.fueleconomy.gov (DOE. 2016)]*

The introduction of HEVs presented problems for rating FE and quantifying emissions. Procedures had to be developed to ensure that fuel consumption over the testing protocol was not offset by consumption or storage of electrical energy. SAE International formed a task force to develop procedures for testing HEVs, which led to SAE J1711, a standard for measuring exhaust emissions and FE in HEVs that accounts for transient energy storage and partial electric-only engine-off operation (Duoba, 1997; Duoba et al., 2000). Real-world FE achieved by consumers was reported to vary significantly from EPA ratings, even more than that of conventional vehicles. Research into the sensitivity of different powertrain topologies found that generally the vehicles that achieve the highest efficiencies are the most sensitive to changes in drive cycle, vehicle mass, and ambient temperature (An and Santini, 2004; Lohse-Busch et al., 2013; Thomas et al, 2017). Challenges for HEVs have spurred innovations resulting in greater comfort, better performance and FE, and cost savings. Improvements in batteries, power electronics, warm-up emissions controls, accessory electrification, and driver-feedback telematic systems have aided consumer acceptance and environmental benefits (Rask et al., 2011). Electrification of accessories in an HEV can significantly minimize idling, even compared to nonhybrid vehicles equipped with engine stop-start technology, due to the ability to electrically drive the air conditioning compressor and other traditionally engine-driven accessories (Wishart and Shirk, 2012). Technology developments from HEVs have benefited recent plug-in electric vehicle development, which will in turn likely benefit future HEVs as well.

4.2 Plug-In Hybrid Vehicles and Electric Vehicles

Plug-in electric vehicles (PEV) are often categorized as plug-in hybrid vehicles (PHEVs) and pure electric vehicles (pure EVs). PEVs increase fuel diversity in transportation by substituting electrical energy for gasoline. While pure EVs consume no petroleum directly, plug-in hybrid electric vehicles can use both gasoline and grid-sourced electricity, with the proportion of the two fuels depending largely on vehicle architecture and driving and charging patterns. The electric-only range of the PHEVs varies significantly, so there is essentially a “gradient” from PHEVs to pure EVs.

4.2.1 PEV Market Growth

While PEVs have existed in very limited numbers alongside internal-combustion engine-powered vehicles at times during the history of the automobile, there has been a recent resurgence of production. Currently most major OEMs produce PEVs. Introduction of PEVs is successful relative to the very limited market presence of the technology in the past, but limited in absolute terms. Growth in sales is shown by Figure 4-3. The number of available PEV models has been increasing and sales were near 0.7% of all new U.S. vehicle sales in 2014 and 2015 (AFDC 2016f). For MY 2015, there were nine distinct EV models and ten distinct PHEV models marketed domestically (DOE, 2016). Pure EV sales are currently dominated by the Nissan Leaf, Tesla Models S and X, and the BMW i3 (introduced in 2014), and PHEV sales have been dominated by the Chevrolet Volt, Toyota Prius Plug-in, Ford Fusion Energi, Ford C-Max Energi and the BMW X5.

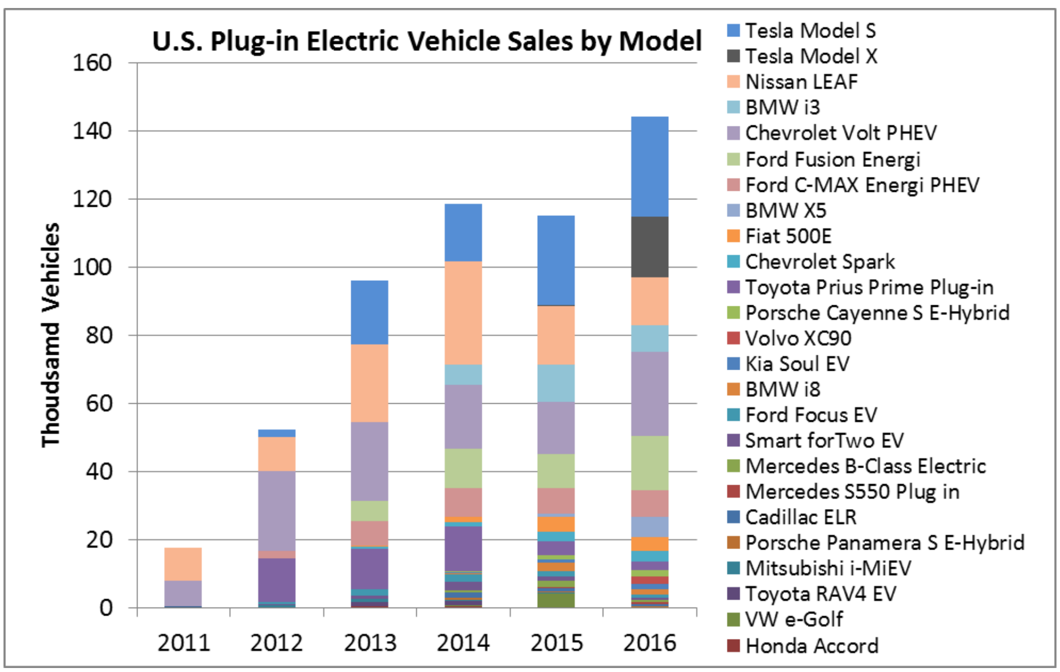

Figure 4-3. PEV Sales by Model *(AFDC, 2017)*

Recent federal and state tax incentives have undoubtedly increased adoption of PEVs, significantly offsetting their higher purchase price, which is related largely to the cost of energy storage. The California ZEV mandate in the early 1990s, combined with nine other states adopting CARB ZEV regulations, was a significant driver for PEV development (Santini, 2011) with nearly 25% of the light-duty vehicle market being subject to the ZEV regulation (see Sect. 5.2 for expansion). Furthermore, plug-in hybrids and pure electric vehicles receive credits for FE and GHG emissions far beyond those actually realized by the technology with the objective of encouraging such technology introductions (FedReg, 2012). Examination of laws and incentives influencing PEVs is presented in a companion report (Alleman et al., 2017).

4.2.2 Charging Infrastructure and Relevant Standards

The introduction of PEVs was coincident with efforts to harmonize charging infrastructure to help ensure interoperability between cars and electric vehicle supply equipment. SAE International issued standard J1772 in 1996, which states the recommended practice for PEV conductive charging couplers for North America. Since then, the standard has been revised several times, with a major revision in 2010 to coincide with the rollout of new EVs and PHEVs. Aside from Tesla, all OEM PEVs since 2010 have utilized this SAE recommended standard coupler for AC charging, where 120V-240V AC power is delivered to the vehicle's onboard charger for conversion to DC power to charge the battery. Vehicles utilizing DC fast charging, where high-power DC is delivered directly to the high-voltage battery per vehicle control limits, currently have one of two common couplers; SAE 'combo' or CHAdeMO. Vehicles utilizing the Japenese CHAdeMO typically have the SAE J1772 coupler for AC level 1 (120 V) and level 2 (208V or 240 V) charging, and a separate CHAdeMO port for fast charging. The SAE 'combo' connector, specified in the J1772-201210, combines auxiliary fast charging pins in tandem with the SAE AC charging port, and is considered by SAE to be the only worldwide fast charging standard going forward (SAE 2012), though several EV models are currently offered with CHAdeMO fast charging. CHAdeMO and SAE 'combo' connectors are not interoperable, and the lack of a single North American standard for several years led to deployment of both types of fast charging systems. Some fast charger companies are producing units with hardware to support both fast charge standards via separate couplers and communication protocols. Tesla maintains a proprietary charging coupler for their cars, along with a network of fast chargers, dubbed the supercharger network, dedicated solely to Tesla PEVs (Tesla 2016).

4.2.3 PHEV Fuel Use Characterization

PHEVs' use of electric power and electrical charge depleting strategies poses special challenges for measuring and characterizing FE/energy use and then communicating FE/energy use to the consumer. SAE J1711, "Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles, Including Plug-in Hybrid Vehicles," provides a uniform recommended practice to handle these nuances. The FE testing methodology used by EPA and CARB for certification and labeling, adopts key features of the SAE procedure which maintains separate reporting of gasoline FE and electrical energy consumption as MPG and AC Watt-hours per mile. However EPA combines the energy consumption on an electrical energy to fuel lower heating value of gasoline equivalency, such that the label FE is primarily expressed as miles per gallon equivalent, or MPGe for all-electric operating modes, and when fuel and electricity use is blended. Gasoline and electrical energy consumption are also broken out for blended PHEV operation as secondary metrics on the fuel economy label. The FE of PHEVs in charge sustaining mode, consuming only gasoline and no net electrical energy, is rated in familiar MPG. While the FE testing and labeling have evolved to offer the consumer a wealth of information on the energy consumption of PEVs in their different operating modes, the energy equivalency based MPGe is limited in usefulness to comparing overall energy efficiency between models. A breakdown of gasoline and energy consumption is required to understand operating costs due to the changing price of each fuel and large differences in the efficiency of operation using gasoline and electricity.

DOE developed a tool called 'eGallon' to help consumers estimate the cost of electricity having the same utility as a gallon of gasoline when consumed in a PEV using their state average gasoline and electricity cost. Regional variations in electricity pricing can greatly affect the fuel cost savings achievable by vehicle electrification. The tool is based on a comparison of the energy consumption of several EVs and fuel consumption of their equivalent gasoline powered models (DOE 2016). Comparing the utility of electricity and gasoline at economic parity, rather than a heating value equivalency, is particularly useful because the efficiencies of the drivetrains utilizing those fuels are very different.

The actual petroleum reduction benefit realized from electric charge depleting operation of PHEVs depends on driving and charging behaviors. Utility Factor, a metric to determine the proportion of charge-depleting miles to total miles for a fleet of vehicles, was developed in SAE J2841 using data from the 2001 National Household Transportation Survey (NHTS). This methodology makes the assumption that vehicles will be fully charged once per day. Studies have evaluated the effect of varying the once-per-day charging assumption coupled with the NHTS data and found significant utility factor increase using more frequent charging (Bradley and Quinn, 2010). A study of privately owned Chevrolet Volt operation was performed on data from the DOE funded EV Project, and found the realized UF to be higher on average than the J2841 estimated eVMT due to both fewer long drives and more frequent charging (Smart et al, 2014). Idaho National Laboratory, in partnership with Nissan, General Motors, Ford, Honda, and Toyota, performed a study to characterize the number of electric vehicle miles travelled (eVMT). Data were analyzed from 158 million miles of private PEV operation to determine eVMT across 3 EV and 5 PHEV models. EVs averaged less total mileage per year, while the PHEVs averaged more total mileage, with their share of eVMT being proportional to battery pack size.

5 Vehicle Technologies Limited to Niche Markets

5.1 Flexible Fuel Vehicles

Flexible fuel vehicles are designed to utilize gasoline combined with levels of ethanol up to 85% (see Section 3.2) and in most other respects are essentially no different from gasoline-only vehicles. Development and marketing of these vehicles stemmed from the 1988 Alternative Motor Fuels Act which provided CAFE credits for sales of such vehicles. Because flex-fuel was not widely available the vehicles were designed to use all types of gasoline.

Due to incentives, FFV production grew steadily, with more than 500,000 FFVs sold in 2000, more than 1 million in 2007, and more than 2 million in 2011 and 2012 (AFDC, 2013). Under the 2012 FE rule, the manufacturers will only receive CAFE credit for FFVs beyond 2019 if they can prove the vehicles are using flex fuel. Under this scenario it is expected that FFV production will decrease sharply. As explained in Section 3.2, only a relatively small amount of flex fuel is actually utilized in FFVs. A combination of inconsistent value (in cost per mile) to the consumer, and flex fuel not being broadly available has led to the current market situation with flex fuel having a minor impact in the fuel market and limited incentives creating consumer demand for FFVs or flex fuel.

5.2 Early Electric Vehicles

A significant level of technology advancement, regulations, and subsidies in the United States and many other places worldwide has brought the modern EV to market in a substantial way. In the past, EVs could not compete with liquid-fueled vehicles, in large part due to the relatively poor energy density of batteries when fully charged. Essentially, EVs were much too heavy and expensive and had highly limited range. Furthermore, battery charging times were quite long compared to conventional refueling. Again, these limitations stem directly from battery technology limitations. Modern EV development is still addressing these same problems of energy density, cost, weight, and charging time (DOE, 2014).

EVs were introduced to the light-duty vehicle market beginning around the turn of the 20th century, though they had faded compared to gasoline-powered vehicles by the 1930s, when better roads and abundant gasoline enabled more widespread travel, highlighting the limited range and performance of EVs. Oil shortages in the 1970s rekindled interest in the use of domestic energy for transportation, though EV reintroduction was limited primarily to urban areas where the limited speed and range were less severe handicaps. Despite abundant oil supply and low fuel prices in the mid-1990s, federal and state legislation and regulations pushed development and introduction of the first wave of modern EVs (Alleman et al., 2017; DOE, 2014). Several factors combined to limit the success and momentum of those EVs, and these will be explored in this section, noting that relevant laws and incentives are investigated more comprehensively in a complementary report focusing on that subject (Alleman et al., 2017).

EV development programs were initiated by several OEMs in the early 1990s, due in large part to CARB's adoption of a zero emissions vehicle (ZEV) regulation in 1990 and the federal Energy Policy Act of 1992 (Santini, 2011). The California regulation required large auto manufacturers to make 2% of new vehicles produced for sale in California ZEVs by 1998, increasing to 10% by 2003 (CARB, 1990). The federal act required a share of government vehicles to be alternative fuel vehicles, including but not limited to ZEVs (Davis and McFarlin, 1996). The California ZEV mandate has been cited as an example of "technology-forcing," requiring use of a technology that, at the time of the requirement, was not competitive in the market and still required significant technological advances (Calef and Goble, 2007). Several OEMs began to produce EVs following the ZEV mandate, but GM had begun an EV development program before the mandate, hiring AeroVironment, Inc., to design the Impact, a concept car that would later become the basis for the GM EV1—the first mass-produced EV. The Impact was introduced in 1990, and its relative success may have influenced California's ZEV rulemaking that same year. Most of the EV models developed by the other major OEMs selling cars in California were highly modified versions of conventional vehicles, including minivans and small pickup trucks. In contrast, the EV1 was developed specifically for this market from the ground up. EV models offered by the major OEMs through MY 2001 are shown in Table 5-1.

Table 5-1. Original equipment manufacturer light-duty electric vehicles offered from 1997 through 2001

Vehicle	Type	Limitations[a]
Daimler Chrysler Epic	Minivan	CA & NY, lease only
Ford Ranger	Standard Pickup	
General Motors EV1	Two-seater	CA and AZ, lease only
Chevrolet S-10	Small Pickup	
Honda EV Plus	Sedan	Fleet lease only
Nissan Altra EV	Mid-size Wagon	CA, fleet only
Toyota RAV4-EV	SUV	Fleet only

[a] Limitations may not be exhaustive, and all listed EVs may not have been available each year.
Data compiled from Transportation Energy Data Book, Editions 18–21 (Davis, 1998; Davis, 1999; Davis, 2000; Davis, 2001).

At the time, one of the most underdeveloped technologies required for successful EVs was energy storage. Chrysler Corporation, Ford Motor Company, and GM collectively formed the United States Advanced Battery Consortium in 1991 and entered into a cooperative agreement with DOE with the goal of developing battery technologies capable of sustaining a competitive EV market (NRC, 1998). The Partnership for a New Generation of Vehicles (PNGV), formed between government agencies and auto OEMs in 1993, funded research on low-GHG-emitting vehicles. Hybrid-electric technology (rather than pure EVs) emerged from the PNGV program as a promising path to meet emissions and petroleum consumption reduction goals and was chosen by DaimlerChrysler, Ford, and GM for PNGV concept cars (diesel engine HEVs). Though immature, battery technology developments for EVs were further spurred by the ZEV mandate. The incumbent energy storage technology, lead acid batteries, lacked the energy density required for the range useful to most drivers. Several EVs were developed with lead acid battery packs, but as the nickel–metal hydride battery technology matured, models were equipped with such batteries, enabling longer range, higher performance, and more reliable operation (DOE, 2001; Francfort et al., 1999). The range of vehicles powered with nickel–metal hydride packs in on-road testing in southern California was typically from 60 to 100 miles, depending on payload and auxiliary loads (INEEL, 2002). Though range improved, with the exception of GM's EV1, EV models had notably slow acceleration, with 0–60 times in the mid-to-high teens.

The costs of power electronics, motors, and batteries during this period are difficult to estimate, and the cost of EVs is further obfuscated by the fact that most during this period were leased (and mainly in California), some only to fleets. Typical lease prices were around $400 per month, and operation required installation of charging infrastructure (Calef and Goble, 2007). This is evidence that EV initial cost was far from competitive at this time. The wave of EVs peaked in California in 2000 at 3,900 vehicles, of which roughly half were operated by government and utility fleets. This number declined sharply due to recall of many leased vehicles by several OEMs (Calef and Goble, 2007). Changes to the CARB legislation in the early 2000s, motivated by litigation and reviews of limited technology progress, among other factors, led to technologies other than ZEVs such as hybrid-electric vehicles being qualified to partially meet the ZEV requirement (CARB, 1990). This coincided with the introduction of hybrids to the U.S. market by Toyota and Honda. Demonstrated improvements in energy storage performance were not enough to propel EVs into a self-sustained market, and if consumer demand did exist, vehicles for consumption largely did not by the early 2000s.

5.3 Natural Gas and Propane

5.3.1 Natural Gas

NG as an alternative transportation fuel has been a focus of development and deployment in light-duty and medium/heavy-duty vehicle segments. Compressed natural gas (CNG) fueling technology has been applied to light-duty vehicles, while both CNG and liquid natural gas (LNG) fueling has been employed for medium and heavy-duty vehicles.

Light-duty

A variety of initiatives have been implemented to promote NG vehicles (NGVs), including purchase incentives offered by states and the federal government, leasing agreements, a push in some rental car businesses in California, and NGV access to high-occupancy vehicle lanes. Vehicle performance has generally been equal to that of conventionally fueled vehicles; however, several vehicle conversions were released prematurely, and those did not always perform with the emissions, power, and reliability that customers were expecting.

Barriers to more widespread adoption of NG as a light-duty vehicle fuel include the following.

- Limited product offering (makes and models) for fleets and consumers.
- Storage for NG on board takes up vehicle cargo space (challenging for fleets and consumers).
- Limited fueling station access (training may be required, special cards, limited access to facilities).
- High cost vs. conventional vehicle difficult to overcome via fuel savings at the average annual miles driven.
- Additional training for mechanics.

Medium and Heavy-duty

Among NGVs, heavy-duty vehicles have seen the greatest success in terms of market impact. With heavy-duty vehicles, one engine design can be installed in several applications, creating a larger market for the same product. Nevertheless, the market is still limited enough that it has been less attractive, in terms of time and cost, for engine OEMs to certify a significant number of engines for CNG or LNG.

Some of the barriers to more widespread adoption of NG for medium and heavy-duty vehicles include the following.

- Limited efficiency compared to diesel (SI vs. compression ignited).
- Limited product availability.
- Higher initial costs for vehicles.
- High infrastructure costs.
- Additional training for mechanics.

The benefits of NG fueling in the medium-duty and heavy-duty sectors have been significant cost savings, quieter engines (than diesel), and robust aftertreatment for stoichiometric three-way catalyst applications (Melendez and Gonzales, 2016; CIEE, 2009).

5.3.2 Propane

Propane is also known as liquefied petroleum gas and propane autogas. Propane vehicles can be a viable alternative to conventional light, medium, and heavy-duty vehicles, especially for centrally refueled applications. There is continuing interest in propane as an alternative fuel due to an abundant domestic supply and significant vehicle and engine offerings.

Current Market Status

Propane is a byproduct of NG processing and crude oil refining. Markets for propane include vehicles, agricultural (e.g., irrigation) and other industrial engines, commercial mowers, chemical feedstocks, and commercial/residential uses such as heating and cooking. What is marketed as propane autogas is identical to propane used for other purposes. Propane is shipped from the point of production to bulk distribution terminals via pipeline, railroad, barge, or truck. Marketers purchase propane at terminals for distribution to fueling stations.

Vehicles

Key on-road transportation markets include school and shuttle buses, taxis, delivery vehicles, law enforcement vehicles, and other centrally fueled fleets. There are currently more than 140,000 propane vehicles operating in the United States (AFDC, 2016e; EIA 2015a). As shown in Figure 5-1, the number has declined from a high of nearly 200,000 in 2003, and has been relatively constant at 140,000 in recently years. As of 2011, the largest numbers of propane vehicles were found in Texas, California, Georgia, Florida, and North Carolina (EIA, 2015b).

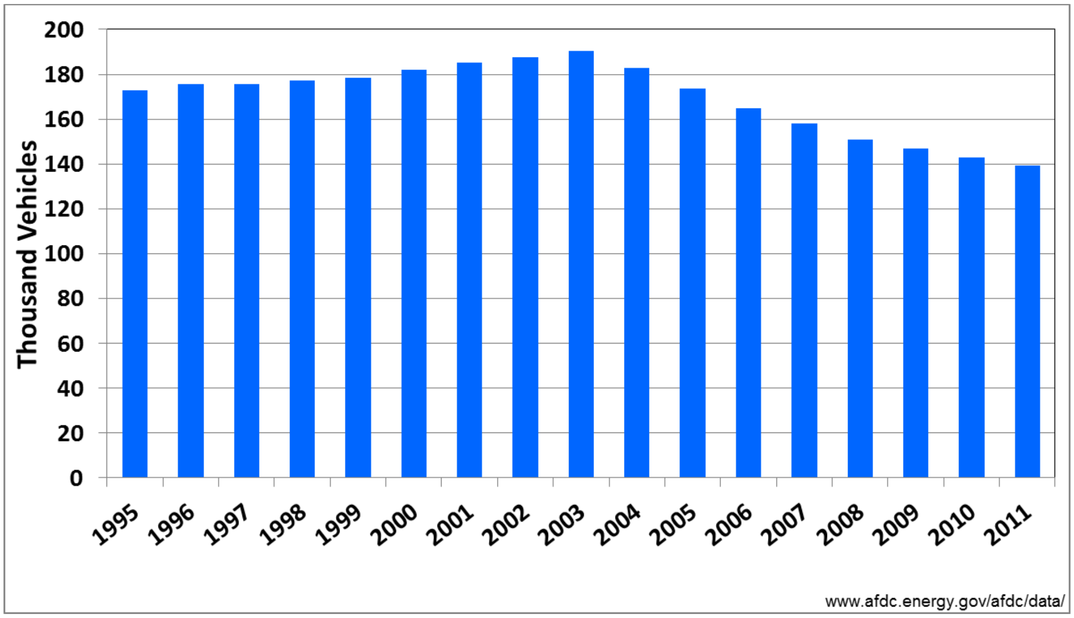

Figure 5-1. Number of propane vehicles in use by year. *(AFDC, 2015b)*

Vehicle Technology

Propane vehicles operate like conventional gasoline vehicles with spark-ignited engines (Sloan and Wilczewski, 2013). Light, medium, and heavy-duty propane vehicles are available in two configurations: (1) dedicated vehicles that run exclusively on propane and (2) bi-fuel vehicles that have two separate fueling systems, enabling the vehicles to switch between propane and gasoline.

Propane-ready vehicles can be obtained directly from certain OEMs, or vehicles may be modified with “prep” packages, which enable qualified vehicle modifiers to install the propane fuel delivery system. More than a dozen propane-compatible engines are currently certified for on-road use by EPA and/or CARB. These engines provide a variety of options for fleets, including school and transit buses, shuttles, service vehicles, delivery vehicles, street sweepers, vocational trucks, and law enforcement vehicles (PERC, 2014; AFDC, 2015).[1]

Light-duty propane vehicle engines for cars, trucks, SUVs, and vans range from 2.0 to 6.0 L displacement and are commonly used by fleets for police cruisers, taxicabs, and pickup trucks. The engine options for medium-duty propane vehicles range in displacement from 6.0 to 8.8 L, with applications including government, university, and commercial fleets that use walk-in vans (e.g., package delivery and industrial laundry); tool and utility service trucks; box trucks; service vehicles; and shuttle buses. Propane buses are an option for school districts, with a selection of buses manufactured by OEMs such as Blue Bird Corporation, Collins Bus Corporation, Navistar International Corporation (IC Bus), and Thomas Built Buses, Inc.

A light-duty conversion may cost as little as $6,000, while a new propane school bus may have an incremental cost of $15,000 or more. As compared to their compression-ignition (diesel) counterparts, spark-ignited engines are typically less expensive (Sloan and Wilczewski, 2013).

[1] Examples of on-road engines that can operate on propane include the Ford 2.0 L and 2.5 L V4; 3.7 L V6; 4.6 L, 5.4 L, and 6.2 L V8; and 6.8 L V10; GM 4.8 L, 5.3 L, 6.0 L, and 8.0 L V8; PI 8.0 L; and PSI 8.8 L.

Infrastructure

Limited fueling station access is commonly cited as a barrier to propane adoption. Some fueling sites only fuel vehicles as a secondary business to filling propane bottles or recreation vehicle tanks, which can make fueling vehicles challenging. According to AFDC, nearly 3,000 public and private propane fueling stations are in operation or are planned in the United States (AFDC, 2016).

Vehicle and Fuel Incentives and Policies

Many states offer financial incentives including tax credits and exemptions, grants, loans, vouchers, and rebates and some offer nonfinancial incentives, including emissions testing, high-occupancy vehicle lane access, and vehicle weight limit exemptions. Similarly, some state laws and regulations encourage the use of propane in transportation (e.g., fleet acquisition requirements) and ensure safe operation of the vehicles. Federal incentives and laws have encouraged propane utilization, such as the American Recovery and Reinvestment Act of 2009. Federal incentives including a $0.50 per gallon alternative fuel excise tax credit and fueling infrastructure tax credit expired at the end of 2014.

5.4 Light-duty Diesel

Most vehicles classified as light-duty in the United States are gasoline powered. Diesel engine–powered light-duty trucks are less than 1% of that market sector and are generally offered for sustained high-torque duty requirements. Light-duty diesel vehicles classified as cars are about 1% of that market sector (EPA, 2015a). Cost of ownership is the most obvious reason for low market penetration of diesel vehicles, in contrast to Europe where cost can favor light-duty diesel vehicles.

Recent emission standards and gasoline powertrain innovations have had the overall effect of lowering the efficiency advantage that diesel powertrains have over gasoline powertrains, although diesels still have an efficiency advantage (Thomas, 2016). Diesel engine and emission systems have a cost premium over comparable gasoline systems, causing the initial cost of the diesel vehicles to be higher. While diesel fuel is widely available in the United States, the limited number of light-duty diesel vehicle options includes many relatively expensive vehicles. The price per gallon of diesel compared to regular gasoline has fluctuated over the years, but has generally been within a few percent. However, as worldwide diesel demand has grown, diesel has generally been more expensive than gasoline for the past decade, and by a sizeable margin, as shown in Figure 5-2. Overall high fuel prices can drive consumers to vehicles with high FE, including diesel vehicles but this has likely been be negated by high diesel fuel prices.

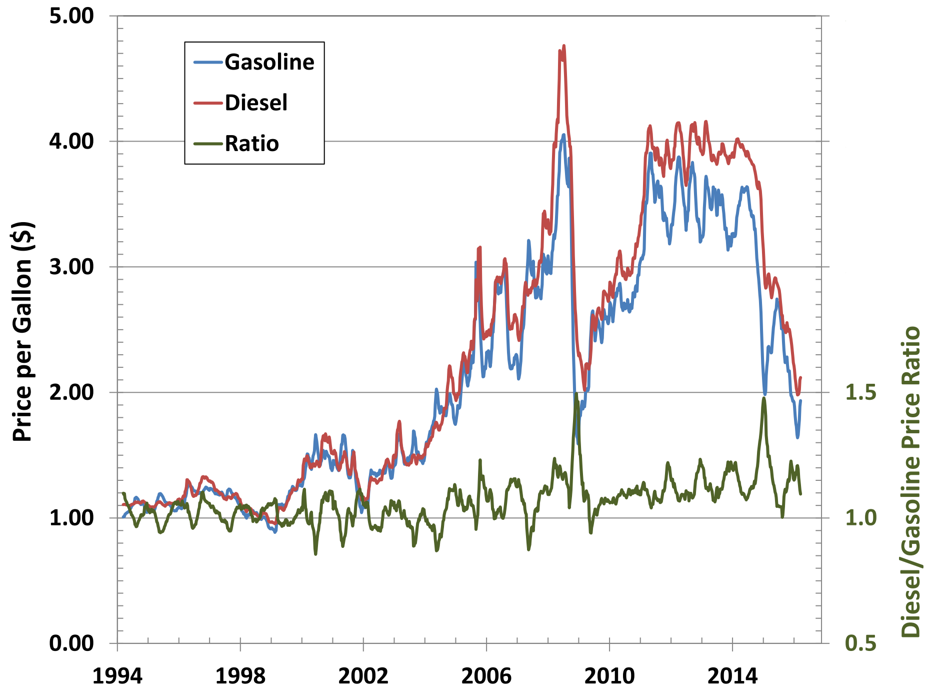

Figure 5.2. Gasoline and diesel price history. *(EIA, 2016c)*

Compared to gasoline, diesel fuel contains about 14.5% more carbon and 13.5% more energy. This higher carbon fraction slightly diminishes the GHG advantages of the diesel engines being more efficient than gasoline engines. There is generally a small but significant incentive for vehicle OEMs to market diesel vehicles to meet FE and GHG standards.

6 Conclusions

Significant fuel and vehicle introductions have occurred in the United States during the past several decades. Examining these past introductions reveals how combinations of societal needs, politics, and business interests have influenced fuel- and vehicle-related regulations, lack of regulations, or delayed regulations. Successful new fuel and related vehicle changes in the United States have largely been driven by regulation, governmental incentives, and in some cases with much consideration of economic effects.

The leaded to unleaded gasoline transition is the most well-known example of a difficult and initially expensive transition that was driven by regulation. The rise of fuel ethanol use also was driven largely by regulation and incentives. It is almost certain that worldwide fuel economy and greenhouse gas emissions regulations will drive a large increase in electrified powertrains (including mild and full HEVs, PHEVs, and PEVs) in the light-duty vehicle market in the coming years.

Vehicle choices are driven in large part by economics. In the last decade, when oil prices were high, more consumers embraced hybrid and plug-in electric vehicles, and some heavy truck companies adopted NG conversions. As oil prices have fallen, interest in these fuels and technologies has leveled off or waned.

Alternative fuels and vehicles have made varying contributions to the reduction of petroleum use in the United States. Some have generated significant initial interest that has waned over time, and others (e.g., EVs) have become steadily more entrenched in the marketplace.

Fuels such as propane and NG have limited use partly due to difficulties with refueling and handling. High energy density liquid fuels dominate the market and offer long driving range, rapid refueling, and an existing network of production and supply infrastructure. In consideration of these market factors, the current Co-Optima effort is exploring production pathways for high energy density liquid fuels and conducting detailed assessments of compatibility with current mainstream fuels.

The Co-Optima initiative is focused on identifying fuel properties that enable optimized engine performance while conducting a systematic study of biomass-derived blendstocks that could offer a broad range of feasible options while also providing technical and societal benefits. For maximum benefit a new fuel will have to become a significant part of the United States transportation market. This report has reviewed the past fuel and vehicle introductions to enable experience and lessons from the past to help researchers and stakeholders to understand some of the challenges. If such a fuel or fuel/engine combination is achieved, it is likely that the already highly regulated road transportation fuels and vehicle sector will require significant changes to regulations and perhaps government incentives of some form to bring about successful market introduction.

Close collaboration between research, government, and industry stakeholders has enabled successful transitions in the past, and some less successful attempts may have not considered all aspects of the transportation industry sectors. The Department of Energy and its national laboratories can play key roles in convening stakeholders to help ensure that effective pathways to market introduction are identified. Objective data and analyses from the national laboratories have been cited by regulators in the past, and can help identify and compare options on a comprehensive and consistent basis to allow stakeholders to make the most informed decisions about future fuel and engine solutions.

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