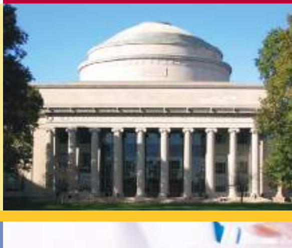
Prospects for Bi-Fuel and Flex-Fuel Light-Duty Vehicles



MITei

MIT Energy Initiative

An MIT Energy Initiative
Symposium

April 19, 2012

Massachusetts
Institute of
Technology

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Summary for Policy Makers

The April 19, 2012, MIT Energy Initiative Symposium addressed *Prospects for Bi-Fuel and Flex-Fuel Light-Duty Vehicles*. The symposium focused on natural gas, biofuels, and motor gasoline as fuels for light-duty vehicles (LDVs) with a time horizon of the next two to three decades. The important transportation alternatives of electric and hybrid vehicles (this was the subject of the 2010 MITEi Symposium[1]) and hydrogen/fuel-cell vehicles, a longer-term alternative, were not considered.

There are three motivations for examining alternative transportation fuels for LDVs: (1) lower life cycle cost of transportation for the consumer, (2) reduction in the greenhouse gas (GHG) footprint of the transportation sector (an important contributor to total US GHG emissions), and (3) improved energy security resulting from greater use of domestic fuels and reduced liquid fuel imports. An underlying question is whether a flex-fuel/bi-fuel mandate for new LDVs would drive development of a robust alternative fuels market and infrastructure versus alternative fuel use requirements.

Symposium participants agreed on these motivations. However, in this symposium in contrast to past symposiums, there was a striking lack of agreement about the direction to which the market might evolve, about the most promising technologies, and about desirable government action. This lack of consensus is itself instructive, pointing to the paucity of data in the public domain about vehicle performance and emissions for a spectrum of fuel alternatives.

Despite this lack of consensus, there was agreement on two overarching realities. First, the introduction of new technology will be greatly facilitated by “backward compatibility” with the existing fuel and vehicle infrastructure. Second, the key factor is the extent that the stock of LDVs on the road is compatible with a range of fuels.

The sessions dealt with different aspects of the engine/fuel system.

Prospects for bi-fuel vehicles The dramatic difference in the US of oil and natural gas prices on an equal energy basis is a strong incentive for examining alternatives to the motor gasoline internal combustion engine (ICE) (in today’s configuration and with future improvements, e.g., turbocharging). Participants discussed a wide range of different vehicle/fuel combinations. Here is a sample list:

- Methanol fueled LDVs
- Compressed Natural Gas (CNG) LDVs
- Bi-fuel natural gas and motor gasoline vehicles
- Ethanol-gasoline flex fuel vehicles (FFVs) in range of E-15 to E-85
- Tri-flex fuel vehicles fueled by gasoline/ethanol/methanol (GEM) mixtures.

For each of these alternatives there was considerable discussion (but little agreement) about drivability, emissions, cost, and maintainability.

One session of the symposium was devoted to consumer choice as expressed in various countries, e.g., ethanol in Brazil, Germany, and the United States, bio-diesel and propane-fueled vehicles in Germany, and CNG in Asia and Europe. Unfortunately, the symposium did not hear an assessment about how useful vehicle choice models, widely used by industry and government agencies, were for projecting vehicle fleet composition among a wide range of vehicle/fuel options under a variety of policy assumptions.

Some interesting tentative conclusions were inferred from the discussion offered here, but it is important to stress that these conclusions are tentative and require both technical development and verification from field experience.

1. It is possible to manufacture LDVs capable of operating on a wide range of GEM mixtures, with a cost penalty under $1,000 per vehicle, possibly substantially less.

2. These LDV engine/fuel combinations may comply with prevailing and anticipated air emission standards over the wide range of expected driving conditions, e.g., start-stop, summer-winter.

3. There is insufficient field experience with many LDV engine/fuel combinations that are proposed.

4. Attention must be given to fuel efficiency, on-board electronic fuel controls, and super charging to optimize vehicle performance with respect to emissions, cost, and consumer satisfaction.

The lack of agreement about the most promising fuel/vehicle combinations from the point of view of cost, sustainability, and environmental effects meant that no clear direction emerged for desirable federal or governmental policy. Individual participants did propose a wide range of mechanisms: fuel economy standards, vehicle fuel flexibility standards, and various mechanisms to subsidize rapid deployment of fueling infrastructure. However, there also was recognition that the government was neither in a position to select one preferred alternative vehicle direction nor to provide the funds to subsidize multiple approaches.

There certainly are research, development, and deployment (R,D, & D) programs in alternative fuel vehicles (AFVs) that deserve federal support although this topic was not sufficiently addressed to either endorse present programs or offer many concrete suggestions. There was general sympathy with the view that there was little field data for small fleets of AFVs and that a suite of properly instrumented small fleet (less than 100 vehicles) demonstration projects could yield valuable information about the cost, practicality, and consumer satisfaction of the technology alternatives.

John Deutch
Institute Professor, MIT

MITEI Associates Program/Symposium Series

The MITEI Associates Program/Symposium Series is designed to bring together groups of energy experts to examine, analyze, and report on critical and timely energy policy/technology issues with implications for near-term actions. The centerpiece of the program is a one-day symposium in which invited experts, under Chatham house rule, discuss the selected topic. Topical white papers, which are sent to the participants in advance, are commissioned to focus and inform the discussion. The information from these white papers is supplemented by work from graduate students, who generate data and provide background information.

Potential symposium topics are solicited from MITEI members and are provided to the Steering Committee for consideration. Four MITEI Associate members — Cummins, Entergy, Exelon, and Hess — support the program with a two-year commitment and serve on the Steering Committee.

After each symposium, a report is prepared and published, detailing the proceedings to include a range of findings and a list of recommendations. Two students are assigned to each session. They serve as rapporteurs for the symposium and focus their master's theses on topics identified from the symposium.

This report is the fifth in the series, following *Retrofitting of Coal-Fired Power Plants for* CO_2 *Emissions Reductions, Electrification of the Transportation System, The Role of Enhanced Oil Recovery in Accelerating the Deployment of Carbon Capture and Sequestration,* and *Managing the Large-Scale Penetration of Intermittent Renewables*.

These reports are available electronically on the MITEI web site at http://web.mit.edu/mitei/research/energy-studies.html. If you would like to receive a hard copy of one or more of the reports, please send an email with your requested titles and quantities and your mailing address to askmitei@mit.edu.

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The MIT Energy Initiative's Symposium on Prospects for Bi-Fuel and Flex-Fuel Light-Duty Vehicles

SECTION 1 OVERVIEW AND SUMMARY

The 2012 MIT Energy Initiative symposium brought together experts and policy makers to discuss prospects for alternative fuel technologies for LDVs. As its starting point, the symposium accepted the proposition of a significant policy value in a greatly expanded alternative fuel market and focused on the question of how it might be achieved.

The objective of the symposium was to examine alternative approaches that could lead to the deployment of a large number of bi-fuel and flex-fuel vehicles. The symposium also examined the relationships between AFV deployment and expansion of alternative fuel infrastructure (the so-called "chicken and egg" problem). The symposium addressed this problem from the vehicle perspective, assuming that adequate supplies of alternative fuels could be produced to satisfy demand created by expansion of the AFV fleet. The scope of the symposium was focused on AFV technologies using liquid fuels or natural gas. A previous MIT Energy Initiative symposium examined prospects for electrification of the transportation sector.[2]

Rationale for the Symposium

Symposium organizers started from the premise that a greatly expanded alternative fuels market would advance key US policy objectives. The rationale for organizing the symposium was built on four fundamental premises:

1. **Alternative fuel solutions for the transportation sector are key to addressing major policy challenges:** The fuel mix for the LDV segment of the US transportation sector is dominated by use of petroleum-based fuels; gasoline consumption accounted for 51% (by volume) of total US petroleum demand in 2011.[3] The scale of current petroleum usage in LDVs poses significant challenges to national policy objectives.

2. **Energy and economic security:** Nearly 8% of average household income is spent on gasoline, and price volatility in gasoline markets is a recurring issue with policy makers. Although physical quantities of petroleum imports have decreased from a peak in 2005, the dollar value has increased. The United States spent $335 billion on foreign oil in 2011, an increase of 84% from 2005 (the year of peak oil imports).[4] The US oil import bill is estimated to account for over half of the net trade deficit.[5]

3. **National security:** Regardless of the source of physical supply, the price of petroleum is set globally. Currently, 49% of US petroleum imports are from the Western Hemisphere, while the remainder arrives via longer and less secure routes.[6] The price of gasoline in the United States tracks the price of crude oil, and crude oil prices are set in the global market not in the United States. 79% of global conventional oil reserves are controlled by the Organization of the Petroleum Exporting Countries (OPEC) cartel, which seeks to set global prices through its control of production levels to maximize the revenue of its member countries. At $100 per barrel, the value of OPEC-proved reserves is more than double the market capitalization of all the world's publicly traded companies combined.[7] Global petroleum resources are concentrated in countries that may wish to leverage this petroleum-derived wealth in ways that could constrain and limit US foreign policy options.

4. **Climate change:** Gasoline-powered LDVs comprise nearly one-third of total net US GHG emissions.[8] To be effective, any climate policy will need to include measures to reduce GHG emissions from this sector. However, reliance on policies that place a price on a carbon may be insufficient to induce a shift in demand to lower carbon alternative fuels. For example, a carbon price of $40 ton CO_2 could result in significant changes in energy use in the electric power sector, but it corresponds to only a $0.35 per gallon increase in the price of gasoline.[9]

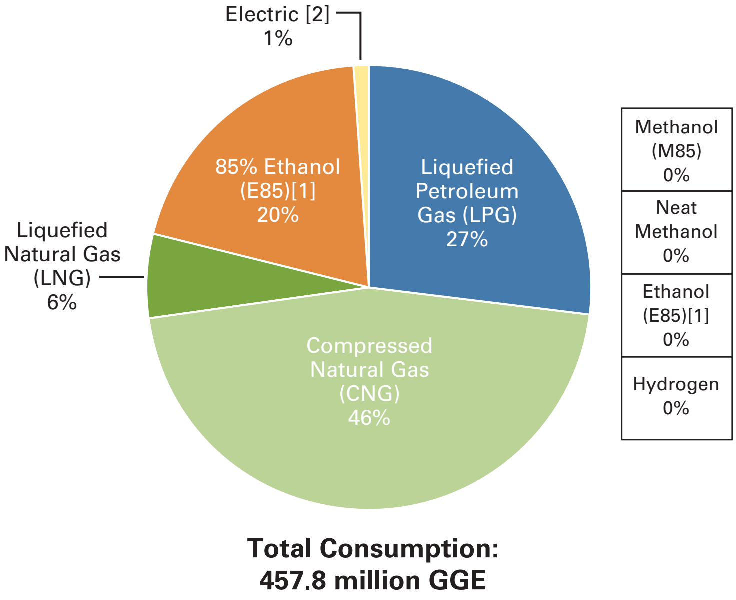
Addressing these challenges is further complicated by the massive scale and tightly regulated nature of the current LDV market and its associated petroleum-based fueling infrastructure. Automobile manufacturing and petroleum refiners report that they account for about 10% of US Gross Domestic Product (GDP) and 17 million jobs.[10] Any changes in the outputs from these sectors will require significant lead times, large-scale capital investment, and rigorous regulatory reviews.

- **Achieving a greatly expanded alternative fuels market requires significant levels of AFV deployment in the mass market of LDVs:** Addressing the major policy challenges requires an informed discussion of the feasibility of alternative fuels in the mass market for LDVs. The past three decades have seen growth in the number of AFVs primarily in the heavy-duty vehicle (trucks and buses) and LDV fleet markets. This growth has been market driven, assisted with modest federal incentives (both financial incentive and mandates on fleets). The dramatic expansion of ethanol supply in LDVs has been driven by federal mandates that led to the blending of ethanol with gasoline in low-level blends (current 10% ethanol, or E10).

  In recent years, penetration of FFVs in the LDV market has been growing steadily. As of late 2011, over 9 million FFVs (ethanol (E85) and gasoline) were registered in the United States (approximately 4% of all LDVs). New registrations of FFVs are at a pace of about 1 million/year (yr), comprising about 17% of total new registrations annually.[11] Energy Information Administration (EIA) estimates, however, that only 0.6 million of these FFVs actually operate on E85.[12]

  While FFVs currently comprise about 4% of the LDV fleet, consumption of E85 in 2010 was 90 million gallons of gasoline equivalent (GGE), or about 1% of total gasoline consumption.[13] Excluding ethanol in E10, total alternative fuel composition in 2010 is estimated at 457.8 million gallons, or only 0.3% of the total gasoline market (excluding diesel and biodiesel). Figure 1 illustrates the composition of alternative fuels consumed in the United States in 2010, with

Figure 1 – Consumption of Alternative Fuels by Fuel Type, 2010 (Excludes E10)



Notes: [1] Excludes ethanol blended with gasoline (E10)
[2] Excludes electricity generated internally by hybrid electric vehicles

Source: EIA Annual Energy Review. Available online at http://www.eia.gov/renewable/afv/index.cfm

natural gas accounting for half of consumption (on a GGE basis). This figure addresses alternative fuel use in FFVs and AFVs. The total of nearly 0.5 billion GGE is significantly smaller than the nearly 13 billion gallons of ethanol currently blended with gasoline for consumption in conventional vehicles with spark-ignition engines.

The symposium was focused on the LDV mass market, recognizing that there has been less activity as well as greater challenges than in LDV fleets or in medium and heavy-duty vehicle markets. Light-duty vehicles constitute 95% of total road vehicles and they account for 64% of the total liquid fuel consumption.

- **Increased domestic natural gas resources create new market opportunities:** The development of domestic unconventional natural gas resources creates opportunities to expand the role of natural gas in the transportation sector. The US natural gas resource base has been estimated to support about 90 years of natural gas supply at current production rates. The MIT *Future of Natural Gas* study estimated that a considerable portion of the shale resource base can be produced economically at prices between $4/thousand cubic feet (mcf) and $8/mcf.[14] Discussion of AFV technologies was motivated in part by the desire to explore vehicle technologies that could effectively utilize natural gas, either in the form of CNG or in the form of liquid fuels derived from natural gas.

Framing the Scope of the Symposium

Several key questions were posed to frame the symposium discussion. These include:

1. What are the most promising AFV technologies for use of liquid and gaseous fuels (excluding electricity)?

2. How do the technology, performance, cost, and other characteristics of various alternative vehicle/fuel combinations compare with conventional gasoline-powered LDVs?

3. What are the perspectives of vehicle manufacturers, fuel distributors, consumers, and policy makers regarding the difference in characteristics of alternative vehicle/fuel combinations?

4. What are the barriers posed by the existing fueling infrastructure, and how can these barriers best be overcome?

5. How will the different characteristics of AFVs (including fueling process) affect consumer preferences, and are the benefits of AFVs sufficient to stimulate consumer demand?

6. Do the societal benefits of a robust alternative fuel LDV market justify government policy intervention to stimulate deployment?

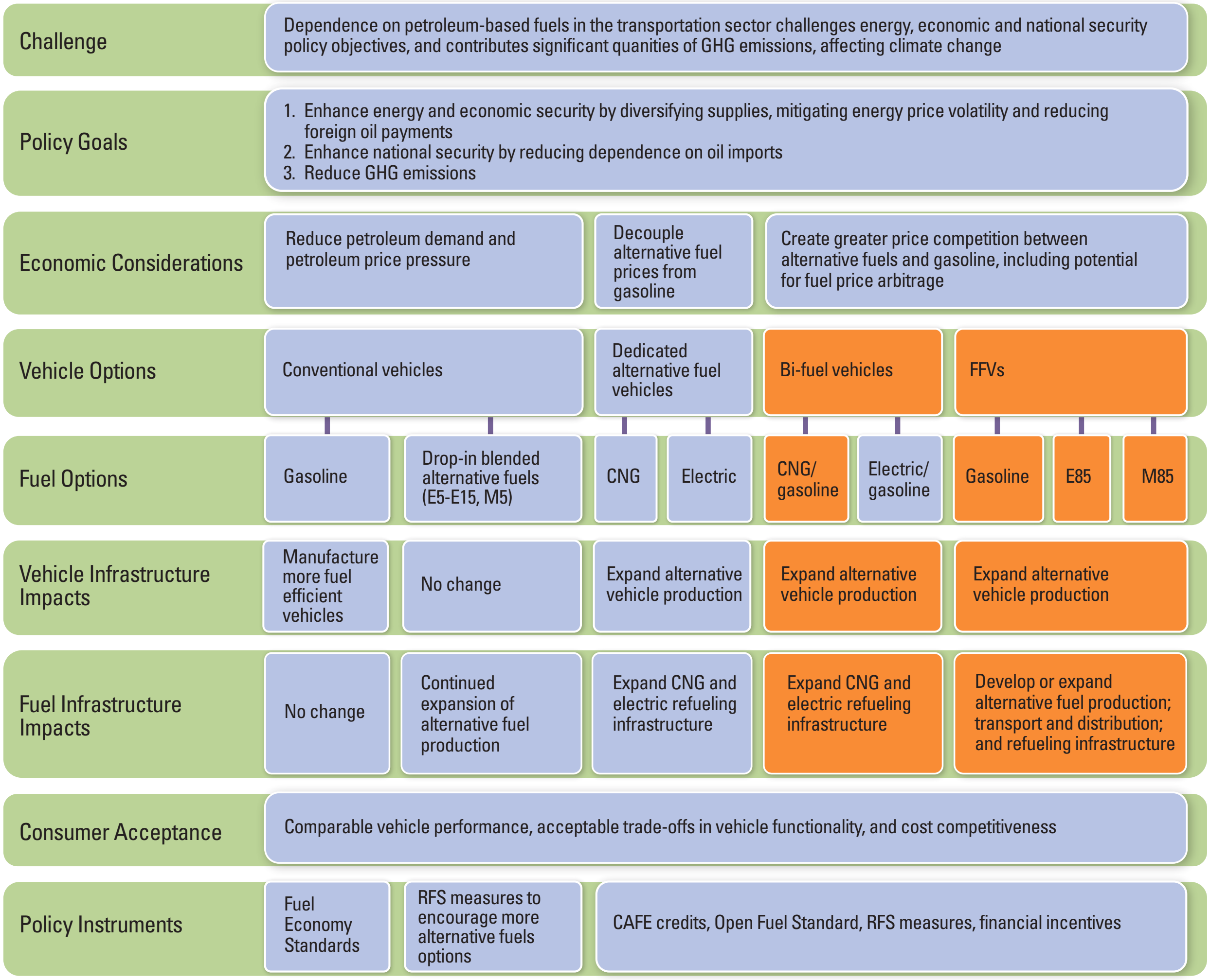
7. Is there a need for an alternative fuels program, or should the United States focus its policy efforts solely on increasing automotive fuel economy?

Establishing a Conceptual Framework of Alternative LDVs and Fuels

Consideration of AFVs and fuels involves a complex set of interrelationships among governmental policies, vehicle manufacturing, the fuel supply, and consumer acceptance. Adopting the policy challenges as the starting point, Figure 2 illustrates how the conceptual framework of vehicle technology options, fuel type options, infrastructure considerations, and alternative policy instruments interact. The framework identifies four major classes of LDVs: (1) conventional vehicles, (2) dedicated AFVs, (3) bi-fuel vehicles, and (4) FFVs. The principal fueling alternatives were then identified for each vehicle category. The discussion of vehicle technologies centered on the use of spark-ignition engines and compression-ignition engines using diesel fuel; other propulsion systems such as hydrogen-powered fuel cell vehicles were not considered. Prospects for electric vehicles (EV) and hybrid-electric vehicles (HEV)were discussed in depth in a previous MITEI symposium.[15]

Figure 2 also identifies that the various combinations of alternative fuels/AFVs are linked to the alternative fuel supply base and the availability of processing, distribution, and refueling infrastructure, whether it be integrated with the existing petroleum-based infrastructure or parallel to it.

Figure 2 – The Interaction of Policy, Technical, and Economic Constraints on Alternative Vehicle-Fuel Adoption, Deployment, and Use



<table>
<tr><td>Challenge</td><td colspan="9">Dependence on petroleum-based fuels in the transportation sector challenges energy, economic and national security policy objectives, and contributes significant quanities of GHG emissions, affecting climate change</td></tr>
<tr><td>Policy Goals</td><td colspan="9">1. Enhance energy and economic security by diversifying supplies, mitigating energy price volatility and reducing foreign oil payments
2. Enhance national security by reducing dependence on oil imports
3. Reduce GHG emissions</td></tr>
<tr><td>Economic Considerations</td><td colspan="2">Reduce petroleum demand and petroleum price pressure</td><td colspan="2">Decouple alternative fuel prices from gasoline</td><td colspan="5">Create greater price competition between alternative fuels and gasoline, including potential for fuel price arbitrage</td></tr>
<tr><td>Vehicle Options</td><td colspan="2">Conventional vehicles</td><td colspan="2">Dedicated alternative fuel vehicles</td><td colspan="2">Bi-fuel vehicles</td><td colspan="3">FFVs</td></tr>
<tr><td>Fuel Options</td><td>Gasoline</td><td>Drop-in blended alternative fuels (E5-E15, M5)</td><td>CNG</td><td>Electric</td><td>CNG/ gasoline</td><td>Electric/ gasoline</td><td>Gasoline</td><td>E85</td><td>M85</td></tr>
<tr><td>Vehicle Infrastructure Impacts</td><td>Manufacture more fuel efficient vehicles</td><td>No change</td><td colspan="2">Expand alternative vehicle production</td><td colspan="2">Expand alternative vehicle production</td><td colspan="3">Expand alternative vehicle production</td></tr>
<tr><td>Fuel Infrastructure Impacts</td><td>No change</td><td>Continued expansion of alternative fuel production</td><td colspan="2">Expand CNG and electric refueling infrastructure</td><td colspan="2">Expand CNG and electric refueling infrastructure</td><td colspan="3">Develop or expand alternative fuel production; transport and distribution; and refueling infrastructure</td></tr>
<tr><td>Consumer Acceptance</td><td colspan="9">Comparable vehicle performance, acceptable trade-offs in vehicle functionality, and cost competitiveness</td></tr>
<tr><td>Policy Instruments</td><td>Fuel Economy Standards</td><td>RFS measures to encourage more alternative fuels options</td><td colspan="7">CAFE credits, Open Fuel Standard, RFS measures, financial incentives</td></tr>
</table>

Source: MITEI.

The purpose of this framework was to establish a starting point for the symposium discussion from a comprehensive perspective of the LDV market. The framework is driven by policy and economic considerations. A recurring theme throughout the symposium discussion was whether the various options for alternative vehicles and fuels not only be cost effective but also whether they would exert downward price pressure if oil prices rose relative to other fuel feedstock. This issue of price coupling is discussed in detail later in the report. Within this comprehensive framework, the symposium focused on two alternative vehicle categories — bi-fuel vehicles and FFVs — and three alternative fuel options — natural gas, ethanol, and methanol.[16] While the symposium did not delve into other options, such as EVs or HEVs, the discussion was cognizant that gaseous and liquid fuel alternative vehicles ultimately would have to compete with electric-based options for consumer acceptance and market share.

- **Alternative fuel vehicle categories:** The framework identified the major AFV options, which are further defined in Table 1.

Table 1 – Types of Alternative Fuel Light-Duty AFVs[17]

Conventional fuel vehicle	Any vehicle engineered and designed to be operated using gasoline or a gasoline blend containing ethanol or methanol that can be dropped-into the vehicle without need for engine modifications.
Dedicated mono-fuel AFV	Any vehicle engineered and designed to be operated using a single source of alternative fuel. This category includes battery electric vehicles (BEV) and dedicated natural gas vehicles (NGV).
Bi-fuel vehicle	Any vehicle engineered and designed with two independent fuel systems, which can be operated on either of the two fueling systems separately, but not in combined operation simultaneously. This category includes gasoline/natural gas vehicles and plug-in hybrid electric vehicles (PHEV).
FFV	Any vehicle engineered and designed to be operated on a single fueling system that can accommodate mixtures of varying quantities of two or more liquid fuels that are combusted together. This category includes vehicles that can operate on either gasoline or E85 or gasoline and methanol (M85). This also includes vehicles with two liquid fueling systems that can operate individually or simultaneously, employing up to three liquid fuels (tri-flex fuel vehicles).

Source: MITEI.

- **Alternative fuel options:** In the introductory presentation, it was proposed that the categories of AFVs be further categorized by their ability to use either "drop-in" or drop-out" alternative fuels. The distinction between the two was based on physical fungibility with gasoline.

  A "drop-in" fuel is one that can be blended with gasoline and used in conventional gasoline-powered vehicles without requiring vehicle modifications.[18] The fuel's compatibility with the current gasoline distribution infrastructure is not a condition in defining the term. Thus, for example, gasoline blended with ethanol or methanol up to a certain limit and used in conventional spark-ignition gasoline vehicles without modification is considered a drop-in fuel. For this purpose, the blending limit for ethanol with gasoline is 15% (E5-E15),[19] and 5% for methanol with gasoline (M5); gasoline blends with higher ethanol or methanol content would require engine modifications.

  By comparison, a "drop-out" fuel is one that either cannot be blended with gasoline, or if so, requires modifications to the vehicle technology. These two types can be characterized as:

  - **Physical drop-out fuel:** a fuel that cannot be blended with gasoline, such as electricity or CNG; and

  - **Blendable drop-out fuel:** a fuel that can be blended with gasoline but cannot readily be used in a conventional gasoline-powered vehicle. Drop-out fuels include blends of ethanol or methanol exceeding current Environmental Protection Agency (EPA) approved blending limits (15% for ethanol, or 5% for methanol).

  Some participants believed that the distinction between drop-in and drop-out fuels had important implications for the pricing of alternative fuels as well as the question of whether consumers would actually realize cost savings from alternative fuel purchases. These participants believed that consumers would realize the benefits of lower prices for alternative fuels if the alternative were drop-out fuels, and not fully substitutable with gasoline. Others believed that the distinction between drop-in and drop-out fuels was less important in determining relative fuel prices as compared with the source of feedstock for the fuel. So, for example, methanol produced from natural gas would be priced more favorably than gasoline regardless of whether the methanol was used in a drop-in fuel (i.e., M5 blend) or a drop-out fuel (i.e., M85). The issue of the degree of coupling between the price of alternative fuels and the price of gasoline was a recurring topic of discussion throughout the symposium, with no final consensus position reached. The economics of price coupling are discussed in detail later in this report.

Key Issues Arising from the Symposium

The symposium discussion quickly revealed a more complex set of issues and a broad range of views on the framing questions. Symposium participants developed a better understanding of the key issues, but little consensus was achieved on specific conclusions and recommendations. Participants agreed that the evolution of the large-scale flexible and bi-fuel LDV market required large-scale quantities of competitively priced alternative fuels. But there was no consensus among the participants on either the preferred alternative vehicle-fuel combination or the public policy measures that would be most cost effective in effecting the transition. Some participants questioned the fundamental need for alternative vehicles and fuels altogether and instead favored fuel-efficiency standards as the preferred path to meeting the overarching policy challenges.

- **Vehicle/fuel options:** It became obvious at the beginning of the symposium that there was no established taxonomy of alternative vehicle and fuel options. Working from the conceptual framework in Figure 2, a detailed set of 11 possible combinations was developed. These are described in Appendix B. While this provided a useful benchmark, most of the symposium discussion centered on two principal combinations: bi-fuel vehicles capable of operation on either gasoline or natural gas, and FFVs capable of operating on a wide range of blends of gasoline, ethanol, or methanol.

  The current price differential between natural gas and petroleum is exceptionally large by historical standards. The historical rule-of-thumb price differential has been about 10-to-1 for a barrel of oil to 1,000 cubic feet (cf) of natural gas; at the time of the symposium, it was over 20-to-1. This makes use of natural gas economically attractive in vehicles. This market signal is currently incentivizing owners of heavy-duty vehicles in long-haul service to convert diesel-powered trucks to natural gas.

  What are the prospects for LDVs? Globally, almost 15 million LDVs have the capability to use natural gas as a fuel. The majority of these vehicles have bi-fuel capability, allowing them to take advantage of lower-cost natural gas where it is available. Bi-fuel vehicles powered by gasoline and natural gas are similar to gasoline vehicles in engine design and capability with regard to power, acceleration, and cruising speed. Due to the fuel's gaseous nature and lower energy content, however, NGVs require tank modifications that have different technical and economic trade-offs. Symposium participants discussed the trade-offs involved in the choice of fuel tank for CNG. For example, it was pointed out that the heavier but less expensive fuel tanks (i.e., the Type I fuel tank) reduce overall driving range, fuel economy, and cargo capacity more than the lighter but more expensive types (i.e., the Type IV fuel tank). Presenters noted that while this trade-off was very important in dedicated mono-fueled NGVs, the issue of reduced range was of less importance to consumers for the use of natural gas in a bi-fuel vehicle, since the gasoline mode was always available as an option.

Currently, only one automaker (Honda) in the United States offers an original equipment manufacturer (OEM) vehicle that is a dedicated NGV; there are no OEM bi-fuel vehicles. Conversions of gasoline-powered vehicles to dedicated NGVs have been incentivized for vehicle fleets through tax credits (for dedicated NGVs only, but not bi-fuel) and alternative fuel mandates for fleet vehicles. Larger-scale conversions in the light-duty fleet, either to dedicated NGVs or bi-fuel vehicles, have been challenged by cost considerations, EPA certification requirements, and fueling availability. Participants discussed a key impediment to bi-fuel vehicles, namely the lack of a CNG refueling infrastructure. Current CNG refueling stations are located along interstate highways, serving the long-haul heavy truck market, and at fleet operations centers providing central fueling to natural gas fleet vehicles. Home refueling systems were discussed as a possible solution, but currently the cost of such systems is an impediment, as the payback period may not justify the investment.

Participants generally agreed that a bi-fuel vehicle was valuable as an insurance policy or option. The greater the fuel price volatility, for instance, the greater the opportunity for the owner to exercise the option of fueling a vehicle with CNG instead of gasoline and arbitrage the prices. Or, in the event that CNG refueling stations were scarce, the owner would not be forced to change behavior and could continue to rely upon gasoline.

Flex-fuel vehicles have the distinct advantage of utilizing a wide range of blends of gasoline, ethanol, or methanol. The technology for FFVs is well established. In the late 1980s and early 1990s, one US automaker (Ford) manufactured gasoline-methanol FFVs for an extensive pilot program in California. Fuel distributors generally opted for methyl-tertiary-butyl-ether (MTBE) to meet Clean Air Act requirements for oxygenated fuels instead of methanol-gasoline blends. Subsequent concerns regarding the environmental impacts of MTBE coupled with a continued requirement (some would say unnecessary with advanced refining) for oxygenates, automakers then shifted to gasoline–ethanol FFVs. The establishment of alternative fuels credits as part of the federal Corporate Average Fuel Economy (CAFE) standards, combined with the mandate for ethanol production as part of the federal Renewable Fuels Standard (RFS) has led to the manufacture and sale of approximately 1 million FFVs annually.[20]

Owners of FFVs have the opportunity to utilize gasoline or E85 ethanol blend interchangeably, enabling them to take advantage of price arbitrage among the fuels. While promising in theory, FFVs have not gained significant acceptance in the United States due to the fact that the distribution of E85 is limited; where it is available, it is not always less expensive, and it has a lower driving range.

Current FFVs are not certified to operate on gasoline-methanol blends exceeding M5. Presenters at the symposium offered a new option: a GEM blend with similar stoichiometric properties to E85, making it a potential substitute and possibly facilitating the introduction of methanol into the current fleet of FFVs. While the combustion characteristics of GEM blends were similar to E85, participants noted that other issues, such as fuel system engine materials and sensors and gauges could be adversely affected by this alternative. Another option for methanol use involved minor vehicle modifications to add a second tank. In the "two-tank" FFV, one tank could hold gasoline and the second tank could hold methanol or ethanol or gasoline blends containing a high concentration of either alcohols.

The alcohol in the second tank is directly injected into the engine when needed to prevent engine "knock" that would otherwise occur at high torque. This "alcohol boosted gasoline engine "concept would allow the engine to be optimized (e.g., higher compression ratio and a higher level of turbocharging) for higher fuel efficiency and/or better performance. While it is still in the research and development stage, this system represents a substantial technological advancement. Concerns were however raised about methanol in general, centering on the experience with MTBE.

- **Price coupling:** There was considerable discussion throughout the symposium about the potential for alternative fuels to offer cost savings to consumers. There was general agreement among the participants that two conditions were necessary for greater market penetration of alternative vehicles and fuels: 1) the price of alternative fuel needed to be lower than the price of gasoline on an energy-equivalent basis, and 2) this price-spread, between gasoline and the alternative fuel, had to be reliably sustained over time. Maintaining a spread between the price of alternative fuels relative to the price of gasoline was referred to as the price decoupling. If alternative fuels could be produced at a lower cost than the price of gasoline, and if the alternative fuel supplies were prices at their marginal cost of production, then the price behavior of alternative fuels would be "decoupled" from gasoline prices. If, on the other hand, suppliers of alternative fuels priced their product at or near the price of gasoline, then alternative fuels would be price-coupled to gasoline. However, participants were in fundamental disagreement regarding which alternative vehicle fuel options could satisfy these criteria, currently or in the near term, and how this might be achieved.

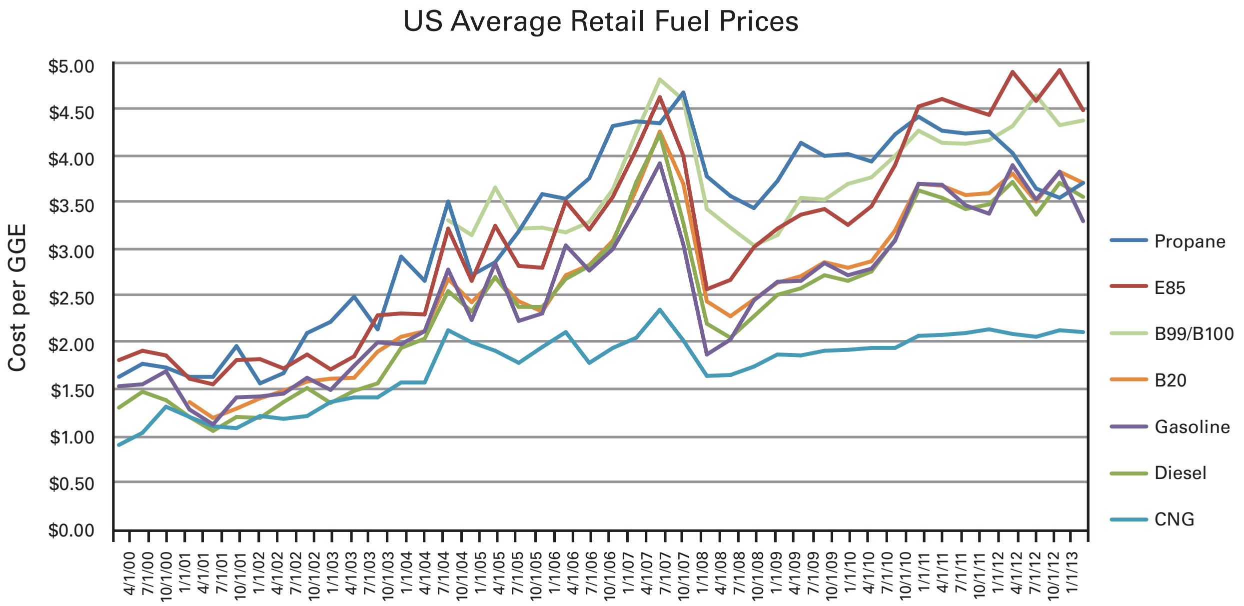
    – Some participants noted that the prices of alternative liquid fuels typically were only slightly discounted relative to gasoline prices, and that alternative fuel prices generally tracked both the long-term prices and short-term price volatility of gasoline, as shown in Figure 3. The only exception is natural gas. These participants concluded that drop-in fuels employing blends of alternative fuels would generally be price-coupled to the price of gasoline.

    – Other participants believed that the use of different feedstock could lead to greater price decoupling, regardless of whether the fuel was drop-in or drop-out. For example, while the price of corn-based ethanol was generally comparable to or higher than gasoline (on an energy-equivalent basis), production of ethanol from another feedstock could result in a lower cost. Similarly, natural gas to methanol conversion that took advantage of ample domestic gas supplies combined with new large-scale conversion plants could achieve lower methanol costs than the current US price for methanol imported in relatively small quantities. Some participants noted that production of alternative fuels in large quantities might not only be price-decoupled, but actually exert downward pressure on gasoline prices.

The differences between these two viewpoints centered on the question as to whether producers and distributors of alternative fuels would be willing to pass through the lower cost of production in the form of lower fuel prices, to establish market position, or whether gasoline, as the marginal fuel, would set the market price regardless.

Other participants believed that the only way for consumers to achieve cost savings from alternative fuels was from a drop-out fuel vehicle in which there was no fuel relationship to petroleum; this is currently limited to natural gas or electric vehicles. For example, a recent study examined the statistical relationship between natural gas and petroleum prices and found that, in the short term, there was an enormous amount of unexplained volatility in natural gas prices, and that, over the long term, the relationship does not appear to be stable.[21]

Figure 3 – Relationship among the Prices of Various Alternative Fuels



Source: Clean Cities Alternative Fuel Price Reports, http://www.afdc.energy.gov/fuels/prices.html

In addition, the possibility of home refueling systems for both EVs and NGVs would mean that consumers would be paying a price commensurate with the residential price of these fuels. In the case of natural gas, the cost of the home compressor also would need to be factored in. The cost of refueling with a home CNG compressor and residential natural gas rates would yield a cost of CNG fuel in the range of $3–$5 per GGE; decoupling would be achieved but not necessarily a lower fuel price.[22] In the case of residential electricity, the cost of installing special charging equipment also needs to be considered.

Participants did not achieve a consensus view on how alternative fuels would be priced in the marketplace and in fact, had strongly competing views. This suggests the need for additional, rigorous study and analysis of these issues.

- **Consumer choice:** Participants discussed the attributes of AFVs and fuels that would affect consumer choice. While participants drew some observations about consumer choices, they noted that there were few available methods to model consumer behavior. Participants noted that each of the economic models that could be used to understand and forecast consumer behavior had particular limitations. Participants discussed several attributes of AFVs and fuels that would impact consumer choice, including vehicle performance, functionality, ease of fueling, safety, and most importantly, cost competitiveness.

  Bi-fuel vehicles require vehicle modifications that can compromise certain key vehicle attributes that are important factors in consumer choice. These include cargo capacity, fuel economy, and driving range. Consumers will need to carefully evaluate the trade-off of having continued reliance on gasoline fueling and cost savings. Apprising consumers of the costs of these trade-offs to inform their decisions and choices would likely require a significant public education effort.

Flex-fuel vehicles utilizing gasoline and E85 mixtures are already on the road and appear to have gained consumer acceptance. The introduction of methanol as a flex-fuel may pose challenges. There are concerns about methanol toxicity (although the overall risk is similar to gasoline). Methanol requires additional safety measures such as sufficient gasoline content to ensure flame visibility and the addition of bitterants to deter ingestion, but it would cause fewer deaths by energy release in a car crash. Some symposium participants believed that public perception of methanol's risks may be exaggerated, creating additional challenges for achieving public acceptance. The prospect for achieving sustainable cost savings could serve as a key countervailing element in winning consumer acceptance. Others noted the lack of consumer utilization of the E85 option.

Participants appreciated the experiences of alternative fuels deployment in other countries, but questioned their application in the US market. On the whole, the adoption and deployment of AFVs have been much more rapid internationally than domestically (including CNG use in Europe and the introduction of methanol in China). Some of the drivers for these differences include vehicle cost competitiveness, fuel backward compatibility, and strong government involvement in building fuel distribution infrastructure. Participants noted that the key lessons learned from experiences in other countries included:

1. Cost competitiveness is the most important requirement for new alternative fuels to attract consumers at scale.

2. Backward compatibility of a vehicle greatly facilitates successful market penetration.

3. Sufficient fuel distribution infrastructure for alternative fuels is necessary for market penetration at scale.

4. Bi-fuel capability is very important for AFVs that are not backward compatible to the vehicle fleet and/or supported by a sufficient supply infrastructure.

5. The widespread availability of relatively low cost and easily adoptable retrofit kits can significantly help to develop an alternative fuel market (e.g., Liquefied Petroleum Gas (LPG) in Europe; CNG in Italy, Pakistan, India) because they allow the conversion of used vehicles already in the fleet.

6. Most alternative fuels have shorter travel ranges than gasoline or diesel. Shorter travel ranges should be compensated by other positive features of alternative fuels.

7. Incentives for sustainable alternative fuels are initially required if they have higher production and/or distribution costs than gasoline/diesel (after tax) in order to be affordable and cost competitive.

8. For any alternative fuel, there must be enough feedstock available to develop and sustain the market in the long term while maintaining a competitive fuel price.

- **Government policy role:** Current governmental policies provide incentives for both the manufacture of AFVs and the establishment of alternative fuel distribution facilities. Symposium participants acknowledged that there has been progress in the medium- and heavy-duty vehicles arena, principally because these can be operated as centrally managed and fueled fleets.

  Participants acknowledged that there has been limited alternative fuel penetration of the LDV market — both the numbers of AFVs and the availability and volumes of alternative fuels are insufficient to “bootstrap” each other sufficient to have a material impact on the market. Even with improvement in these areas, the long fuel savings payback time for standard driving would remain a challenge. Some participants argued that gasoline should be allowed to compete with other alternative fuels in order to lower prices, while others noted that federal assistance in infrastructure development was crucial to enable the fuels to effectively compete.

  A threshold issue was whether government policy should rely principally on increasingly stringent fuel economy standards as the policy mechanism of choice for meeting the set of public goods articulated earlier.

  Some participants noted that proposed new CAFE standards will have significant benefits, and that government policy should not complicate these standards by simultaneously promoting the deployment of AFVs. Other participants noted that there are limits to efficiency standards, including: the documented problem of the rebound effect (i.e., a portion of the fuel savings from increased efficiency is offset by an increase in vehicle miles driven); financial cost avoidance by maintaining older, less efficient vehicles in service for longer periods; and diminishing fuel economy improvements as CAFE standards become more stringent. These participants believed that government policies to promote the use of AFVs and fuels could complement a national strategy of increased fuel economy in the LDV fleet. Such measures could provide “policy signaling” that could stimulate market-driven efforts as well.

  Participants who favored an increased government role also believed that government policy should not seek to identify particular “winners and losers” among various alternative vehicles and fuels options. Participants discussed the merits of an Open Fuel Standard that would provide a relatively low-cost policy to assure large-scale manufacturing of various types of AFVs — dedicated “mono-fuel,” bi-fuel, and flex-fuel. In addition, participants discussed the importance of public education programs to assist consumers in making sound choices among competing AFVs and fuels. Finally, participants discussed increased federal investments in RD&D and innovation in order to enhance the technological capabilities and cost effectiveness of AFVs and fuels. Participants noted that current policies that focused on extant vehicle technologies may be placing too much emphasis on “low-hanging fruit.”

Guide to the Report

The remaining sections of the report discuss these issues in greater detail. The sections are organized from the perspective of the three major players in the alternative fuels market — the vehicle technology and manufacturing perspective, the fuel distribution perspective, and the consumer perspective — and the government policy perspective.

SECTION 2 VEHICLE TECHNOLOGY AND MANUFACTURING PERSPECTIVES

Overview

The key characteristics defining the distinction among dedicated, mono-fuel, bi-fuel, and flex-fuel vehicles with spark-ignited engines are the number of fuel tanks, the fuel delivery components, control systems, and the changes in engine control settings. For purposes of the symposium discussion, several alternative configurations were considered as shown in Table 2. Specific vehicle and operational modifications for each configuration are discussed in further detail in this section.

Table 2 – Configurations of AFVs and Fueling Systems

	Mono-fuel (dedicated)	Bi-fuel	Flex-fuel	
Number of tanks	One	Two	One	Two
Fuel combustion	Only one fuel	Each fuel separately	Fuels simultaneously	Fuels simultaneously or separately
Liquid fuels	Yes	No	Yes	Yes
Liquid fuel mixtures	No	No	Yes	Yes
Gaseous fuels	Yes	Yes	No	No
Fuel types	• Gasoline • CNG	Tank 1: Gasoline Tank 2: CNG	Optimized for E85	Tank 1: Gasoline Tank 2: Ethanol, methanol

Source: MITEI.

Dedicated Mono-Fuel Vehicles

In 2009, the United States had a total of about 245 million vehicles on the road, of which about 235 million were light-duty cars — passenger cars, sport utility vehicles (SUV), and light trucks (the remainder were buses and medium- and heavy-duty trucks).[23] Only 4% were vehicles with either dedicated fuels (other than gasoline or diesel fuel) or flex-fuel systems.

Natural Gas Vehicles

Other than gasoline and diesel, the only significant dedicated mono-fuel vehicles are NGVs. Currently, there are about 116,000 NGVs in the United States.[24] One estimate is that over 80% of these vehicles are predominantly dedicated CNG fleet vehicles that are unable to operate on gasoline.[25] (This pattern is very different from the global market, where most NGVs are bi-fuel vehicles). The deployment of dedicated NGVs has largely been driven by government policy:

- Purchases of dedicated NGVs have been eligible for federal tax credits (bi-fuel vehicles are not);[26] and
- Many dedicated NGVs were purchased by state governments and alternative fuel provider fleets to comply with the requirements of the Energy Policy Act of 1992.[27]

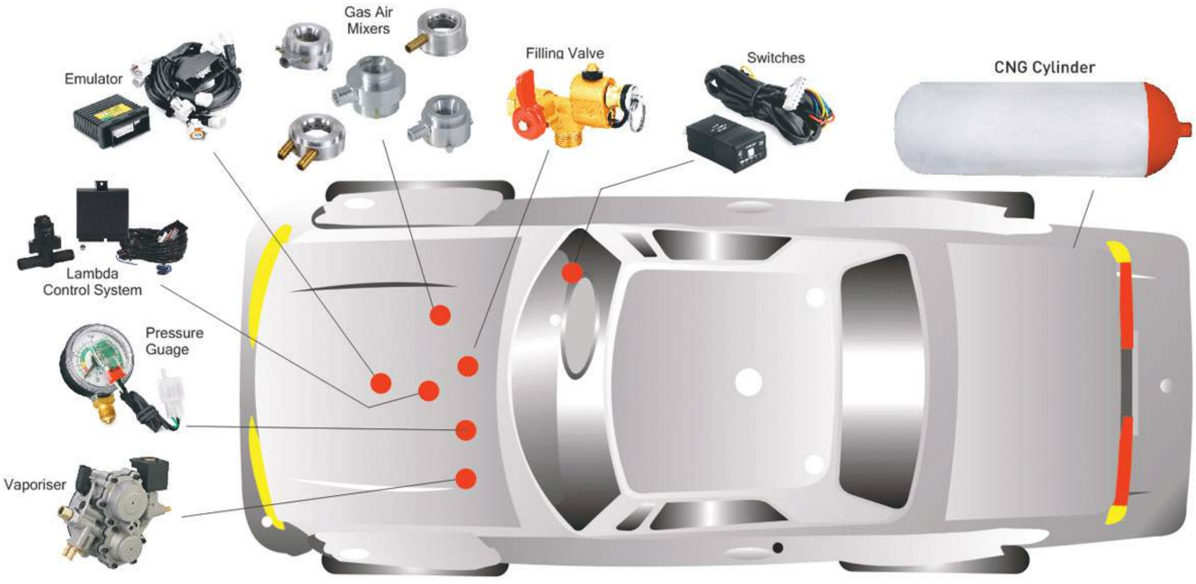
In the United States, dedicated NGVs typically operate on CNG. (Some long-haul heavy-duty trucks are being converted to operate on LNG. Dedicated NGVs can either be offered by OEMs or NGV capability can be retrofitted to conventional gasoline-powered vehicles.

Currently, Honda is the only OEM offering a NGV, the Honda GX model. Market penetration of dedicated NGVs in the United States has been primarily aftermarket conversions of gasoline vehicles by small volume manufacturers. Conversions have been concentrated in specific models, because of EPA certification requirements established under the Clean Air Act. A small volume manufacturer must obtain EPA certification for each make and model to be converted. The cost of obtaining an EPA certification has been estimated to be as much as $200,000 per vehicle make and model.[28] This cost is then amortized over the number of vehicles converted to operate as NGVs. It is estimated that a certified conversion by a small vehicle manufacturer costs an additional $10,000 compared to the price of a comparable gasoline-powered vehicle.

Engine Design and Vehicle Performance

Figure 4 illustrates the modifications to enable a spark-ignition, gasoline-fueled vehicle to operate on natural gas. The hardware modifications are designed to deliver comparable vehicle performance (although with considerably less range with CNG). Because CNG has a higher octane rating than gasoline, engine controls can be optimized for greater performance and fuel economy. However, to maximize performance potential, the engine cylinder compression ratio would need to be increased, which is typically not implemented in engines originally manufactured for gasoline operation. Increasing the compression ratio to improve fuel economy with CNG would prevent acceptable gasoline operation (because of engine knock).

Figure 4 – Modifications for CNG-Dedicated Vehicles



Source: http://www.mijoautogas.co.in/cng-mixer-system-lambda-control-stystem.htm

Economics of Dedicated NGVs

Participants discussed the fact that NGVs have a higher initial vehicle cost than conventional gasoline-powered LDVs as shown in Table 3. Several different perspectives were provided on the magnitude of this cost premium. Data from Honda, which is the only producer of dedicated NGVs in the United States, shows the retail price for the Honda Civic GX model is $26,305, while its equivalent gasoline model is $18,360 — a premium of about $8,000 in retail price. However, presently Honda is offering a $3,000 fuel card upon purchase of its GX model, effectively making the cost premium about $5,000.

Table 3 – Cost Comparison of Dedicated NGV and Conventional Gasoline-Powered Vehicle

Vehicle Make and Model	MSRP	(Miles per Gallon (MPG)
Honda Civic GX (dedicated CNG)	$26,305	28
Honda Civic LX (dedicated gasoline)	$18,360	29

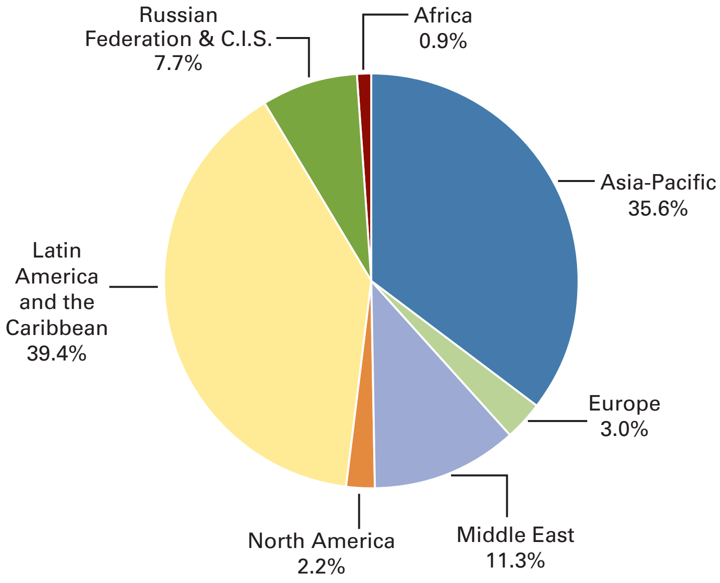
Source: Honda.com

The cost premium for NGV conversions by small volume manufacturers is higher, with estimates of $10,000 or more per vehicle.[29]

Bi-Fuel Vehicles

The most common type of bi-fuel vehicle is one that can operate on either gasoline or CNG. Currently, bi-fuel vehicles are primarily in other countries than the United States. It is estimated that there are more than 14.8 million vehicles worldwide that can operate on natural gas.[30] The majority of these vehicles are bi-fuel. The geographical distribution of natural gas capable vehicles is predominantly in developing countries in Latin America, Asia-Pacific, and to some extent, the Middle East as shown in Figure 5.

Figure 5 – Global Distribution of Mono-Fuel and Bi-Fuel NGVs, 2010



Regional NGV Distribution – 2010

Source: J. Seisler, Clean Fuels Consulting working paper to TIAX on "International Perspective NGV Market Analysis: Light- and Medium-Duty Vehicle Ownership and Production," April 2011.

- **Bi-fuel vehicle technology and fueling systems:** Bi-fuel vehicles operate with a conventional spark-ignition engine on either gasoline or CNG stored in two separate tanks, but are not combusted simultaneously. This requires modifications in the vehicle design to accommodate two tanks — a gasoline tank and a new CNG-optimized tank to withstand pressures of the gas — an engine that can operate between the two fuels, and a fuel processing system (e.g., fuel regulator, injector, engine management, manual switch) that can switch fuel operations. The fuel system technology to support the CNG mode is similar to that in a dedicated NGV. The additional requirement is for an engine control system that allows switching between fuels, with the ability to modify engine settings to optimize engine performance for either fuel.

  A CNG bi-fuel vehicle has a second fueling system, fuel tank, and fuel delivery system completely separate from the conventional gasoline fueling system. The modifications to a gasoline vehicle necessary to achieve bi-fuel generation are shown in Figure 6. The four basic types of CNG fuel tanks are illustrated in Table 4. Each of the four meet the same performance and safety requirements, such as resistance to temperature extremes (-40°F to +185°F), multiple fills (pressure changes), cargo spillage, vibration, vehicle fires, corrosion, and collision. There are considerable differences, however, in the choice of material, weight, and cost. Weight is a critical parameter. For LDVs, fuel consumption is reduced by 0.6%–0.9% for every 3% increase in weight.[31]

Table 4 – Various Types of CNG Fuel Tanks

Tank Design	Material	Cost	Weight
Type 1	All metal (aluminum or steel)	Least expensive	Heaviest
Type 2	Metal liner partially reinforced by composite wrap (glass or carbon fiber) around middle ("hoop wrapped")	↓	↑
Type 3	Metal liner reinforced by composite wrap around entire tank ("full wrapped")		
Type 4	Plastic gas-tight liner reinforced by composite wrap around entire tank ("full wrapped")	Most expensive	Lightest

Source: http://www.cleanvehicle.org/technology/CNGCylinderDesignandSafety.pdf

Figure 6 – Components to Convert and Operate Conventional Vehicles with CNG

Note: Attached to the fuel tank [1] is the regulator [2], which reduces tank pressure from 3,600 psi to 125 psi. Fuel is then fed to a parallel fuel rail [3] and to new, secondary injectors plugged into an adapter [4]. A wiring harness [5] plugs into the factory engine-control unit and intercepts throttle information, sending it to a new fueling computer [6], which slightly alters the data and passes it to the CNG injectors [7] through a parallel wiring harness [8].

Source: http://www.popularmechanics.com/cars/how-to/maintenance/should-you-convert-your-car-to-natural-gas-2

The CNG fuel delivery system is illustrated in Figure 6.

There currently are no US OEM bi-fuel vehicles and a relatively limited number of aftermarket conversions to bi-fuel operation. In contrast, the majority of NGVs in other countries are bi-fuel vehicles that have been aftermarket conversions. These conversions have been motivated by market forces, i.e., a relatively short payback period resulting from a combination of low-cost conversion kits and installation as well as having fewer emission controls and no OEM certification requirement.[32] However, with continued higher gasoline prices, Europe has moved steadily toward OEMs, which currently have at least 12 OEM bi-fuel vehicle models.[33] As European OEMs expand their bi-fuel vehicle offerings, further market segmentation is taking place. Some bi-fuel vehicle models have larger CNG and small gasoline tanks, intended primarily for natural gas use, while others have larger gasoline tanks with slightly smaller CNG tanks. The European Union (EU) currently classifies bi-fuel vehicles with gasoline tanks less than 15 liters as mono-fuel, even though these vehicles have bi-fuel capability.[34]

CNG bi-fuel vehicles are similar to dedicated gasoline mono-fuel vehicles with regard to power, acceleration, and cruising speed. Due to the lower energy density of CNG relative to gasoline, and the additional weight associated with the CNG fuel tank, CNG bi-fuel vehicles have a shorter driving range, lower fuel economy, and less cargo capacity. Consumer perspectives on these trade-offs are discussed in detail in Section 4.

Economics of CNG Bi-Fuel Vehicles

Domestically, OEMs have produced only CNG-dedicated fuel vehicles, and not bi-fuel vehicles. As described earlier, the present cost premium in the United States for a CNG-dedicated vehicle is currently about $5,000, reflecting the effects of incentives relative to a comparably equipped gasoline vehicle. Information presented to symposium participants showed a cost premium in Europe of approximately €3,500 (USD 4,500).[35] Symposium participants believed that bi-fuel vehicles could be offered by OEMs in the United States for a comparable premium. Participants also discussed that CNG bi-fuel capability could be retrofitted to gasoline vehicles. Conversions of gasoline vehicles to dedicated NGV use cost about $10,000;[36] participants believed that conversions to bi-fuel operation would be about the same. Some participants noted that aftermarket conversion costs were significantly lower in other countries, for example, the cost of conversion in Singapore is reported to be about $2,500.[37]

Flex-Fuel Vehicles

Conceptually, FFVs can operate with a mixture of more than one liquid fuel. The United States currently has 9 million registered FFVs on the road, representing about 4% of all LDVs.[38] These vehicles are capable of operating on either gasoline or E85 or mixtures of the two. Symposium participants considered a broader range of alternates, including tri-flex fuel vehicles capable of operating on gasoline, ethanol, or methanol in various combinations. For tri-flex fuel mode, participants considered two alternative fueling options: 1) a single tank operation with up to three blended fuels (gasoline, ethanol, and methanol) that are combusted simultaneously; and 2) a two-tank system where one tank contains gasoline and the other tank contains a blend of high concentrations of either ethanol or methanol with gasoline as a supplemental fuel. This arrangement is also referred to as “dual-fuel” operation, where the two fueling systems could be operated either standalone or simultaneously. Presently, FFVs on the road in the United States do not use the two-tank system.

Flex-fuel vehicles on the market today are optimized to operate on gasoline or E85, and not on methanol blends, which technically makes them bi-flex fuel vehicles. However, symposium participants did receive a presentation on a proposed ternary mixture of gasoline, ethanol, and methanol (GEM fuel) that has the same stoichiometric properties of E85. Such a mixture may provide an option for introducing methanol into existing FFVs originally designed for operation with only gasoline or ethanol.

Vehicle Technology Modifications[39]

Flex-fuel vehicles are designed to operate with much higher concentrations of alcohols (ethanol and methanol) in fuel mixtures than the current gasoline content of 10% ethanol. Alcohol fuels have several fuel properties that differ from gasoline. Alcohol fuels (1) have lower energy density; (2) are electrically conductive; (3) are more corrosive to metal, rubber, and plastic materials; (4) have higher oxygen content, affecting the stoichiometry of combustion; and (5) have higher evaporative emissions. These factors drive the nature and types of technology modifications in FFVs.

The modifications can be illustrated by consideration of current FFVs which are designed for bi-flex fuel operation with either gasoline or E85, as shown in Figure 7.

Figure 7 – Special Features of the FFV[40]

Engine calibration updates: Fueling and spark advance calibrations directed by vehicle computer to control combustion, enable cold start, and meet emissions requirements

Fuel system electrical connections and wiring: Must be electrically isolated and made of materials designed to handle ethanol's increased conductivity and corrosiveness (if exposed to fuel)

Fuel pump assembly: In-tank components must be made from ethanol-compatible materials and sized to handle the increased fuel flow needed to compensate for ethanol's lower energy density

Internal engine parts: Piston rings, valve seats, valves, and other components must be made of ethanol-compatible materials that are designed to minimize corrosion and the cleansing effects of alcohol fuels, which can wash lubrication from parts

Fuel filler assembly: Includes anti-siphon and spark-arrestor features

Fuel identifier system: Automatically senses the composition of the fuel and adjusts engine for varying ethanol-gasoline blends

Fuel injection system: Must be made of ethanol-compatible materials and designed for higher flow to compensate for ethanol's lower energy density

Fuel rail and fuel lines: Must be made of ethanol-compatible materials with seals, gaskets, and rubber fuel hoses rated for ethanol use

Fuel tank: Must be made of ethanol-compatible materials and designed to minimize evaporative emissions from ethanol

Source: Flexible Fuel Vehicles, Alternative Fuels Data Center

- **Fuel tank:** Because of ethanol's lower energy density, the driving range for a given size fuel tank is lower for ethanol operation than gasoline operation. To compensate for this difference, fuel tanks may need to have larger capacity to provide a comparable driving range relative to gasoline-only operation. Tanks also need to be fabricated from ethanol-resistant materials, which can include special coatings to existing tank materials. The design of the tank should minimize evaporative emissions. In addition, the fuel filler assembly should have anti-siphon and spark-arresting features.

- **Fuel delivery system:** The fuel sender and the fuel pump materials need to be alcohol compatible and the pump needs to be designed for higher flow rates and pressures to compensate for the lower energy density. Fuel lines and fuel rails, including seals, gaskets, and rubber hoses, should be made of ethanol-compatible materials, such as stainless steel, and be designed for higher pressures. Fuel injectors should utilize materials that are corrosion resistant and should be designed for higher injection pressures. Electrical connections and wiring should be isolated from and made of materials that are unaffected by the increased electrical conductivity of alcohols.

- **Other engine components:** Internal engine parts, including valves and piston rings, should be designed to withstand the corrosiveness and cleaning effects on metals. Lubricant specifications also may require changes. Engine controllers need additional software capability and sensor systems need to be able to continuously sense the incoming alcohol/gasoline composition and adjust air-fuel mixtures and spark timing for optimal performance.

Figure 8 – Illustration of Dielectric Flex-Fuel Sensor (by Duralast)

Source: autozone.com, available at http://www.autozone.com/autozone/parts Duralast-Flex-Fuel-Sensor/_/N-8veh0?itemIdentifier=910217_0_0_

A key element of FFV technology is the flex-fuel sensor, which monitors fuel composition and signals the powertrain control module (PCM) to adjust engine operation (e.g., air-fuel ration and ignition timing) accordingly. The commonly used sensor is an oxygen sensor that can infer the alcohol-gasoline composition based on the oxygen content of the blend. An alternative technology is a dielectric sensor that can measure electrical conductivity of the fuel, with higher conductivity associated with higher concentrations of alcohol in the fuel blend. An example of a dielectric sensor is shown in Figure 8.

Economics of FFVs

Current FFVs, which are certified to operate on either gasoline or E85 (and mixtures of each), do not carry a cost premium relative to comparably equipped gasoline mono-fuel vehicle models. From the outset, FFVs (designed for methanol as the flex-fuel) were generally sold without a price premium relative to comparable gasoline-only versions, despite higher production costs for engineering, tooling, materials, and controls.[41, 42] In 1983, Ford sold a test fleet of Ford Escorts to California at a price premium of $2,200.[43] However, it was believed that the price premium would disappear at higher production volumes, as experience in Brazil with production of ethanol vehicles had shown.[44] So the actual cost premium is unknown. Some symposium participants noted that ethanol flex-fuel capability was essentially provided without incremental cost to consumers because the costs to OEMs were minor. Others suggested that the costs were absorbed by the OEMs in return for the benefits garnered by OEMs from the CAFE credits for producing vehicles with alternative fuel capability. The provisions of the CAFE regulations affecting credits for AFVs are discussed in detail in Section 5.

Symposium participants also discussed the feasibility of operating gasoline mono-fuel vehicles on alcohol fuels, without vehicle modification. They pointed out that many current gasoline mono-fuel vehicles are mechanically capable of operating with alcohol fuels such E85, but are not operationally optimized for them. Such operation would produce inaccurate readings of fuel gauges and the speedometer due to the lower energy density of alcohol fuels. Some participants also noted that operation of conventional vehicles with ethanol would not be feasible on a long-term basis, because the vehicles would sustain damage over time to fuel lines, seals, and valves, among other areas, due to the corrosive properties of alcohol fuels.

Participants also discussed aftermarket conversion of gasoline mono-fuel vehicles to flex-fuel capability. Conversions to flex-fuel operation would require vehicle modifications in three areas: engine, tank design, and fuel processing system. While some participants believed aftermarket conversions were feasible, some necessary parts are not readily available in the aftermarket. Also, there can be challenges in modifying engine controllers to be able to manage flex-fuel operation, depending upon the degree of flex-fuel operation.[45]

FFV/Fuel Combinations

Current FFVs are bi-flex vehicles designed to operate on gasoline, ethanol E85, or mixtures. Symposium participants discussed the possibility of flex-fuel operation with methanol. Current gasoline mono-fuel vehicles and gasoline/ethanol FFVs are EPA-certified to accept methanol-gasoline blends not to exceed 5%, as shown in Table 5. Because of the RFSs for ethanol, gasoline distributors use ethanol almost exclusively, thereby resulting in little or no use of M5 blends.[46]

Table 5 – Approved Methanol Gasoline Blends with Requirements for Co-Solvent Alcohols and Additives

Market Region		Introduction Year	Maximum Volume % Methanol	Minimum Volume % Co-Solvent	Maximum Wt % Oxygen	Corrosion Additives
Europe	EC Directive	1985	3.00	⩾ Methanol	3.7	
United States	Sub Sim*	1979	2.75	⩾ Methanol	2.0	
United States	Fuel Waiver	1981	4.75	⩾ Methanol	3.5	Required
United States	Fuel Waiver	1986	5.00	2.5	3.7	Required
China, Shanxi	M15 Standard	2007	15.00	For Water Tolerance	~7.9	Required

*US EPA's Substantially Similar Regulation for commercial gasolines.

Source: Methanol Gasoline Blends, Methanol Blending Technical Product Bulletin, Methanol Institute.

Participants noted that many of the vehicle modifications needed to permit operation with E85 would also support use of higher blends of methanol (e.g., up to M85). However, additional vehicle modifications would be needed to address characteristics of methanol that differ from ethanol, such as the potential for higher levels of evaporative emissions.

Table 6 compares the physical and chemical properties of various alternative fuels relative to conventional gasoline.

Table 6 – Comparison of Fuel Properties

	Gasoline	CNG	Ethanol	Methanol	n-Butanol
Chemical Structure	C4 to C12	CH4 (83%–99%) C2H6 (1%–13%)	CH_3CH_2OH	CH_3OH	C_4H_9OH
Physical State	Liquid	Compressed Gas	Liquid	Liquid	Liquid
Main Fuel Source	Crude Oil	Underground reserves	Corn, grains, or agricultural waste (cellulose)	Natural gas, coal, or woody biomass	Corn, biomass, cellulose, yeast
Energy Density	32 MJ/L	–	19.6 MJ/L	16 MJ/L	29.2 MJ/L
Specific Energy	2.9 MJ/kg air	–	3.0 MK/kg air	3.1 MJ/kg air	3.2 MJ/kg air
Heat of Vaporization	0.36 MJ/kg	–	0.92 MJ/kg	1.2 MJ/kg	0.43 MJ/kg
Pump Octane Number*	84-93 (a)	120+ (b)	110 (c)	112 (c)	96
Research Octane Number** (RON)	91-99	130	108.7	108.6	92-103
Motor Octane Number (MON)[†]	81-89	120	89	92	78
Energy Content (Lower Heating Value)	116,090 Btu/ gal (d)	20,268 Btu/lb (d)	76,330 Btu/gal for E100 (d)	57,250 Btu/gal (d)	110,000 Btu/gal
Energy Content (Higher Heating Value)	124,340 Btu/ gal (d)	22,453 Btu/lb (d)[‡]	84,530 Btu/gal for E100 (d)	65,200 Btu/gal (d)	–
Energy Contained in Various Alternative Fuels as Compared to One Gallon of Gasoline[§]	100%	5.66 pounds or 126.67 cf of CNG has 100% of the energy of one gallon of gasoline.[14]	1 gallon of E85 has 77% of the energy of one gallon of gasoline.[^]	1 gallon of methanol has 49% of the energy of one gallon of gasoline.	–
Air-Fuel Ratio	14.6	14.2	9.0	6.4	11.1

Table 6 – Comparison of Fuel Properties (continued)

	Gasoline	CNG	Ethanol	Methanol	n-Butanol
Anti-Knock Index (AKI)	–	–	99.15	98.65	83-97
Fueling Stations (Private and Public)	104,845	988	2,498	–	–
Energy Security Impacts	Manufactured using oil, of which nearly 50% is imported (e).	CNG is domestically produced. The United States has vast natural gas reserves.	Ethanol is produced domestically. E85 reduces lifecycle petroleum use by 70% per passenger vehicle and E10 reduces petroleum use by 6.3% (f).	Methanol is domestically produced, sometimes from renewable resources.	Butanol is domestically produced, sometimes from renewable resources.
Maintenance Issues		High-pressure tanks require periodic inspection and certification.	Corrosive and hygroscopic. Special lubricants may be required. Practices are very similar, if not identical, to those for conventionally fueled operations.	Corrosive and hygroscopic. Special lubricants must be used as directed by the supplier and M85-compatible replacement parts must be used.	Toxicity at the rate of 20 grams per liter. Distillation technology is expensive.

* Pump octane number is the average of the research octane number and motor octane number.

** Octane as tested in a single-cylinder octane test engine operated under less severe operating conditions.

† Octane as tested in a single-cylinder octane test engine at more severe operating conditions.

‡ According to the AFDC, cubic feet units were not given because there were infinite combinations of temperature and pressure and their effect on fuel density. Instead, fuels were dispensed by Coriolis flow meters, which track fuel mass and report fuel dispensed on a GGE basis.

§ Energy comparisons are given in percent energy content on a gallon-to-gallon basis unless other units are given.

^ According to the AFDC, the ethanol content of E85 is usually lower than 85% for two reasons: 1) fuel ethanol contains 2%–5% gasoline as a denaturant and 2) fuel ethanol content is lowered to 70% in the winter in cold climates to facilitate cold starts. When the actual composition of E85 is accounted for, the lower heating value of E85 varies from 82,970 Btu/gal to 89,650 Btu/gal, which is 72% to 77% the heat content of gasoline.

Sources:

(a) Petroleum Product Surveys: Motor Gasoline, Summer 1986, Winter 1986/1987. National Institute for Petroleum and Energy Research.

(b) K. Owen and T. Coley. 1995. *Automotive Fuels Reference Book: Second Edition*. Society of Automotive Engineers, Inc., Warrendale, PA.

(c) J. Heywood. 1988. *Internal Combustion Engine Fundamentals*. McGraw-Hill Inc. New York.

(d) Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, version 1.7. 2007. Input Fuel Specifications. Argonne National Laboratory. Chicago, IL.

(e) Energy Information Administration. Monthly Energy Review. Summary for 2006.

(f) M. Wang. 2005. Energy and Greenhouse Gas Emissions Impacts of Fuel Ethanol. Presentation to the NGCA Renewable Fuels Forum, August 23, 2005. Argonne National Laboratory. Chicago, IL.

The data reveal a mixed picture as the relative advantages of alternative fuels compared to conventional gasoline. For example:

- The most commonly cited comparison shows that CNG and alcohol fuels have lower energy density than gasoline, resulting in a shorter driving range for a comparable volume of fuel.
- Alternative fuels generally have a higher octane rating than gasoline. A higher octane rating results in less likelihood of engine knock and enables engines to be set for higher compression ratios, which in turn, leads to better performance and higher fuel economy. This fuel economy gain can partially offset the lower range due to lower energy density.
- Ethanol and methanol have a higher heat of vaporization, which is the energy required to transform a given quantity of a substance from a liquid into a gas at a given pressure (usually atmospheric). A fuel with a high latent heat of vaporization can create engine difficulties in cold conditions, namely, a cold start.
- Although methanol and ethanol operate at lower air-fuel ratios than gasoline, the ratio for each is set at a level close to the stoichiometric ratio of oxygen-to-carbon for that particular fuel, so the differences in values reported in the table do not necessarily infer superiority. Operation of a spark-ignition engine at a stoichiometric fuel/air ratio enables use of the highly effective three-way catalyst for vehicle emissions control.

Ethanol and methanol also are hydroscopic and corrosive, potentially causing damage to metals and polymers used in fuel-handling systems and engine components. The hydroscopic nature of ethanol and methanol also pose challenges for bulk fuel transport and distribution, which is discussed in Section 3.

Introduction of Methanol into FFVs

Use of methanol in FFVs is more challenging than use of ethanol. While methanol possesses many similar properties with ethanol, there are also some significant differences. For example, methanol contains soluble and insoluble contaminants which increase the fuel’s corrosiveness. As an alcohol fuel, methanol is hygroscopic, where it will absorb water vapor from the atmosphere, thereby diluting the fuel. Water contaminants can suppress engine knock and can also cause separation of methanol-gasoline blends.

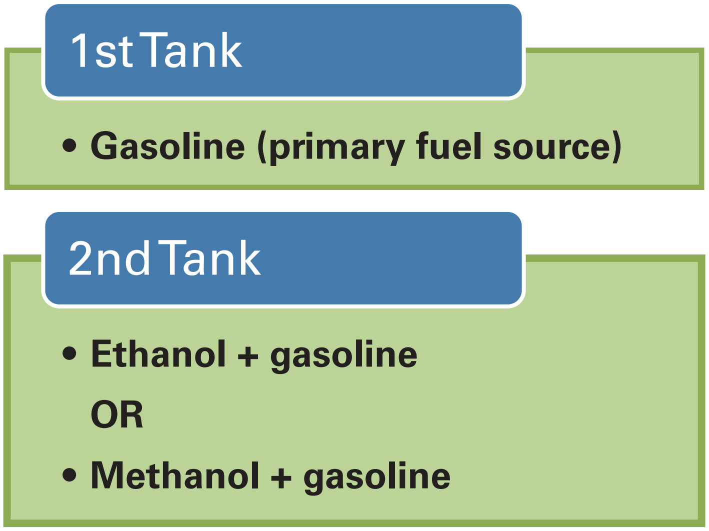
As noted by participants, methanol is currently EPA-certified for use in methanol-gasoline blends of 5% or less and the certification is further limited to blends in which ethanol is not present. The current RFS has led to almost universal use of ethanol in gasoline, thus effectively blocking low-level methanol blends from the market.

Symposium participants discussed several alternative approaches for FFV operation with methanol. One approach was a two-tank flex-fuel system, in which the vehicle contained a second tank holding alcohol (either ethanol or methanol) or a high-concentration alcohol-gasoline blend, with a parallel fuel handling and injection system to separately inject the alcohol into the combustion chambers in parallel with the primary fuel (either gasoline or a low concentration ethanol-gasoline blend). The alcohol is directly injected into the engine when needed to prevent knock at high torque, enabling operation at a high compression ratio and with a higher level of turbocharging, thereby providing greater efficiency and performance.

Another novel idea presented to symposium participants was the possibility of a three-part fuel mixture of gasoline/ethanol/methanol (or GEM) that could be a replacement for E85 in current FFVs.

- **Two-tank system:** A two-tank FFV would have one tank containing gasoline as the primary fuel and the other tank containing a blend of either ethanol or methanol with gasoline as a supplemental fuel, as illustrated in Figure 9.

Figure 9 – Concept of a Two-Tank Design for the FFV



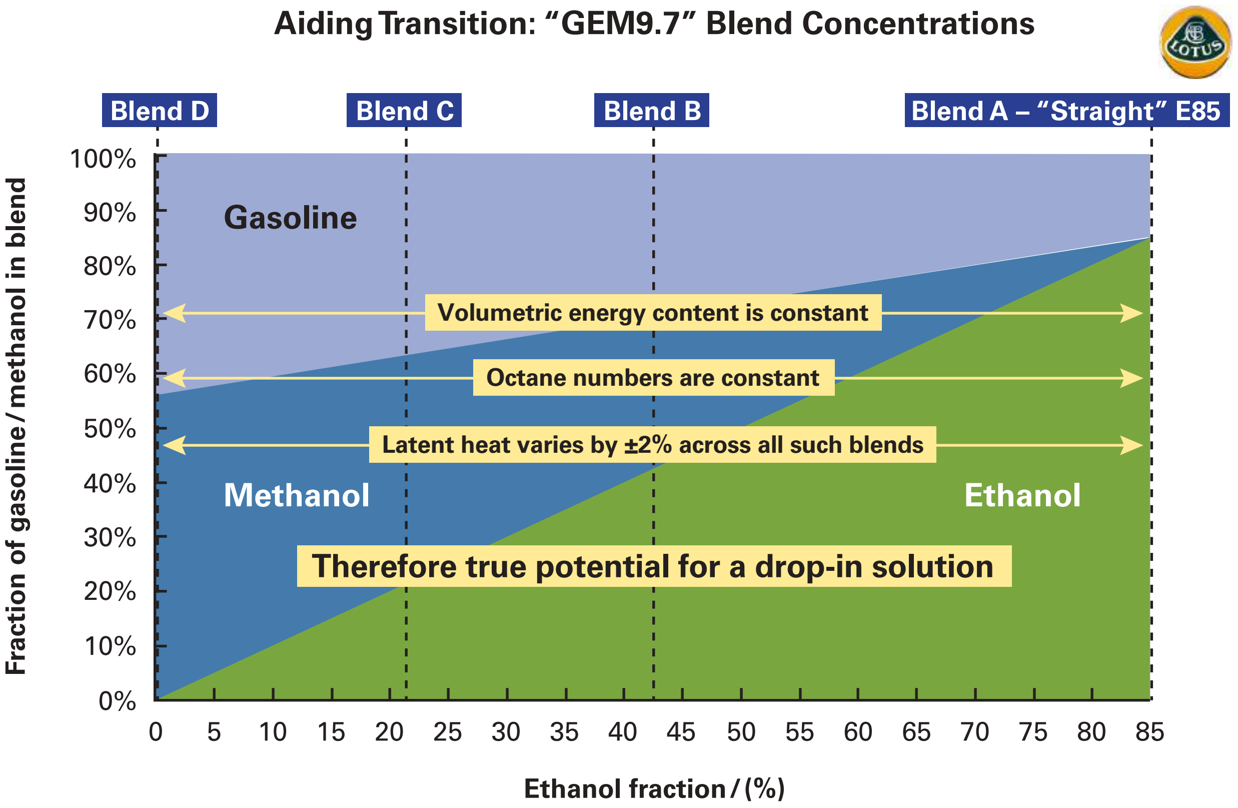
Source: MITEI.

The rationale for this two-tank system was to take advantage of the potential boost or "on-demand octane enhancement" a vehicle could obtain by using a mix of a small amount of alcohol fuel in a separate tank; the high intrinsic octane of the alcohol along with the effective cooling provided by direct injection removes the knock limit on gasoline operation and increases gasoline fuel efficiency. Another benefit of this two-tank system is that it can resolve the evaporative emissions issue. Evaporative emissions only occur when the methanol concentration is low. If methanol is stored in a fuel tank as pure methanol (M100) or as a high-concentration blend, evaporative emissions are minimized.

- **The GEM fuel blend:** The GEM fuel blend was presented as a novel approach that would enable the introduction of large quantities of methanol into the LDV market by taking advantage of the FFVs currently on the road. According to the white paper in this document by Turner et al., the GEM blend has the same stoichiometric properties as that of E85 and, as a result, the difference between the new GEM blend and E85 is indistinguishable to a current FFV designed for the latter. They also argued that producing new FFVs that can run on the GEM blend is not highly challenging since current AFVs have been already tested with M100. However, other participants were skeptical of the reported results and noted that the fuel blend would still have impacts on the vehicle's performance. Details of the GEM fuel blend are highlighted in Figure 10.

- **The GEM fuel:** Symposium participants from Lotus Engineering presented that there were fuel blends of gasoline/ethanol/methanol (or GEM blend) that can be produced in such a way that the blends have the same stoichiometric properties as that of E85 and, as a result, the differences between the GEM blends and E85 are indistinguishable to current FFVs. The stoichiometric relationship can vary, as shown in Figure 10.

Figure 10 – Combinations of GEM Fuel Blends



Source: J.W.G. Turner, R.J. Pearson, et al., "Evolution of Alcohol Fuel Blends Towards a Sustainable Transport Energy Economy," Lotus Engineering, Symposium White Paper, 2012.

Figure 10 highlights four possible GEM blends, whose properties are compared in more detail in Table 7. These blends were selected for detailed engine testing. Note that Blend A is the same as commercial E85.

As shown by the table, Blends C, D4, and D show nearly the same characteristics as those of Blend A (E85); the values of stoichiometric AFR (air-fuel ratio), LHVs and octane numbers (RON and MON) are almost identical. Some participants argued that producing vehicles that can run on the GEM blend is not highly challenging since current AFVs have been already tested with M100 (pure methanol). However, other participants were skeptical of the reported results and noted that the fuel blend would still have impacts on the vehicle performance that could vary with alternative GEM blend composition.

Lotus also performed NOx emissions testing of the selected GEM blends. All GEM blends produced 10%–15% lower amounts of NO_x than gasoline. Furthermore, the amount of NO_x produced from the blends was less than 20% of the legal maximum, which is substantially lower than the normal engineering target of 50%.

Lotus concluded that GEM blends can become a true drop-in fuel for current FFVs. As the number of these vehicles on the road is increasing, this becomes a potential strategy for the introduction of methanol into the fuel supply in a manner that does not require further vehicle modifications.

Table 7 – GEM Ternary Blend Fuels Used in the FFV Tests

Fuel	Blend A	Blend C	Blend D4	Blend D
GEM Component Ratios	G15 E85 M0	G37 E21 M42	G40 E10 M50	G44 E0 M56
Stoichiometric AFR	9.69	9.71	9.65	9.69
Density (kg/L)	0.781	0.769	0.767	0.765
Gravimetric LHV (MJ/kg)	29.09	29.56	29.46	29.66
Volumetric LHV (MJ/L)	22.71	22.71	22.60	22.69
Carbon Intensity (gCO_2/L)	1,627.9	1,623.9	1,613.9	1,620.2
RON (to ASTM D2699)	107.4	106.4	105.6	106.1
MON (to ASTM D2700)	89.7	89.3	89.0	89.0

Notes:

Blend A – G15 E85 M0 is a test fuel representing Straight E85.

Blend B – G29.5 E42.5 M28 – splits the ethanol available for E85 across twice the total volume of fuel.

Blend C – G37 E21 M42 – splits the ethanol available for E85 across four times the total volume of fuel. Methanol is twice the volume of ethanol; alcohol is approximately twice gasoline.

Blend D – G44 E0 M56 – methanol-gasoline equivalent of Straight E85. Extreme of range of ternary blends at 9.7:1 stoichiometric AFR.

Source: J.W.G. Turner and R.J. Pearson, et al., "Evolution of Alcohol Fuel Blends Towards a Sustainable Transport Energy Economy," Lotus Engineering, Symposium White Paper, 2012.

Environmental Performance of FFV/Fuel Combinations

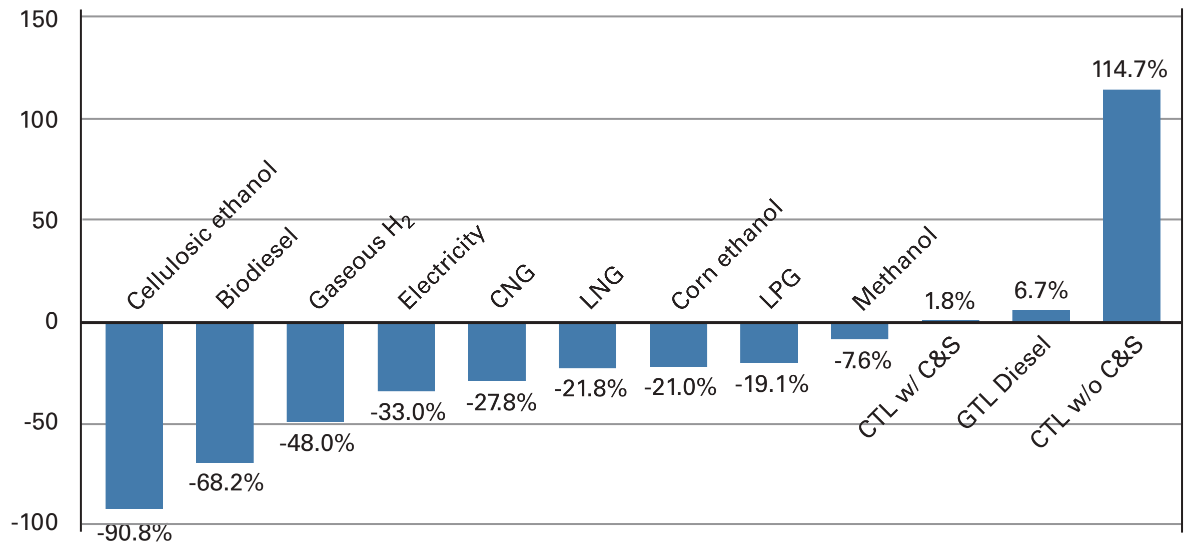
For alcohol fuels made from certain feedstock materials (sugar-based ethanol, used as a major fuel in Brazil; ethanol and methanol from cellulosic material, not yet made in any significant quantities) FFV/fuel alternatives generally are more environmentally beneficial than dedicated gasoline mono-fuel vehicles in terms of GHG emissions and conventional tailpipe emissions. Methane leakage and evaporative emissions, however, were noted by participants as areas of concern for further investigation.

- **Greenhouse gas emissions:** Lifecycle assessments of the GHG emissions associated with the use of alternative fuels in FFVs include upstream emissions (fuel production, processing, and distribution), as well as downstream emissions (tailpipe and evaporative emissions). The comparison in Figure 11 shows that ethanol and butanol derived from various forms of biomass generally have lower GHG emissions than gasoline.

  For methanol, the lifecycle (i.e., well-to-wheels) GHG emissions from natural gas-to-methanol are slightly lower than gasoline. However, the GHG emissions could be somewhat higher than that of gasoline if emissions from methane are included.[47] Several participants noted that the lifecycle emissions of methanol could be reduced through increased energy efficiency from methanol engines that can take advantage of very high octane.

  Estimates of GHG emissions from various tri-FFV configurations, including GEM fuel blends, were not available for symposium participants to review.

Figure 11 – Percent Change in GHG Emissions Relative to Gasoline



Note: All estimates derived from Argonne National Lab GREET Model v2.7.

Source: Carmine Difiglio, "Background: US Alternative Fuel Policies and Methanol," US DOE, July 2011.

- **Evaporative emissions:** Evaporative emissions are typically caused by gasoline vapors that escape from storage tanks or fuel lines. They are unburned fuel vapors that are comprised of volatile organic compounds. Evaporative emissions are potentially a much greater source of hydrocarbons than tailpipe emissions. Evaporative emissions highly contribute to ground-level ozone concentrations.

  Mixtures of gasoline and methanol generally have higher levels of evaporative emissions. The level of evaporative emissions is higher with blends containing low concentrations of methanol; as the methanol content of the blend increases, the level of evaporative emissions decreases.

  Control systems for evaporative emissions are well established, and new vehicles currently are required to have evaporative emission control systems. The system consists of a canister of charcoal that captures vapors created in the fuel tank and releases them to the engine intake manifold. Current evaporative emission control systems are designed for gasoline vehicles. Therefore, using blends of methanol and gasoline will almost certainly result in canister saturation and higher evaporative emissions.[48] Thus, higher capacity systems may be required for FFVs.

- **Conventional tailpipe emissions:** Because of their oxygen content, fuel blends with ethanol and methanol generally have lower carbon emissions than conventional gasoline. NO_x emissions also are lower. Data presented at the symposium showed that NO_x emissions were generally lower for fuels with ethanol or methanol blends relative to current NO_x emission standards for LDVs.

SECTION 3 FUEL PRODUCTION AND DISTRIBUTION INFRASTRUCTURE PERSPECTIVE

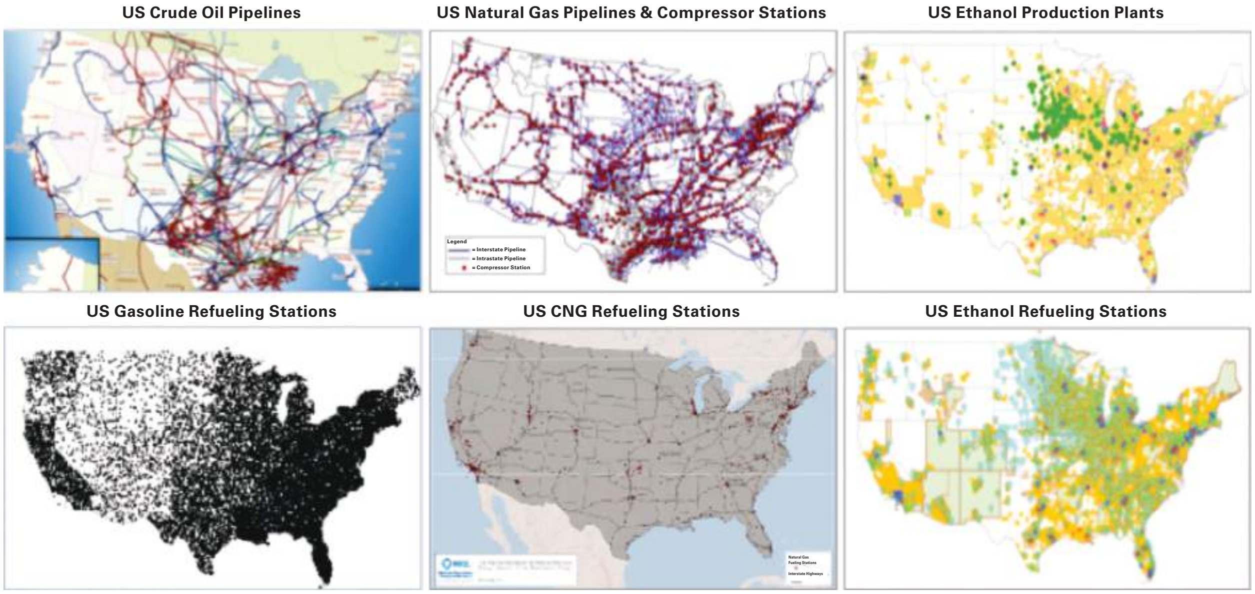
Introduction

This section summarizes the symposium discussion from the viewpoint of fuel production and distribution infrastructure. It examines the issues related to production capacity to serve the LDV market, distribution systems to move alternative fuel products from production and processing locations to markets, and the infrastructure issues associated with vehicle fueling.

Figure 12 provides a graphic snapshot comparison of the current infrastructure for gasoline, natural gas, and ethanol as a starting point for discussion. There are several overarching take-away messages, summarized below, that are discussed in more detail in the following sections:

- **CNG –** an extensive pipeline infrastructure, but insufficient number of refueling stations. Worthwhile noting that the stations installed are mostly located at interstate highways.
- **Ethanol –** concentrated and limited production facilities, and a wide area for fuel distribution.
- **Methanol –** US methanol is presently imported (produced from natural gas in other countries). Potentially, the United States could become a large producer of methanol from domestic natural gas, requiring new large-scale production facilities.

Figure 12 – Comparison of Fueling Infrastructure for Various Alternative Fuels



US Crude Oil Pipelines

US Natural Gas Pipelines & Compressor Stations

US Ethanol Production Plants

US Gasoline Refueling Stations

US CNG Refueling Stations

US Ethanol Refueling Stations

Source: Oil diagrams: EIA, Elisheba Spiller's white paper; natural gas: EIA and NREL (http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/ngpipeline_maps.html); ethanol: NREL's TransAtlas maps (http://maps.nrel.gv/transatlas).

As the predominant fuel for LDVs, the gasoline distribution infrastructure is highly developed and responsive to customer demand. It provides a starting point for comparison with the infrastructure requirements for large-scale deployment of alternative fuels. Natural gas has an extensive pipeline infrastructure capable of reaching a very large segment of the LDV market, but the current infrastructure of refueling stations is limited. Moreover, the location of these stations is primarily on interstate highways, designed to serve fleets and long-haul heavy-duty vehicles rather than the LDV market. The ethanol infrastructure also is highly developed, with production concentrated in the major corn and graining growing regions of the country. The infrastructure of E85 refueling stations is generally dispersed in a pattern that matches the current density of FFVs in the market. By comparison, there is virtually no current methanol infrastructure in the United States. The United States is currently a net importer of methanol, and very limited amounts are used for LDVs, due to current regulatory mandates and certification requirements that favor the use of ethanol over methanol.

A more detailed discussion of fuel supply and infrastructure issues, as considered by symposium participants, is provided in the sections that follow, organized by fuel type.

A Note on Comparability among Fuels

US consumers are used to understanding and comparing fuel economy and fuel prices on a volumetric basis — i.e., MPG and $ per gallon (gal) respectively. When comparing conventional gasoline with alternative fuels, the volumetric comparison can be misleading, due to key differences in fuel properties such as energy density (i.e., how much energy is contained in a unit volume of liquid fuel), performance (i.e., amount of power output from an engine optimized for an alternative fuel), and price. For purposes of the symposium, the following conversion factors were used where appropriate in order to arrive at comparable estimates of gallons of GGE shown in Table 8. The retail prices are shown in Table 9.

Table 8 – Conversion Factors

	Unit of Measure	Gallon Equivalent	BTUs/Unit
Gasoline (regular)	gal	1.00 gal	114,100
Ethanol (E85)	gal	1.39 gal	81,800
Methanol (M85)	gal	1.74 gal	65,400
CNG	cf	126.67 cf	900
Propane (LPG)	gal	1.35 gal	84,300
Diesel #2	gal	0.88 gal	129,500
Biodiesel (B20)	gal	0.90 gal	127,250
Ethanol (E100)	gal	1.50 gal	76,100
Methanol (M100)	gal	2.01 gal	56,800
Biodiesel (B100)	gal	0.96 gal	118,300

Source: Alternative Fuels and Advanced Vehicles Data Center (AFDC) Quarterly Report, January 2012.

A comparison of January 2012 prices also is noted, in both actual physical units and in terms of price per gallon of GGE.

Table 9 – January 2012 Overall Average US Retail Fuel Prices

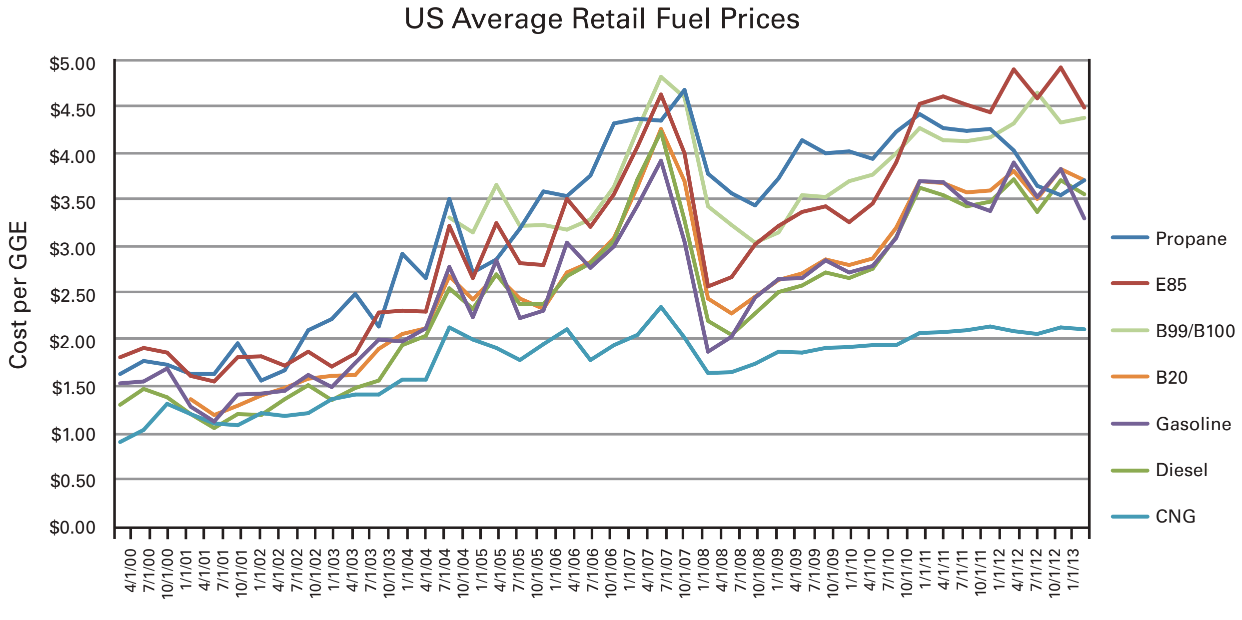
	Retail Price	Retail Price per Gasoline Gallon Equivalent (GGE)	Retail Price per Million Btu (based on GGE)
Gasoline	$3.37/gal	$3.37	$29.23
CNG	$2.13/GGE	$2.13	$18.49
Propane (LPG)	$3.08/gal	$4.26	$36.93
Ethanol (E85)	$3.14/gal	$4.44	$38.50
Methanol	$1.34/gal		
Diesel	$3.86/gal	$3.46	$30.00
Biodiesel (B20)	$3.95/gal	$3.61	$31.24
Biodiesel (B99/B100)	$4.20/gal	$4.14	$35.84

Note: The price shown for methanol is the contract price of $1.34/gal reported by Methanex. This is equivalent to $2.69/GGE. The methanol contract price is more comparable to the spot wholesale price of gasoline. In January 2012, the gasoline wholesale spot price as $2.82/gal for New York harbor and $2.77/gal for the US Gulf Coast.

Source: Alternative Fuels and Advanced Vehicles Data Center (AFDC) Quarterly Report, January 2012.

Figure 13 illustrates historical trends in the prices of various alternative fuels. Note that the liquid fuels generally follow the same pattern of price volatility as gasoline. Natural gas does not. The issue of price coupling is discussed in more detail later in the report.

Figure 13 – Comparison of US Average Retail Fuel Prices per GGE



Source: AFDC, January 2012.

Gasoline

The US gasoline market is a large, efficient, and mature industry. As a point of departure for discussing the scale needed for an alternative fuels infrastructure, it was noted that the current US petroleum infrastructure consisted of 55,000 miles of crude oil pipelines, feeding 150 refineries. Gasoline product from these refineries is transported through another 95,000 miles of refined product pipelines and many local delivery trucks, supplying approximately 160,000 gasoline refueling stations.[49] By comparison, it was reported that one major petroleum company estimated that a FFV market using methanol would require that 10% of current gasoline refueling stations be equipped with methanol refueling capability.[50]

As Table 10 illustrates, the total number of refueling stations for all types of alternative fuels constitutes about 14% of the total number of gasoline refueling stations; excluding electricity, the number of alternative liquid and gaseous alternative refueling stations constitutes only 4% of gasoline stations.

Table 10 – Comparison of the Number of Refueling Stations in the US

Biodiesel	CNG	E85	Electric	Hydrogen	LNG	LPG
696	1,190	2,583	15,192	58	66	2,776

Note: Includes both public and private refueling stations, as of Dec 31, 2012.

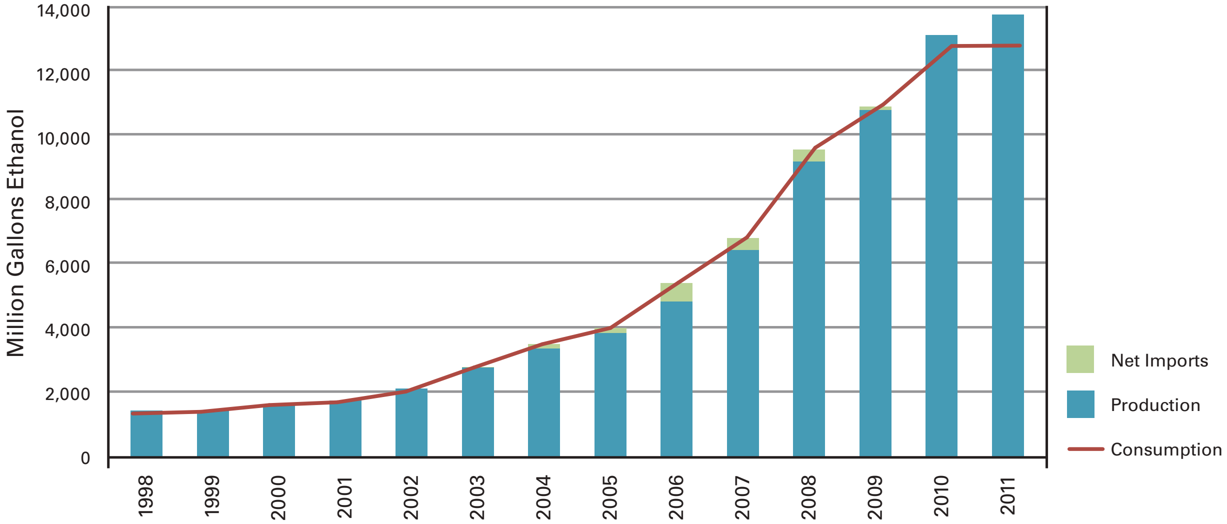
Source: Alternative Fueling Station Counts by State, AFDC http://www.afdc.energy.gov/fuels/stations_counts.html

Ethanol

Supply

In 2010, US consumption of ethanol was 13,189 million gallons, most of which was from domestic production [Figure 14].

Figure 14 – US Production, Consumption, and Trade* of Fuel Ethanol



*Trade includes small changes in stock

Source: AFDC, 2012.

In 2011, ethanol production was about 14 billion gallons.[51] According to the Renewable Fuels Association, out of this total production, only 67.4 million gallons, or 0.47%, were from non-corn feedstock materials, including brewery/beverage waste, milo/wheat starch, waste sugars, wood waste, cheese whey, potato waste, and sugar cane.

The cost of production varies depending on the choice of feedstock material, which affects both the cost of raw materials as well as the cost of processing. A 2006 US Department of Agriculture (USDA) study provided a comparison of these costs on an equivalent basis, as summarized in Table 11. Notably, producing ethanol from US raw or refined sugar is significantly higher than from other domestic feedstock crops, particularly corn, though Brazil still has the lowest ethanol production costs.

Table 11 – Ethanol Production Costs from Various US Feedstock Materials

Summary of Estimated Ethanol Production Costs (Dollars per Gallon)*

Cost Item	US Corn Wet Milling	US Corn Dry Milling	US Sugar Cane	US Sugar Beets	US Molasses†	US Raw Sugar†	US Refined Sugar†	Brazil Sugar Cane‡	EU Sugar Beets‡
Feedstock Costs**	0.40	0.53	1.48	1.58	0.91	3.12	3.61	0.30	0.97
Processing Costs	0.63	0.52	0.92	0.77	0.36	0.36	0.36	0.51	1.92
Total Cost	1.03	1.05	2.40	2.35	1.27	3.48	3.97	0.81	2.89

*Excludes capital costs.

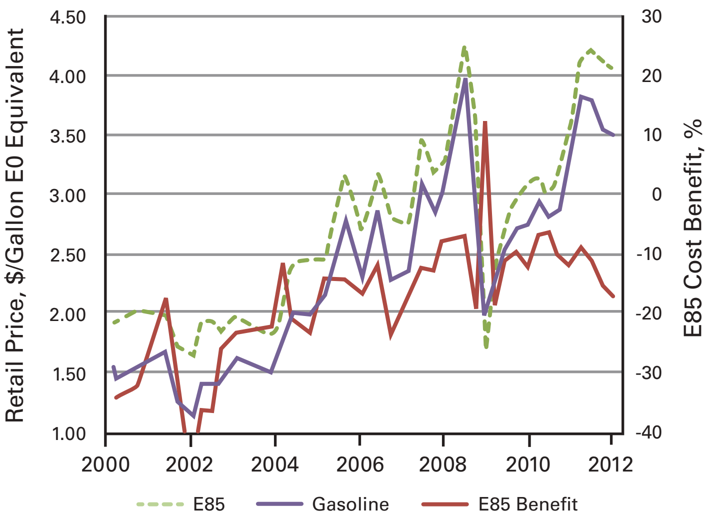
**Feedstock costs for US corn wet and dry milling are net feedstock costs; feedstock costs for US sugar cane and sugar beets are gross feedstock costs.

†Excludes transportation costs.

‡Average of published estimates.

Source: US Department of Agriculture, "The Economic Feasibility of Ethanol Production from Sugar in the United States," July 2006.

Figure 15 – Historical Relationship between E85 and Gasoline Prices



Source: Ulrich Kramer and James Anderson, Symposium White Paper.

Table 11 shows that the cost of ethanol production from most feedstock materials was less than the price of gasoline during this same period, which ranged from $2.65/gal to $3.24/gal. Although there were significant differentials, the price of ethanol, in the form of E85, was slightly higher than gasoline (on an energy-equivalent basis). In fact, on an energy-equivalent basis, the price of E85 has been slightly higher than gasoline since 2000, except for a brief period in early 2009, as shown in Figure 15. Consequently, the lack of any significant price discount for E85 has probably contributed to the low levels of E85 consumption in the United States.[52]

Production of ethanol has been encouraged and subsidized by the government for decades. Through fiscal year 2010, the EIA reported that the US ethanol fuel industry had received approximately $5.68 billion in Volumetric Ethanol Excise Tax Credit (VEETC).[53]

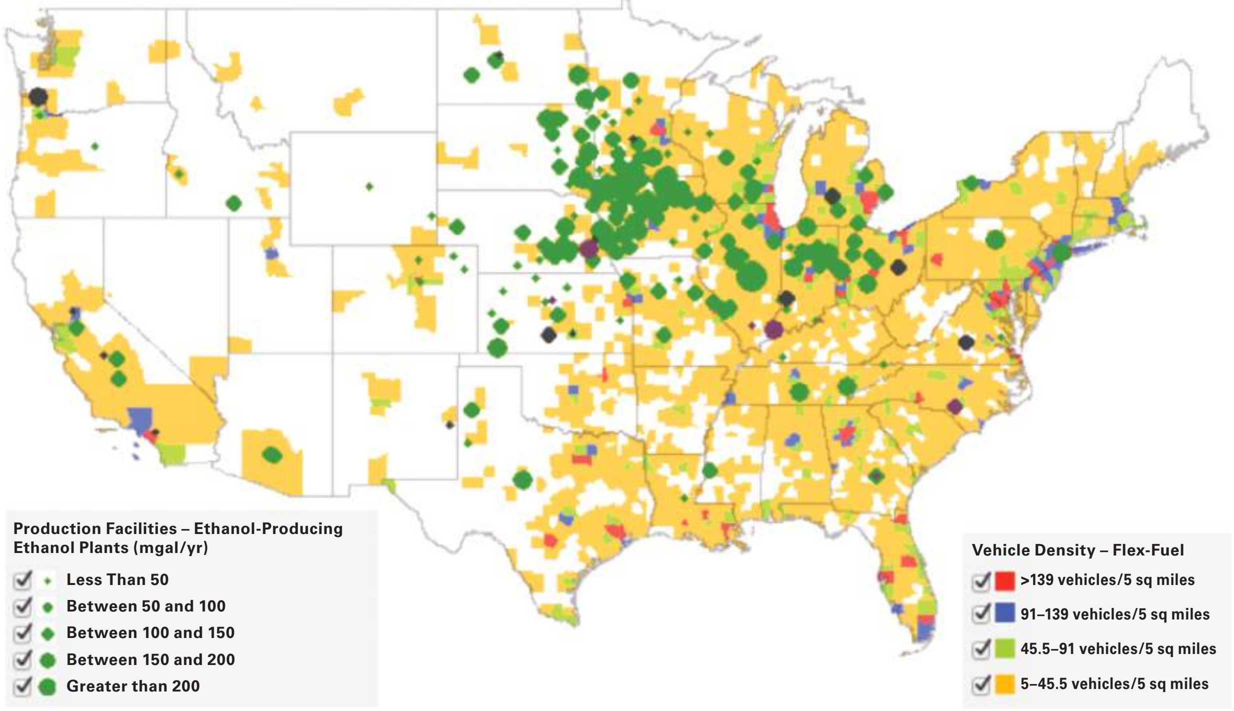
Ethanol Transport Infrastructure

While most US ethanol plants are concentrated in the Midwest, gasoline consumption is highest along the coastlines. The population of FFVs capable of using E85, while more concentrated in the Midwest, also exhibits a greater population density on the coasts [Figure 16].

Due to its high oxygen content and solvent properties, ethanol is corrosive and tends to absorb water and impurities when transported through pipelines, which currently only distribute less than 10% of fuel ethanol. As illustrated in Figure 17, over 90% of ethanol production is transported by rail or truck from production facilities to gasoline storage terminals, where it is splash blended with gasoline.

The significant ramp-up in production and consumption has caused consideration of the need for dedicated ethanol pipelines, specifically designed to suit the chemical characteristics of ethanol. One such pipeline in current operation is the Central Florida Pipeline Project. POET LLC and Magellan Midstream Partners have proposed to construct a new dedicated ethanol pipeline connecting the Midwestern and Northeastern states [Figure 18].

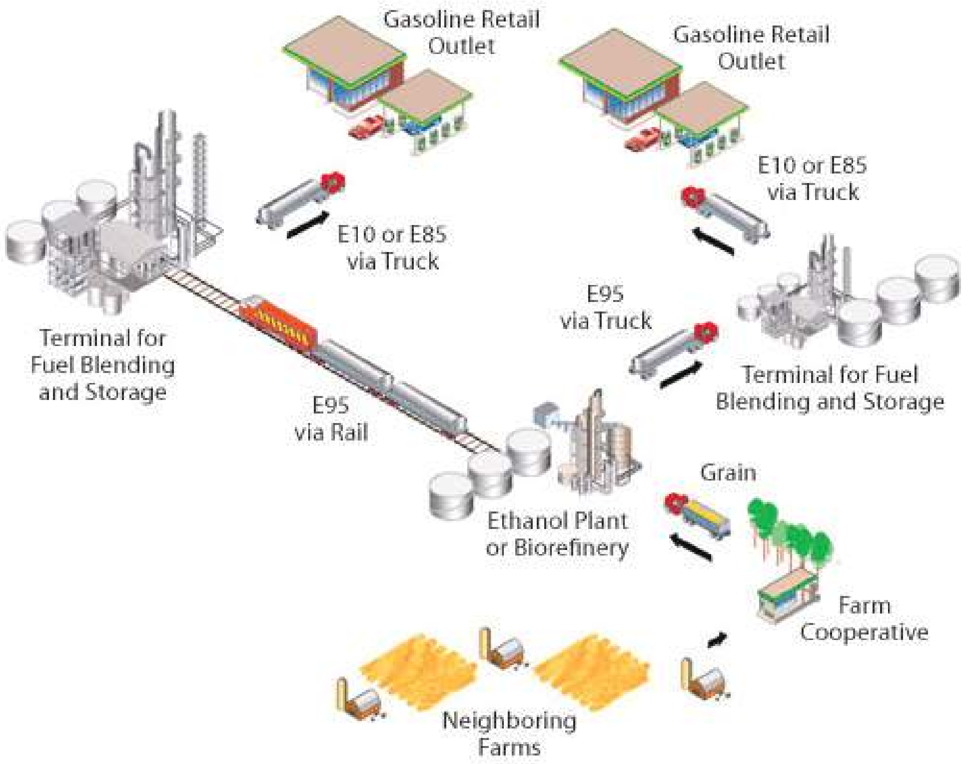
Figure 16 – US Ethanol Production Facilities and Areas of FFVs



Note: Shaded areas on the map denote the density of registrations of FFVs.

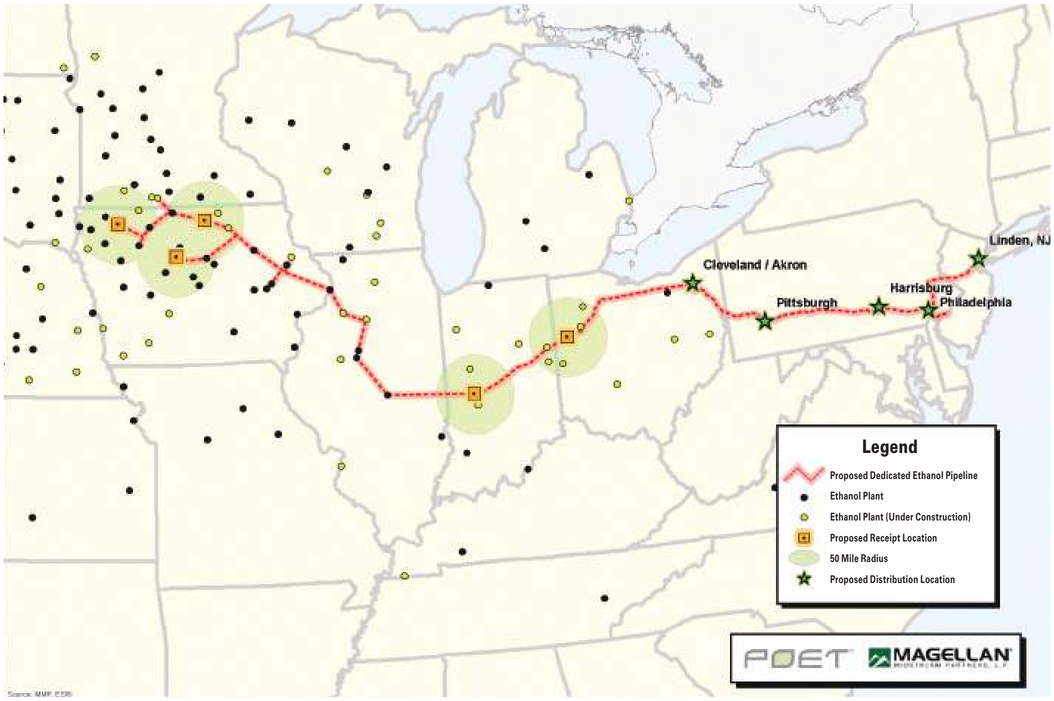
Source: National Renewable Energy Laboratory (NREL), 2009–2012, available at http://maps.nrel.gov/transatlas

Figure 17 – Schematic of US Rail and Truck Ethanol Distribution System



Source: AFDC, 2012. Available at http://www.afdc.energy.gov/afdc/fuels/ethanol_production.html

Figure 18 – Proposed Dedicated Ethanol Pipeline



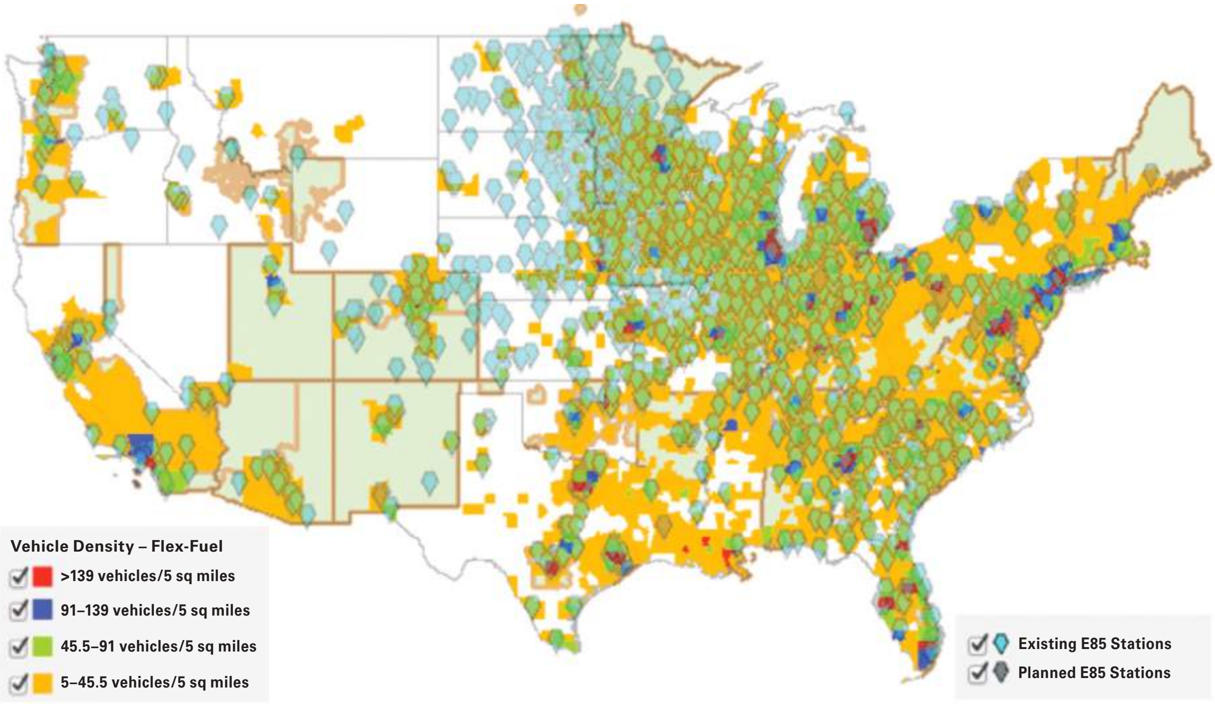
Source: AFDC, 2012. Available at http://www.afdc.energy.gov/afdc/fuels/ethanol_production.html

Ethanol Fueling Infrastructure

Currently, there are 2,498 E85 refueling stations in the United States. Figure 19 shows the location and density of refueling stations correlated with the location of FFVs.

According to the Alternative Fuels Data Center (AFDC) and a 2008 National Renewable Energy Laboratory (NREL) report, US gasoline stations generally only have an average of 3.3 tanks. To provide E85 fueling capability, a gasoline station could either install an additional tank or convert an existing tank. A new tank costs on average $71,735 (median $59,153), while converting an existing tank is an average of $21,031 (median $11,237) [Table 12].

Figure 19 – US Ethanol Refueling Stations and Areas with FFVs



Source: NREL, 2009–2012 (http://maps.nrel.gov/transatlas).

Table 12 – Cost of Adding E85 Fueling Capability to Existing Gasoline Stations

Scenario	Cost	Source*	Description	Major Variables Affecting Cost
New tank, new or retrofit dispenser(s)	Mean: $71,735 Median: $59,153	NREL Survey	Includes new storage tank, pump, dispenser(s), piping, wiring, excavation, and concrete work	Dispenser needs, excavation, concrete work, sell backs, canopy, tank size, location, labor price, regulations
	$50,000–$200,000	NACS		
	$50,000–$70,000	DOT, EPA, DOE		
	>$50,000	NEVC		
	<$62,407	DAI		
Convert existing tank, new or retrofit dispenser(s)	Mean: $21,031 Median: $11,237	NREL Survey	Tank cleaning, replace non-compatible components in piping and dispensers	Dispenser needs, number of non-compatible components, location, labor price, regulations
	$19,000–$30,000	DAI		
	$5,000–$30,000	DOT, EPA, DOE		
	$2,500–$25,000	NEVC		

*NREL estimates based on invoices and cost estimates provided by grant administrators, station owners, and project managers for 120 E85 fueling stations, of which 84 were new tank installations and 36 were conversions of existing tanks. The range of costs for a new tank was between $7,559 and $247,600 and for conversion of an existing tank, $1,736 to $6,800. NREL notes that the lowest-cost tank conversions may have taken shortcuts and "are not recommended because of concerns about safety and materials."

Source: AFDC, March 2008. Available at http://www.afdc.energy.gov/afdc/pdfs/42390.pdf

Natural Gas

Supply

In 2011, natural gas supply and demand reached record levels, with 23 trillion cubic feet (tcf) of domestic dry gas production and total consumption of 24.4 tcf.[54] The average wellhead price was $3.95/mcf, and the natural gas price at city gate locations was the lowest (in inflation-adjusted terms) in a decade.[55]

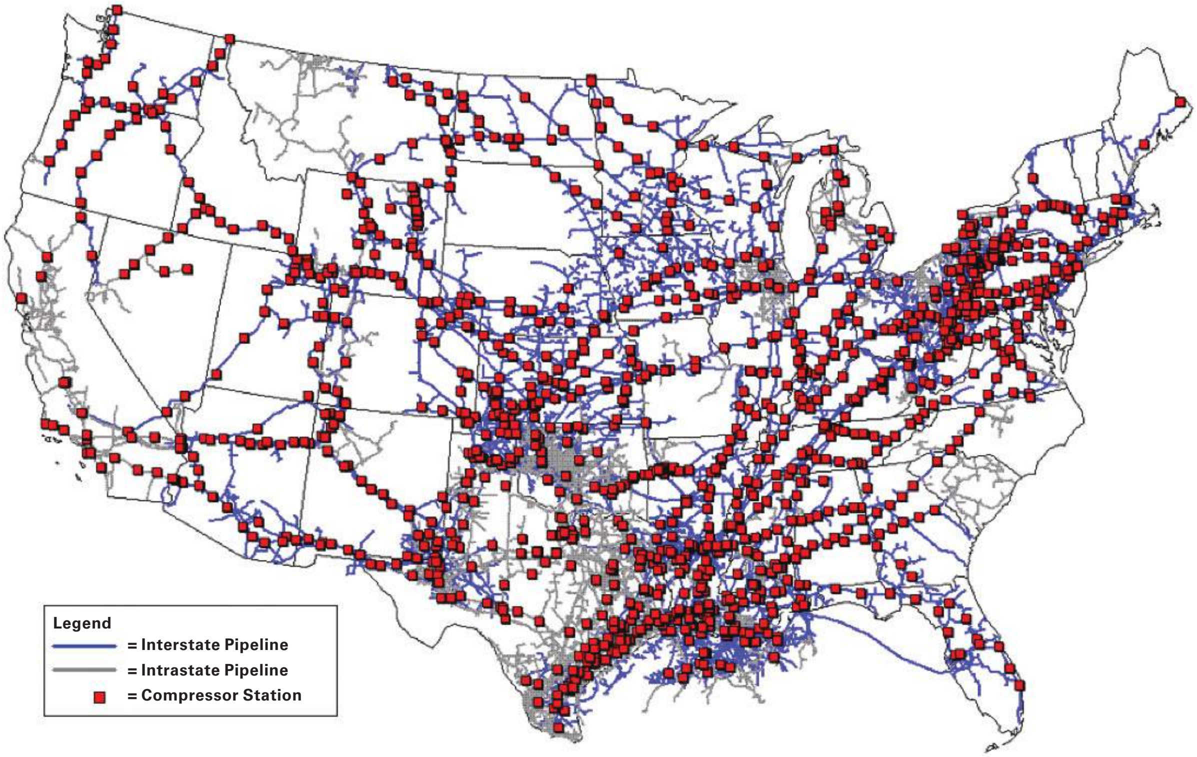
The US natural gas resource base has been estimated at about 2,100 tcf, including shale gas and Alaska natural gas.[56] This corresponds to about 90 years of natural gas supply at current production rates. The potential supply base of shale gas is very large, and may not yet be fully characterized. The MIT *Future of Natural Gas* study estimated that a considerable portion of the shale resource base can be produced economically at prices between $4/mcf and $8/mcf.

The current supply outlook suggests that domestic natural gas resources could support a significant alternative fuels infrastructure, either in the form of CNG or through conversion to methanol. For example, it was estimated that operating 50% of the current LDV fleet on CNG would increase current natural gas demand by about one-third.[57]

Transport Infrastructure

The United States has a robust and mature interstate and intrastate transportation system, consisting of 300,000 miles of transmission pipelines [illustrated in Figure 20] and 1.9 million miles of distribution lines.[58]

Figure 20 – US Natural Gas Pipeline Compressor Stations Illustration, 2008



Source: Energy Information Administration, Office of Oil & Gas, Natural Gas Division, Natural Gas Transportation Information System.

Changes in the geographical pattern of natural gas production (e.g., increased production from the Marcellus gas shale region) as well as changes in the geographical pattern of demand for natural gas likely will require additions to the pipeline system. However, the processes for planning, regulatory approvals, and financing of new natural gas pipeline infrastructure are well established and not likely to pose a barrier to increased use of natural gas in AFVs.

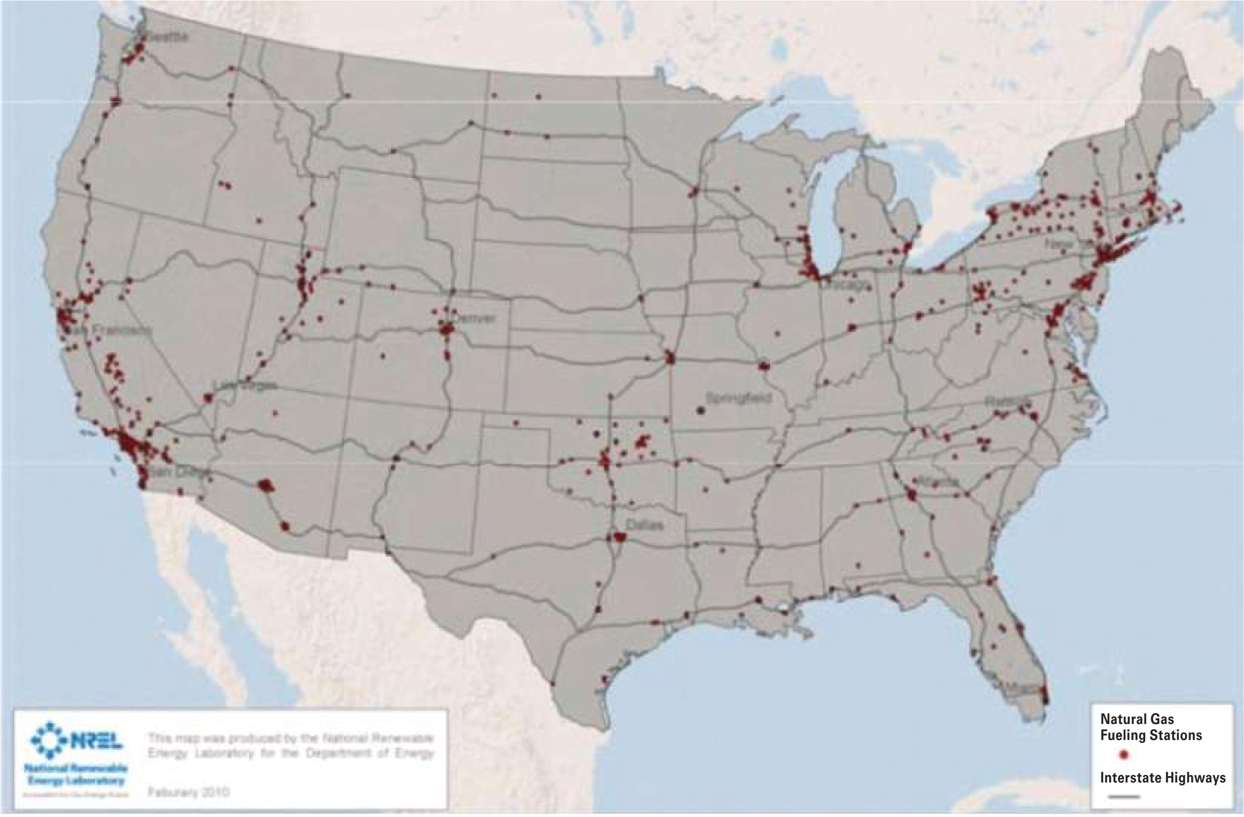
Fueling Infrastructure

The current fueling infrastructure for CNG has evolved around the two principal sources of vehicle demand: heavy-duty trucks in long-haul interstate transport and inner-city fleets mainly of trucks and buses. This pattern is illustrated in Figure 21.

Consequently, the current CNG fueling infrastructure is limited and concentrated along the interstate highway system. It was designed to serve centrally fueled fleets of LDVs, trucks, and buses and longer-haul heavy-duty vehicles rather than the light-duty market.

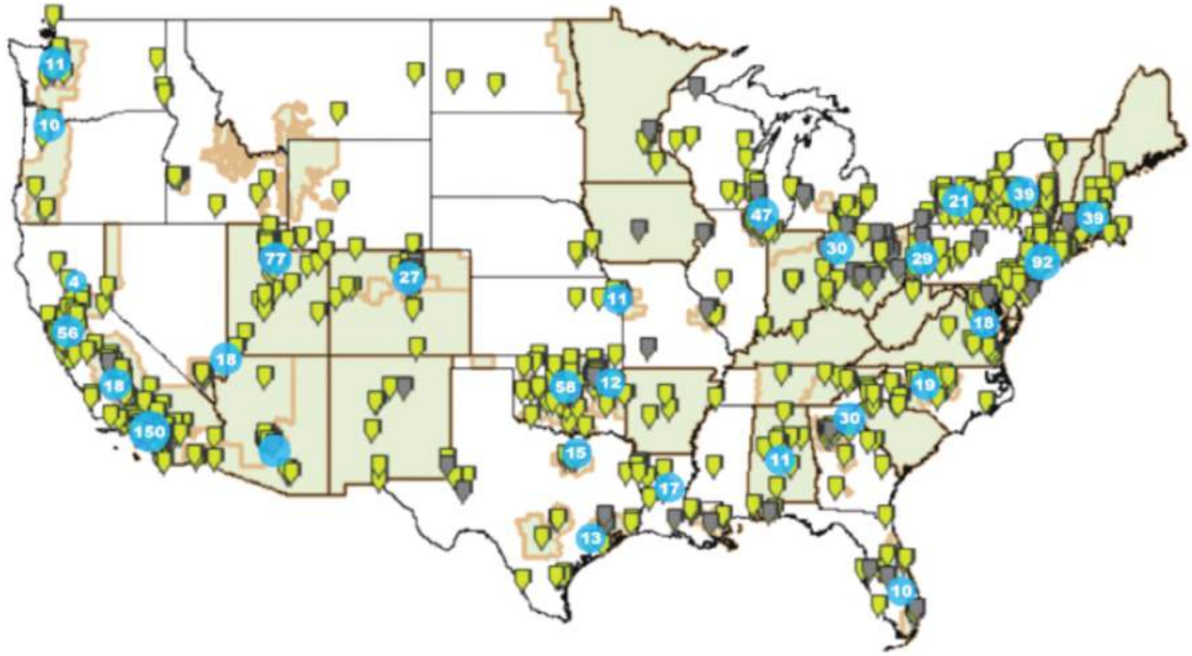
The Clean Cities program has been working to promote expansion of this network so that it can support the broader LDV market.[59] Current proposals to expand the CNG refueling infrastructure are illustrated in Figure 22.

Figure 21 – US CNG Refueling Stations and Interstate Highways



Source: NREL, February 2010.

Figure 22 – US CNG Existing and Proposed Refueling Stations and Clean Cities Coalitions



Source: AFDC, April 2012 and NREL, 2012. Available at http://maps.nrel.gov/transatlas

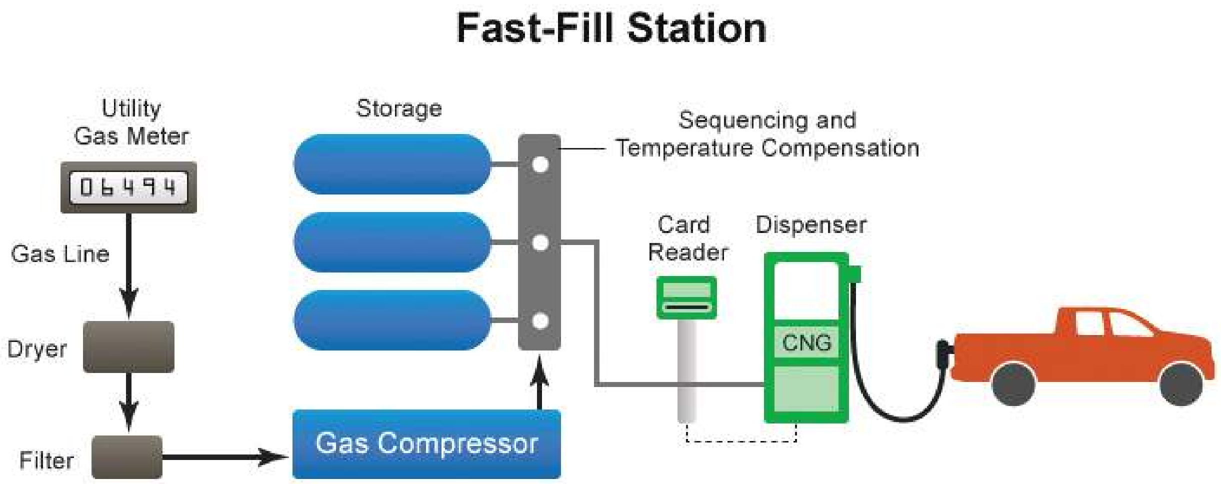
This proposed expansion will make an important contribution to removing current barriers to CNG refueling.

Bi-fuel vehicles operating on CNG require a high-pressurized compressor station for natural gas, and special nozzles to ensure a tight seal during the refueling process. Earlier refueling station designs used nozzles that required training to use, but recent nozzle designs more closely resemble those used to pump gasoline. There are two types of CNG refueling stations: fast fill and time fill (described in Figures 23 and 24). The different terms refer to the capacity of storage tanks and the throughput of gas compressors.

Fast-fill stations typically have a large storage capacity of CNG available for rapid refueling. The natural gas is compressed to pressures in the range of about 4,000 pounds per square inch (psi) and held in storage for refueling. In the refueling process, the vehicle tanks are pressurized to a level of about 3,500 psi. Fast-fill stations are necessary for non-fleet LDVs. These vehicles generally arrive at the refueling station randomly and need to be refueled quickly. For a 20-gallon equivalent tank, refueling can take about 5 minutes, which is similar to a gasoline refueling experience. The equipment needed for fast-fill stations is about the size of a parking space.

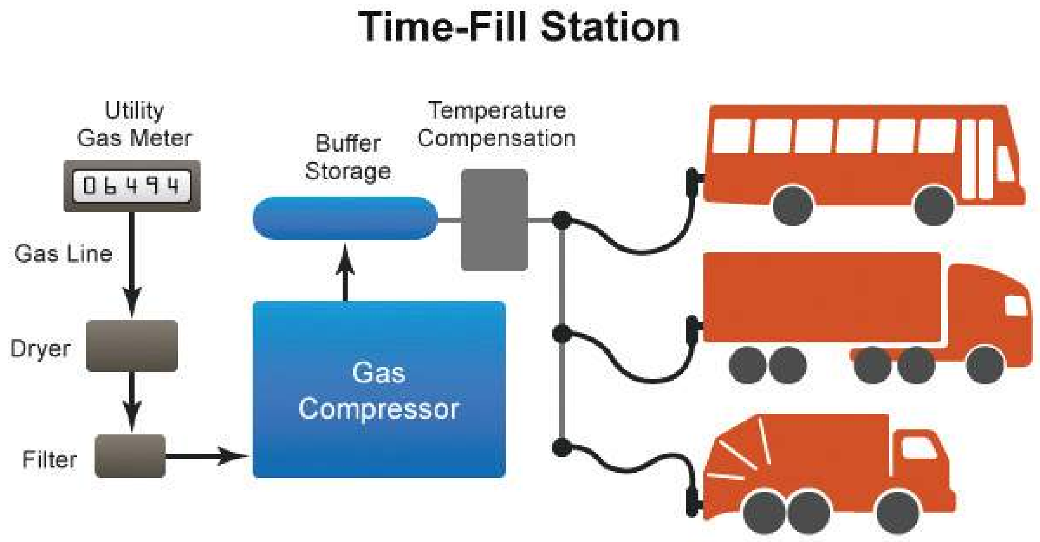
By comparison, time-fill stations are designed for fleets. In this case, vehicles refuel at a central refueling location overnight. Time-fill stations typically have a relatively small amount of buffering storage. Instead, the refueling operation is directly linked to the compressor, and refueling times are linked to compressor throughput. Depending on the number of vehicles, compressor size, and the amount of buffer storage, refueling can take from several minutes to several hours. One advantage of time fill is that the user can choose the time to refuel vehicles; electricity needed for running the compressor can cost less at off-peak hours.[60]

Figure 23 – Illustration of a CNG Fast-Fill Fueling Station



Source: Compressed Natural Gas Fueling Stations, AFDC http://www.afdc.energy.gov/fuels/natural_gas_cng_stations.html#fastfill

Figure 24 – Illustration of a CNG Time-Fill Fueling Station



Source: Compressed Natural Gas Fueling Stations, AFDC http://www.afdc.energy.gov/fuels/natural_gas_cng_stations.html#fastfill

Participants discussed that bi-fuel vehicles may have less demanding requirements for refueling than dedicated NGVs. For example, it may be acceptable to fill bi-fuel vehicle tanks to lower pressures, reducing fill times or allowing for lower-rated (and less expensive) compressors. Also, improvements in compressor technology may allow for faster fill rates with lower temperature buildup.

The cost for CNG refueling stations depends upon the size of stations and the types of natural gases (CNG, LNG, or both) that the stations offer. Whether a station is a fast-fill or a time-fill station also affects the cost. According to a 2010 report by US DOE Pacific Northwest National Laboratory, a CNG refueling station can cost from $400,000 to $2 million as shown by Table 13.

Table 13 – Cost for CNG Refueling Station

Refueling station type	Maximum Capacity	Maximum Capacity, GGE	Estimated Cost
CNG, small	<500 scfm	4.0 gge/min	$400,000
CNG, medium	500–2000 scfm	4.0–15.8 gge/min	$600,000
CNG, large	>2000 scfm	>15.8 gge/min	$1,700,000

Source: US DOE, Pacific Northwest National Laboratory, “Issues Affecting Adoption of Natural Gas Fuel in Light and Heavy-Duty Vehicles,” PNNL-19745, September 2010.

Participants also discussed the possibility of at-home CNG refueling capability. An at-home refueling capability would create a more level playing field between CNG bi-fuel vehicles and PHEVs. For a period of time, Honda, which produces and sells a dedicated NGV (the Accord GX), also marketed a home CNG refueling appliance called Phill, through a separate company (Fuelmaker). The appliance is now being marketed by the Italian Company BRC Gas Equipment. Phill's costs were about $4,500 and depending on the customer's residential gas rate, and installation, operating, and maintenance costs, the resulting cost of CNG could be in the $3 to $5 per GGE. Phill was a relatively low pressure (0.5 psi) CNG refueling system, requiring about 8 hours to fill a CNG tank. Anecdotal comments on Honda's experience of selling both the GX and Phill in Southern California indicated that once customers became accustomed to the existing CNG fueling infrastructure, they did not see the value of the additional investment for home CNG refueling. Consumers in other regions where the density of CNG refueling stations is lower may have a greater interest in at-home refueling capability. DOE, through the Advanced Research Projects Agency — Energy (ARPA-E), recently awarded grants for development of low-cost at-home refueling systems. Development of a cost-effective at-home refueling system could represent a "disruptive technology" that could significantly impact the demand for both dedicated NGVs as well as CNG bi-fuel vehicles.

Methanol

Supply

Methanol can be produced from several feedstock materials, including natural gas, coal, and biomass. In 2009, US demand for methanol was 1.85 billion gallons, of which about 90% was used for chemicals production.[61] 86% of US methanol demand is imported, mainly from the Caribbean and South America. There currently is limited domestic production of methanol; the largest four facilities, shown in Table 14, total 329 million gallons of production, the bulk of domestic supply.

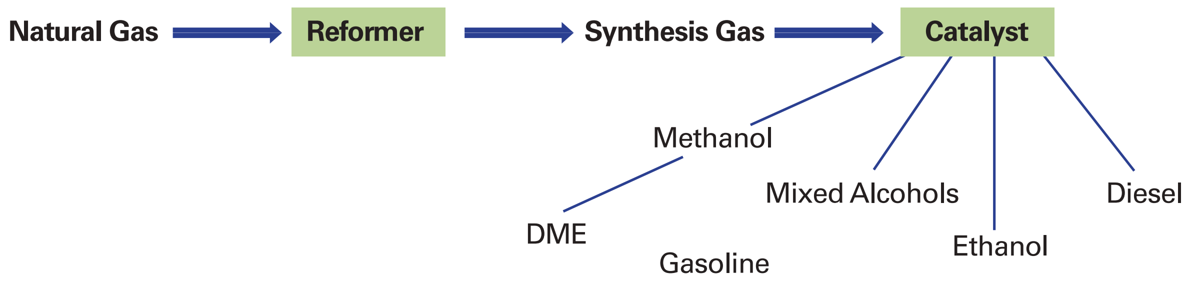
Table 14 – US Methanol Production (2009) (Millions of Gallons)

	Production	Feedstock
Eastman Chemical, Kingsport, TN	71	coal
LaPorte Methanol/Lyondell, Deer Park, TX	203	NG
CF Industries, Woodward. OK	40	NG
Praxair, Geismar, LA	15	NG

Source: L. Bromberg and W.K. Cheng, "Methanol as an Alternative Transportation Fuel in the US: Options for Sustainable and/or Energy-Secure Transportation," Sloan Automotive Laboratory, Massachusetts Institute of Technology, November 2010.

Natural gas is an ideal feedstock for the production of methanol, and symposium participants assumed that large-scale use of methanol would require new domestic natural gas to methanol conversion facilities. There is considerable global experience in large-scale natural gas to methanol conversion, mainly as a feedstock for chemical production, and the conversion process is relatively efficient. Figure 25 shows that natural gas can be converted into a variety of liquid products, including methanol. A range of liquid fuels can be produced from natural gas by thermochemical conversion to a synthesis gas followed by catalytic conversion to the liquid fuel. These fuels include methanol, ethanol, mixed alcohols (methanol, ethanol, and others), and diesel. Methanol can in turn be converted into gasoline or into dimethyl ether (DME), a clean-burning fuel for diesel engines.

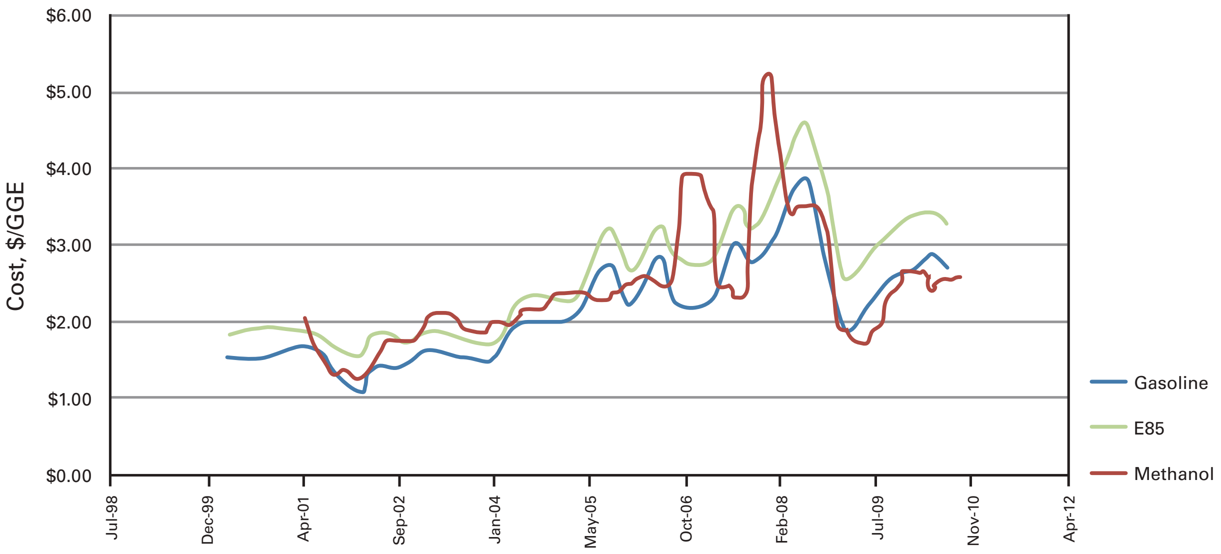
Figure 25 – Conversion of Natural Gas to Alternative Fuels



Source: MITEI 2011, "The Future of Natural Gas: An MIT Interdisciplinary Study, 2011.

Methanol imported into the United States, mainly from the Caribbean and South America, has been priced comparable to gasoline over the period 2005 to 2010 on an energy-equivalent basis. Currently, the wholesale price cost of methanol (on an energy-equivalent basis) is comparable to the wholesale price of gasoline. According to Methanex, the contract cost of methanol in January 2012 was equivalent to $2.70/GGE. At the same time, the spot price for gasoline was $2.82/gal for New York Harbor conventional gasoline and $2.77/gal for US Gulf Coast conventional gasoline. The coupling of methanol prices to gasoline and to ethanol is illustrated in Figure 26.

Figure 26 – Normalized Costs of Liquid Fuels, E85, Gasoline at the Gas Station, and Estimated Costs of Methanol at the Station



Source: L. Bromberg and W.K. Cheng, "Methanol as an Alternative Transportation Fuel in the US: Options for Sustainable and/or Energy-Secure Transportation," Sloan Automotive Laboratory, Massachusetts Institute of Technology, November 2010.

Construction of state-of-the-art methanol plants in the United States and use of US natural gas at present prices could provide methanol at a significantly lower cost than gasoline. With deployment of new plants, using existing technology, methanol could be produced from US natural gas at a cost less than the 2010 US gasoline price of around $2.30/gal (excluding the tax). Table 15 shows an illustrative projection of methanol production costs (for a large state-of-the-art plant with an ROI appropriate for large-scale deployment of well-established technology). It is based on a 67% energy conversion efficiency of natural gas into methanol and a contribution of amortized capital and operating costs of $0.50/GGE of methanol production.[62, 63] Under these assumptions, the spread between gasoline price and methanol cost is around $1.00/GGE. The cost advantage of methanol at the fueling station is reduced by around $0.10/GGE due to higher cost per unit energy of transporting methanol to fueling stations. The production cost of methanol at this assumed natural gas price would be lower than the cost of corn-based ethanol by more than $1.00/GGE.[64] The issue about the price of methanol from a large-scale domestic natural gas to methanol conversion industry was sharply debated by symposium participants. While some believed that a significant fraction of the cost savings would be passed along by producers to consumers, others believed that methanol prices would continue to be coupled to gasoline prices. The issue of price coupling is discussed further in Section 4.

Table 15 – Illustrative Methanol Production Costs, Relative to Gasoline (Excluding Taxes) at $2.30 per Gallon

Natural Gas Price	Methanol Production Cost, per GGE	Cost Reduction Relative to Gasoline, per GGE
$4/MMBtu	$1.30	$1.00
$6/MMBtu	$1.60	$0.70
$8/MMBtu	$2.00	$0.30

Source: MITEI, "*The Future of Natural Gas: An Interdisciplinary MIT Study*," 2011.

While the economics of natural gas to methanol conversion appear promising, the market for methanol as an alternative fuel in the transportation sector faces a number of challenges. They include the financial risk for private investment in US methanol production plants. The demand for methanol as a transportation fuel could be reduced by a decline in oil prices and domestic natural gas prices are volatile. In addition, incentives are lacking for building methanol capability into vehicles and incurring the costs of additional infrastructure, such as pumps in fueling stations. It is likely that some form of government assistance would be necessary to facilitate this option at large scale.

Transport Infrastructure

Since methanol is generally produced overseas, it is often shipped through ocean tankers, the largest of which is used by Methanex, a world leader in methanol production. As a liquid at standard temperature and pressures, methanol is fairly easy to transport and has been successfully transported through pipelines in Canada.* Though there is currently no nationwide pipeline network, studies have suggested that only minimal changes of the current infrastructure would be required, namely by compartmentalizing the fuel from other hydrocarbon products in the pipeline or converting existing pipelines to dedicated methanol use.[65]

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*In both demonstrations, 4000 tons of methanol were shipped: the first through the 1146km long Trans Mountain crude oil pipeline, and the second through the ~3000km long Cochin LPG pipeline.

Fueling Infrastructure

Currently there are few M85 stations in the United States. Since methanol is a hazardous chemical and reacts strongly to moisture, it requires a secondary containment unit made of methanol-compatible materials, liners, new dispensers, and filters to ensure health and fire safety. Underground storage tanks cost approximately $50,000.*

Pricing of Alternative Fuels Relative to Gasoline

The cost advantages of alternative fuels relative to gasoline suggest opportunities for market-driven penetration of alternative fuels, if the appropriate AFVs are available. A major focus of discussion among symposium participants is whether this cost differential could be garnered by consumers, thus creating demand for bi-fuel and flex-fuel vehicles. Since the incremental costs of AFVs are relatively small, it may be feasible that some manufacturers would respond to this consumer demand and begin offering more choices in bi-fuel and flex-fuel vehicles. There also may be appropriate role for policy makers in establishing a new mandate such as an Open Fuel Standard that would further encourage the manufacture of AFVs. This scenario could overcome the chicken and egg problem and lead to a pathway for significant penetration of alternative fuels in the LDV market.

The key issue is the sharing of the cost advantages of alternative fuels between producers and consumers. If alternative fuels are priced at or near petroleum-based fuels, the cost-saving advantages to consumers of switching to alternative fuels are greatly diminished. Thus, symposium participants noted that in order for these vehicles to successfully compete in the LDV market, alternative fuels need to be priced below the price of gasoline in order to introduce consumers to synthetic fuels.

Assuming that the cost of production for an alternative fuel is less than that of gasoline, consumers can benefit from switching if the alternative fuel is priced at its marginal cost of production, which is decoupled from the price of gasoline. In this scenario, consumers could arbitrage between the price of alternative fuels and gasoline. If suppliers set the price of alternative fuels at a level comparable to gasoline (i.e., price coupling), consumers would realize little if any benefit from fuel switching. The likelihood of these two options was the topic of lively debate among symposium participants, and ultimately proved inconclusive. Some symposium participants believed that alternative fuel suppliers would pass along lower production costs in the form of lower prices for alternative fuels. Other participants believed that price decoupling could be realized only with alternative vehicle options that were completely divorced from the gasoline-fueled spark-ignition engine.

The issue of fuel price coupling is illustrated in Figure 27, which compares two possible pricing scenarios.

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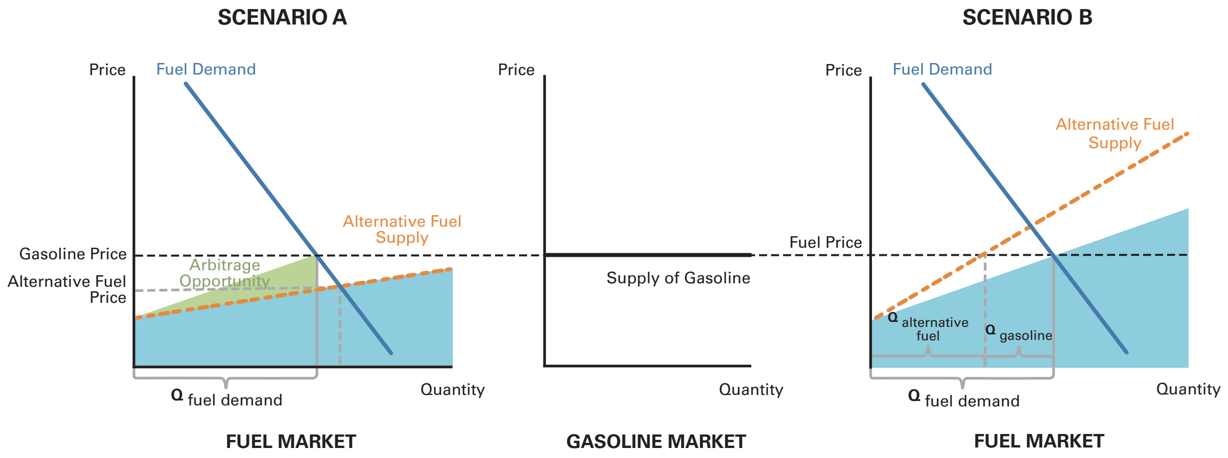
* According to the MIT Bromberg report, this figure may vary, as a California program promoting methanol use subsidized this cost.

Figure 27 – Scenarios for Pricing of Alternative Fuels Relative to Gasoline



Source: MITEI.

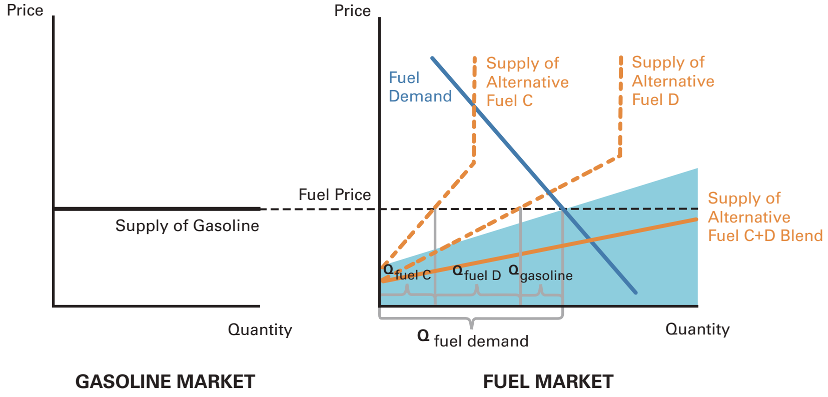
Scenario A illustrates a market that allows for consumers to arbitrage between the price of alternative fuels and gasoline. When the supply of an alternative fuel that satisfies the current fuel demand can be produced and supplied at a cost less than the price of gasoline and assuming that vehicle technologies allow consumers to easily switch between fuels, it allows for the existence of two fuel prices, one for gasoline and one for the alternative fuel, in the market. The existence of two fuel prices enables consumers to arbitrage the price difference in the short run, which is represented by the green wedge. Over the long run, a significant expansion of supply of lower-priced alternative fuels may exert downward pressure on the price of gasoline and ultimately the two prices may converge. Some participants believed that large-volume production of alternative fuels from low-cost feedstock such as natural gas will enable large volumes of alternative fuel gasoline blends to be offered in the market under conditions that would allow for price arbitrage.

Scenario B illustrates a market in which the price of all fuels is set by the market clearing price for gasoline. When the supply of an alternative fuel cannot be supplied at a cost lower than the price of gasoline and assuming that vehicle technologies allow consumers to easily switch between fuels, two fuels can still exist in the market. However, the quantities sold will differ, and only one fuel price will exist. This one fuel price will be set by the marginal fuel, or gasoline. Thus, the quantity of the alternative fuel supplied will be up to the amount that can be produced up to the price of gasoline, and the remaining fuel demand will be supplied by gasoline. If suppliers are able to exercise price coupling, consumers may not see any price advantage, nor would they have the opportunity for price arbitrage. Thus, the prospect for cost savings is eliminated and the incentive for the consumer to purchase a bi-fuel or flex-fuel vehicle is greatly diminished.

Historical market data show that the price of alternative fuels has been at or very near the market price for gasoline.

Figure 28 illustrates a market with two alternative fuels (C and D), competing with gasoline. It is important to note that if the alternative fuels C and D are ethanol and methanol, then the supply of the alternative fuel is a blend of only the alcohol fuels. If blended with gasoline, then the competitiveness of the fuel will be a function of the percentage of gasoline in the blend.

Figure 28 – Possible Price Arbitrage under Conditions of Large Volumes of Alternative Fuel Blends



Source: MITEI.

Some symposium participants believed that this was the key issue affecting the success of alternative fuels, and argued strongly that a viable alternative fuels market for LDVs could occur only if the alternative fuel price was decoupled from the price of petroleum-based fuels. Table 16 summarizes how the various vehicle-fuel options achieve price decoupling or do not achieve price decoupling.

Table 16 – Conditions for Price Decoupling with the Vehicle-Fuel Options

Fuel Options		Corresponding Vehicle Options	Infrastructure Needed	Conditions for Price Decoupling	Benefits Other Than Price Decoupling
Fuel Efficiency		Conventional gasoline vehicle			
Drop-in fuels					
E5–E15		Conventional gasoline vehicle	Ethanol production and distribution	Price decoupling not possible	• Consumer surplus • Consumer flexibility from multiple fuel options up to a certain point
M5		Conventional gasoline vehicle	Methanol production and distribution	Price decoupling not possible	• Consumer surplus • Consumer flexibility from multiple fuel options up to a certain point
Biodiesel up to 100%		Conventional diesel vehicle	Biodiesel production	Price decoupling not possible	Fuel arbitrage
Drop-out fuels					
Blendable drop-out fuels	Ethanol (E16–E85)	Conventional FFV	FFV/ethanol production/ethanol distribution	• Substantial increase in ethanol production • The demand curve for ethanol and the supply curve of ethanol meet at a point where the price of ethanol is lower than the price of gasoline	Fuel arbitrage
	Methanol (M6–M85)	FFV for methanol	FFV for methanol/methanol production/methanol distribution	• Substantial increase in methanol production • The demand curve for methanol and the supply curve of methanol meet at a point where the price of methanol is lower than the price of gasoline	Fuel arbitrage
	Tri-flex fuel (Gasoline + ethanol + methanol)	Tri-flex fuel vehicle	Tri-flex fuel vehicle/ethanol and methanol production and distribution	Market supply and demand curves of ethanol + methanol meet where the price is lower than that of gasoline	Fuel arbitrage
Physical drop-out fuels	CNG	Dedicated CNG vehicle	CNG dedicated vehicle/CNG distribution		
		Bi-fuel vehicle	Bi-fuel vehicle/CNG distribution		Fuel arbitrage
	Electricity	Dedicated electric vehicle	EV/recharging station	The prices of electricity and gasoline are not coupled	
		Hybrid electric vehicle	EV/recharging station	The prices of electricity and gasoline are not coupled	Fuel arbitrage

Source: MITEI.

Modeling the Attributes of Consumer Behavior toward Bi-Fuel and Flex-Fuel Vehicles

Successful deployment of bi-fuel and flex-fuel vehicles ultimately will depend on consumer demand. To predict how consumers will react to new vehicles and fuel options in the market, two methods are generally used. The first method is to conduct consumer surveys. So far, a number of surveys have been done in many countries including the United States and the results have shown that consumers care about prices, safety, and power. The second method of analysis is through the development of economic models based on past consumer data. That is, to take all the vehicles that have been purchased, study various attributes of those vehicles, and try to figure out which attributes are being valued in terms of the additional price people are willing to pay for those attributes. The results from this method also show that consumers value cheap, safe, and powerful cars.

Participants expressed strong reservations regarding the limitations of the use of surveys and models in terms of forecasting consumer attitudes about purchases of bi-fuel and flex-fuel vehicles. Several people pointed out that, contrary to the general conclusions from economic models, consumers do not always look for the most cost-effective vehicles. There exists a demand for highly priced cars and traditional economic models do not very well account for this phenomenon. Others pointed out that another fundamental limitation of the use of models comes from the fact that models use past data sets to predict consumer attitudes toward a new technology that did not exist before. As the bottom line, participants agreed that it is necessary to understand the limitations of choice models before they are implemented.

Despite these limitations, participants generally agreed that there is no practical alternative to models. Therefore, the discussion should be focused on how to improve the modeling of consumer behavior. For example, it was argued that choice models can account for factors that lead customers to choose pricey vehicles. Whether it is the make of the vehicle or any other attribute, anything that has a utility to customers can be taken into account in the model.

After reviewing a number of global and domestic case studies, symposium participants noted that consumers primarily valued the following attributes when making their purchasing decision:

Vehicle performance

Vehicle functionality

Ease of refueling

Cost competitiveness

Backward compatibility

Safety

Using these attributes, and drawing upon the technical information presented at the symposium, a summary matrix comparison was constructed [Table 17] of the various alternative vehicle/alternative fuel alternatives.

Table 17 – Comparison of Vehicle-Fuel Options from a Consumer Perspective

Attributes Consumers Value for Alternative Vehicles	Bi-fuel Vehicle	FFV
Vehicle Performance	• Comparable to gasoline vehicle; less prone to knocking • Lower fuel economy due to fuel tank weight and size	• Comparable to gasoline vehicle, with appropriate engine modifications • Lower fuel economy on volumetric basis, but not necessarily on an energy basis
Vehicle Functionality	• Trunk space reduced due to larger tank	• Potentially no compromises in vehicle design
Ease of Refueling	• Proximity to CNG refueling stations • Time required for refueling (e.g., high-speed filling systems of 4–5 minutes) • Possibility of home refueling (e.g., Phill home compressor systems)	• Availability of alternative fuel stations • No change in fueling process (same as conventional vehicle)
Cost Competitiveness	• Vehicle cost premium • Fuel savings*	Fuel cost premium
Safety	Concerns with pressurized gas	Toxicity concerns

*These savings would be reduced if refueled with a Phill home compressor system. Depending on the customer's residential gas rate and installation, operating, and maintenance costs, the resulting cost of CNG could be $3–$5/GGE.

Source: MITEI.

Vehicle Performance

Symposium participants were in general agreement that current alternative vehicle technologies, both bi-fuel and flex-fuel vehicles, were well optimized to deliver equivalent vehicle performance relative to conventional gasoline-powered LDVs. Therefore, while this is an important attribute in consumer acceptance, it did not appear to be a significant differentiator among the various alternative vehicle/alternative fuel options.

Because their octane ratings exceed that of gasoline, CNG, ethanol, and methanol offer comparable engine and vehicle performance to conventional gasoline vehicles. However, because of their higher heat of vaporization, ethanol and methanol could have more issues with cold start capability. This issue can be avoided by using an appropriate blend with gasoline, e.g., the M85 blend makes cold starts possible in most climates.[66] Participants expressed some uncertainty as to how consumers would react to the fact the CNG, ethanol, and methanol might appear to offer lower fuel economy (on a volumetric basis) due to lower energy density. However, it was believed that consumers would be able to understand that comparisons of actual energy efficiency would be different, and because of lower fuel costs, the cost per mile would actually be lower in the case of the alternative fuels. Vehicle range or reductions in trunk space (if fuel tanks were enlarged) represented another possible area of concern.

Backward Compatibility

Backward compatibility in a vehicle refers to the capability of a vehicle to operate on conventional fuels as well as alternative fuels. Symposium participants agreed that bi-fuel, flex-fuel, and hybrid vehicles are similarly attractive in that they share this advantage of backward compatibility with conventional gasoline, and could potentially attract consumers who value this particular kind of fuel flexibility. Participants described this value as similar to that of an insurance policy or an option. If there are few refueling stations or the price of gasoline remains significantly higher, there are cost advantages to switch between fuels. In case studies abroad where some of these vehicles are more widely used, particularly bi-fuel and flex-fuel vehicles, backward compatibility — and more broadly, fuel flexibility — is a desirable vehicle attribute, particularly when gasoline prices are volatile and alternative fuel prices remain low, or when there is uncertainty in refueling availability.

Ease of Refueling

Ease of fueling includes several factors: availability of refueling stations, length of time to refuel, and operational safety of the refueling process. As described in Section 3, the gasoline refueling infrastructure is well developed. The comparison with alternative fuel refueling stations [Table 18] availability of E85 refueling stations does not appear to be a constraint to use of ethanol in FFVs.

Table 18 – Comparison of the Number of Refueling Stations in the US

Biodiesel	CNG	E85	Electric	Hydrogen	LNG	LPG
696	1,190	2,583	15,192	58	66	2,776

Note: Includes both public and private refueling stations, as of Dec 31, 2012.

Source: Alternative Fueling Station Counts by State, AFDC, http://www.afdc.energy.gov/fuels/stations_counts.html

The availability of CNG refueling stations does pose a challenge; while there are a large number of stations, they are currently located to conveniently serve centrally fueled fleets and vehicles that travel primarily on the interstate highway system. However, symposium participants stated that ease of fueling with CNG would be much less of an issue with a bi-fuel vehicle than with a dedicated NGV. An owner of a bi-fuel vehicle would not be forced to change behavior, especially in cases in which range or resultant drive routes might be impacted. Instead, drivers of such vehicles can selectively take advantage of the lower operating cost and greener footprint of natural gas, knowing that there is no “walk home” factor that threatens their convenience or safety should travel take them beyond natural gas pumps. Despite the shorter range when compared to gasoline vehicles, drivers of CNG bi-fuel vehicles have greater range and greater fuel flexibility relative to other mono-fuel vehicles such as EVs, hydrogen vehicles, and dedicated mono-fueled CNG vehicles.

As liquid fuels, ethanol and methanol would have comparable refueling times with gasoline. In contrast, CNG requires the gas to be compressed. The refueling time at a fast-fill public refueling station, operating with high-pressure storage tanks, is about 4–5 minutes, comparable to refueling times with gasoline. Home refueling times vary depending on the compressor system; Phill, the home compressor system marketed by Honda, is capable of refueling in eight hours (natural gas is delivered at about .5 psi, to reach an ultimate pressure of 3,600 psi).

Safety issues associated with the use of alternative fuels are also a source of concern for consumers. The risk associated with ingestion of methanol is higher than with gasoline; unlike gasoline, methanol does not cause vomiting if ingested, and can cause serious health effects at low levels of ingestion.[67] While there was not a single case of accidental poisoning by methanol reported in California in the 1980s, participants agreed that sufficient safety measures are needed. For example, a very small amount of bitterant can be added to methanol in order to let the consumers know that it should not be ingested.

Although participants agreed that the use of methanol as a transportation fuel will not pose a significant threat to human health, they also acknowledged that the public perception of danger of methanol might not be rigorously based on technical knowledge. In this regard, achieving public acceptance may well be decoupled from technical verification of the safety, and in fact, acquiring public acceptance can be much more challenging than technical verification.

Cost Competitiveness

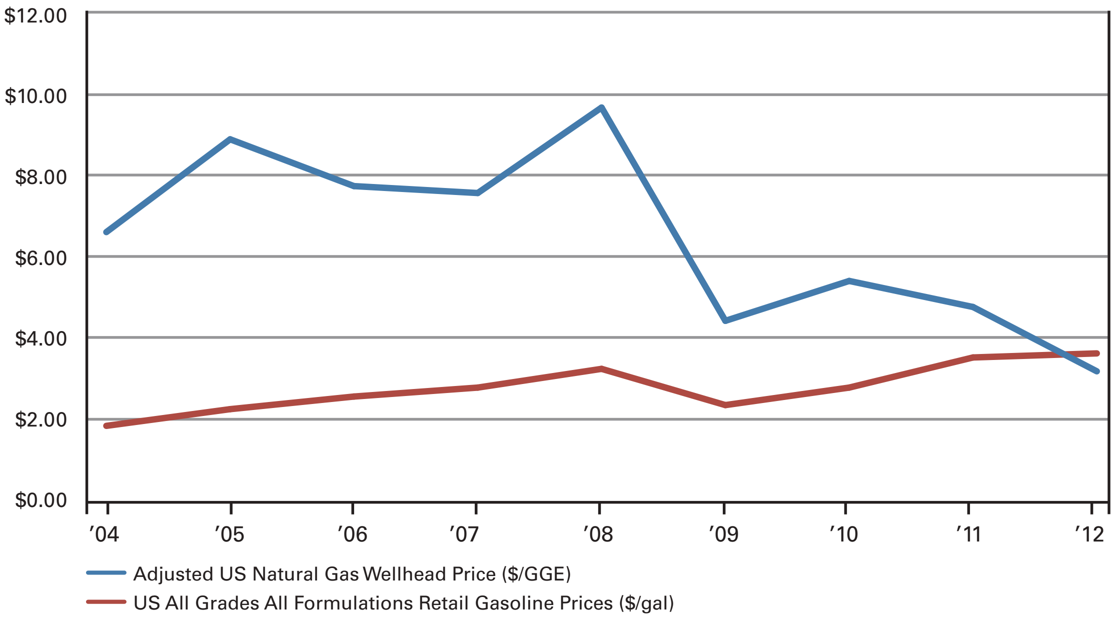
Cost competitiveness is a key determinant of consumer behavior. Some participants discussed whether this in fact is the single most important attribute in consumer behavior, noting that most consumers will choose the least expensive fuel even if the price difference with the second least expensive fuel is very small. Making an assessment of the most cost-competitive choice among competing bi-fuel vehicles and FFVs requires a comparison of the fuel cost savings to the consumer relative to the initial cost-premium on the vehicle and recurring maintenance costs. The fuel cost savings are a function of the retail price of the alternative fuel and the overall fuel efficiency of the AFV. Because fuel cost savings are a critical element of this assessment, the issue of price coupling, discussed in Section 2, is particularly important. If the price of the alternative fuel is coupled with the price of gasoline, or if the consumer perceives a possible coupling, then bi-fuel and flex-fuel vehicles offer no cost savings, and the consumer will make the decision on vehicle type based on other factors. Because bi-fuel and flex-fuel vehicles may not be as attractive in other ways — less trunk space, fewer refueling stations, longer refueling times, performance uncertainties, safety concerns — consumers will continue to prefer conventional gasoline-only vehicles. Conversely, if the consumer believes that a bi-fuel or flex-fuel vehicle offers the possibility of fuel price arbitrage or a measure of insurance against price volatility, then cost competitiveness is more likely to become the deciding factor in vehicle selection.

Cost competitiveness can be analyzed in several ways. One approach is to estimate the payback time (undiscounted) by comparing initial cost premium to annual fuel cost savings. Another approach is to compare actual monthly cash flows, which is possible in cases where the purchase price is largely financed. Both approaches require that, in the case of the bi-fuel or flex-fuel vehicle, the assessment considers the likely pattern of consumption of the alternative fuel options relative to the likely proportion of continued gasoline use. The value of a bi-fuel or flex-fuel vehicle as a hedge against gasoline price volatility, proposed by some participants as an option value or insurance value, was supported in concept by symposium participants, but is not readily quantifiable.

- **Payback estimate for bi-fuel vehicles:** Bi-fuel vehicles are most amenable to payback analysis because they have significant vehicle price premiums while offering the most significant fuel cost savings potential. In recent years, natural gas prices have become largely decoupled from petroleum prices, and with the surge of shale gas production, natural gas prices have been significantly lower than gasoline prices, on an energy-equivalent basis. This difference is shown in Figure 29.

  An analysis of CNG conversions in other countries shows that periods of strong CNG vehicle market penetration occurred when the payback period was less than 3 years.[68] For LDVs, meeting this condition requires a combination of a price spread of $1.50/GGE, vehicles in high mileage service (35,000 miles/yr), and an initial cost premium of less than $5,000.[69]

Figure 29 – Natural Gas and Gasoline Prices, 2004–2012

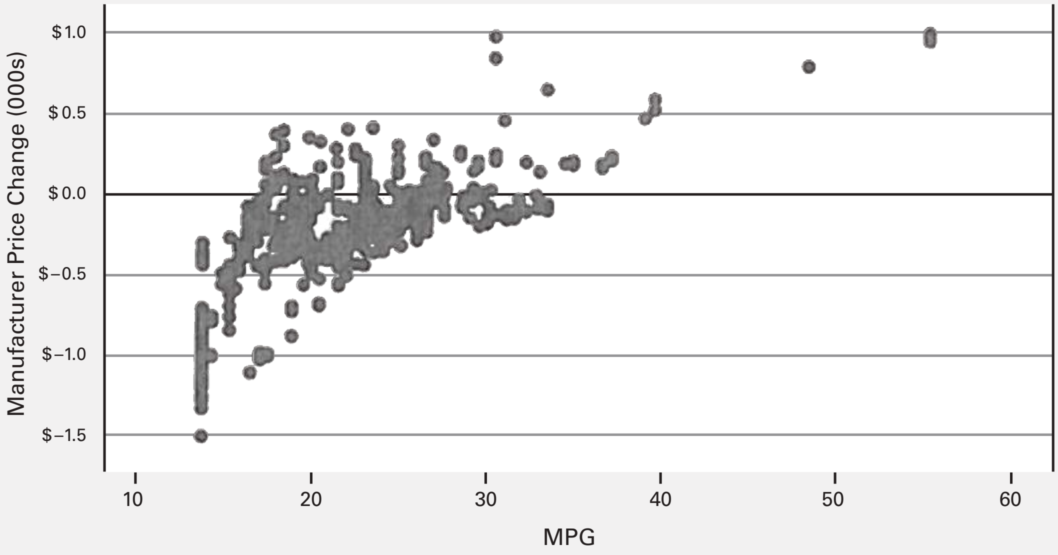


Source: cngprices.com

Gasoline Price Volatility and Consumer Response

In the United States, gasoline prices fluctuate by season and by region. The price is also affected by short-run changes in commodity prices. It was shown that fluctuations in gasoline price causes substitution in vehicle usage and choice. First, when the gasoline price goes up, people with multiple vehicles spend more time driving more fuel-efficient vehicles rather than less-efficient ones. It is rare to find people who choose to reduce their total driving time; rather, they increase the use of high MPG vehicles. This point is confirmed by a study by Granger and Miller as shown by the Table 19. As the gasoline price increases (Y-axis), people prefer higher MPG vehicles.

Table 19 – The Effect of $1 Increase in the Gasoline Price



Source: Symposium presentation, drawn from Granger and Miller.

Participants discussed possible approaches to reduce the payback period for bi-fuel vehicles. One suggestion was to consider a bi-fuel vehicle as analogous to a PHEV. Under this scenario, the cost of the bi-fuel system could be lowered by reducing the size of the CNG tank, which is the largest single item affecting the bi-fuel vehicle price premium. A study indicated 67% of all US drivers drive fewer than 40 miles a day,[70] and a storage tank 10 times smaller than the ones in vehicles currently sold would be sufficient to fuel 40 miles.[71] To extend this concept to PHEVs, a home refueling system for CNG also would be required. This would result in an estimated payback period of about seven years for a low-mileage vehicle.[72] Another approach to lowering initial costs is to reduce the design pressure for a CNG tank. This would reduce tank and compressor costs. However, some symposium participants believed that this would result in an unacceptable reduction in vehicle range.

Symposium participants also generally agreed that there was an additional value proposition to bi-fuel vehicles, which could be described in two ways: 1) as an option value, and 2) as an insurance policy. As with any option, the value of a vehicle capable of operating two different fuels increases with uncertainty, specifically, fuel price volatility. Alternatively, a bi-fuel vehicle could also be viewed as an insurance policy, which is valuable for those who desire to use an alternative fuel, but are not confident in finding close refueling stations, or for the buyer who does not want to be forced to change behavior.

Cost competitiveness of FFVs: The cost competitiveness assessment for FFVs using gasoline or E85 is simpler. Currently, FFVs do not have a price premium, although flex-fuel capability is available in only a limited number of models. Vehicle manufacturers are generally offering FFVs in larger-size class LDVs, in SUVs, and trucks, because they can maximize the value of the alternative fuels CAFE credits in larger vehicles. Looking at the cost comparison among alternative fuels, there is no cost savings. Because of the RFS requirements, gasoline distributors currently purchase over 99% of total ethanol supply for blending into E10 gasoline. Because of the mandate, ethanol producers have no incentive to price ethanol lower than gasoline. In fact, in some markets, ethanol producers may command a small premium, as evidenced by historical price trends.[73] This is possible in situations where gasoline distributors have limited access to ethanol supplies needed to meet RFS requirements. So there is no cost advantage to either alternative on either the vehicle price or the fuel price. What advantages do occur in the market may more likely be due to the effects of federal and state government financial incentives. Nonetheless, consumers may be motivated by the ability to hedge fuel prices against potential future gasoline price volatility (assuming that prices for ethanol do not remain completely coupled).

While there is no significant current market for FFVs and methanol, there is the potential for a cost-competitive FFV/methanol combination in the future. Participants noted that methanol can be produced from natural gas at costs significantly below gasoline (on a GGE basis), providing an opportunity for the introduction of methanol fuels into FFVs on a cost-competitive basis. In addition, methanol can be produced from coal and biomass, providing even greater flexibility in methanol supply and pricing. Participants were not able to develop an estimate of the potential cost savings in this area. The cost of methanol FFVs capable of operation on M85 or M100 was unknown, although participants believed it would not be much higher than for ethanol. In addition, the economics of large-scale methanol production have yet to be demonstrated in the United States. Finally, there is no current fuel distribution infrastructure in place for methanol. While participants generally believed that the prospects for methanol FFVs were attractive, some pointed out that methanol, if used in flex-fuel rather than bi-fuel or dedicated mono-fuel vehicles, could become subject to price coupling with gasoline. China, for its energy security, has adopted an ambitious methanol policy. Chinese methanol is produced from coal and a blend of methanol and gasoline is being widely distributed as transportation fuel. Although background contexts are different in China and the United States, China's methanol case is an important experience to observe for the United States.

Lessons Learned from Alternative Fuels Experience in Other Countries

In many cases, understanding what attitudes the public or consumers have toward a specific product or technology is critical for forecasting its success in the market. Taking into account the fact that both tri-flex fuel vehicles and bi-fuel vehicles are at their nascent stages at the moment, it is essential to discuss the anticipated public attitudes toward these new types of vehicles.

As a starting point for the discussion, Ulrich Kramer and James Anderson from Ford Motor Company provided an analysis on various cases of the use of non-conventional transportation fuels around the world. They looked at the introduction of four different types of non-conventional transportation fuels in more than eight countries. The fuel types and countries analyzed are summarized in Table 20.

Table 20 – Alternative Fuel Experience in Other Countries

Fuel Type	Countries
Ethanol	Brazil, United States, Sweden, Germany (E85 and E10, respectively)
Biodiesel	Germany
LPG	Europe
CNG	Asia and Europe (Pakistan, India, Germany, and Italy)

Source: Ulrich Kramer and James Anderson, Symposium White Paper.

From these case studies, Kramer et al. drew conclusions that helped symposium participants to understand how consumers make choices when new types of transportation fuels are introduced into the market.

The discussion below summarizes several basic requirements for the introduction of alternative transportation fuels at a significant scale into the market, as suggested by Kramer et al.[74]

1. Cost competitiveness

Cost competitiveness is the most important requirement for new alternative fuels to attract consumers at scale. Typically, alternative fuel systems require extra investment. Competitive costs should guarantee a reasonable chance to recover any upfront costs within the first few years.

Table 21 – Minimum Cost-Benefit Recommended for Different Alternative Transportation Fuels

	Consumer On-Cost	Minimum Benefit/Cost Recommended	Case Countries
FFV		5%	Brazil, Germany
OEM LPG vehicle	€2,000–€2,500 (USD 2,600–3,300)	40%	Germany
CNG vehicle	€3,500 (USD 4,500)	50%–70%	Pakistan, India

Source: Ulrich Kramer and James Anderson, Symposium White Paper.

Another important requirement for any alternative fuels introduced is that the prices are stable and reliable in the long term. Fuel prices should remain without significant fluctuations even in the case of rising demand, for example. This point is clearly proven in the cases of Germany and Brazil. To maintain the price within an acceptable range, sufficient feedstock and fuel production capacity are necessary.

In order to guarantee the stability of prices of alternative fuels, government actions are usually needed in the long run. A striking example is illustrated by the German's B100 case. As the government began to reduce incentives for B100 due to the increase in governmental tax loss, B100's market success reversed. Therefore, any government policy for high penetration of alternative fuels into the market should be run for the long term.

2. Backward compatibility

Backward compatibility of a vehicle refers to the vehicle's capacity to use existing fuels and infrastructure. Backward compatibility greatly facilitates successful market penetration. If a vehicle is backward compatible, the minimum amount of fuel cost-benefit can be smaller (a fuel cost-benefit of 5%–15% was sufficient for B100's case in Germany).

3. Distribution infrastructure

A sufficient number of fuel distribution outlets for alternative fuels is necessary to support large-scale market penetration of alternative fuels. However, the high upfront cost for infrastructure development can lead to slow growth in the expansion of alternative fueling stations. Sweden provides a good example of government policy intervention to expand ethanol fueling stations (In 2006, a law was passed that required all fuel stations above a certain size to offer at least one alternative fuel).

4. Vehicle capability for two fuels (bi-fuel vehicle, mono-fuel vehicle, or FFV)

If vehicles can run on two different fuels, it is beneficial to consumers because they can always choose the more cost-competitive fuel among the two options. This is observed in the Brazilian case where E100-dedicated vehicles failed while FFVs succeeded.

Moreover, the lower the extra cost for the second fuel capability, the earlier the payback period for the second fuel system installation cost, which can increase the probability of the market success. While these vehicles can have improved performance thanks to the second fuel, they generally show less-efficient performance when they run on a single fuel compared to mono-fuel vehicles.

5. Retrofit kits

Since retrofit kits allow the conversion of existing vehicles, they can greatly help expand alternative vehicles markets (e.g., LPG in Europe; CNG in Italy, Pakistan, and India). Especially, conversion of vehicles is particularly attractive in markets that are cost sensitive.

As in the case of LPG in Europe, retrofit kits are usually cheaper than purchasing OEM-produced vehicles. However, they may be of lower quality, with fewer upgrade options. For instance, OEM vehicles typically have valve and valve seat insert upgrade options whereas retrofit kits do not offer such things. As a result, retrofitted vehicles can have less durability due to the increased valve seat wear caused by poorer lubricity of gaseous and alcohol fuels. Therefore, when introducing alternative vehicles, conversion of vehicles with retrofit kits should be carefully considered.

6. Sufficient fuel energy density

Generally speaking, a longer travel range of a vehicle is desired by any consumer. Reduction in the travel range can be compensated for cost benefit. Most alternative fuels have shorter travel ranges than gasoline or diesel. To increase travel ranges, larger fuel storage spaces are used at the expense of having smaller interior space. Shorter travel ranges are particularly problematic for gaseous fuel-based vehicles and even more so for BEV.

7. Incentives

In general, sustainable fuels (non-fossil, renewable, and GHG-reducing) are currently more expensive than gasoline or diesel fuel. At least in the beginning, incentives are required to make these sustainable fuel options more cost competitive. Increases in oil prices can be helpful in this sense, but development of large-scale fuel distribution infrastructure usually justifies extra incentives. Governments may use various policy instruments that account for the differences of the situations that each sustainable fuel faces.

8. Scale

In order to maintain the market in the long term, feedstock for any alternative fuel should be sufficient, allowing a competitive fuel price. When this condition is not met, price increase of the alternative fuel is inevitable. Especially when the market solely relies on a dedicated-fuel vehicle, the market will eventually collapse for that vehicle, as witnessed in the E100-dedicated vehicles case in Brazil. Therefore, alternative fuel supply needs be scalable with future demand in the long term (e.g., B100 case in Germany).

Summary of Alternative Fuels Experiences in Other Countries

Methanol Experience in China

Methanol production in China has been growing steadily since the 1980s and it has been accelerated in recent years as China plans to use methanol as an alternative transportation fuel. In 2010, China's methanol production capacity reached 12.8 billion gallons/yr and this is expected to reach 16.6 billion gallons/yr by 2015.[75] In 2010, China consumed 7.6 billion gallons of methanol; this is about 40% of global consumption of methanol.

A major source of Chinese methanol production comes from Chinese coal reserves. Methanol can be produced from gasification of coal. China has 114.5 billion tons of coal, which corresponds to 4.9% of global reserves. Methanol production from coal in China is mainly driven by energy security concerns, not by a reduction in GHG emissions. Although the Chinese government is trying to develop nationwide standards for methanol as transportation fuel, there is not a uniform opinion on the policy in China.

Tri-Flex Fuel Vehicle Experience in Brazil: Use of CNG Instead of Methanol

In Brazil, there are tri-flex fuel vehicles that run on CNG instead of methanol. These vehicles have two separate tanks: one for a liquid gasoline and ethanol blend, and the other for gaseous CNG. These tri-flex fuel vehicles are becoming popular not only because the price of natural gas is low, but also because the government discounts the annual vehicle registration fee for car owners who convert their cars to include a natural gas fueling system. (In Rio de Janeiro, there is a 75% reduction in annual vehicle registration fee, in São Paulo it is 25%.)[76] The cost of conversion ranges from R$1,200 to R$2,500 (USD 580–1,208) in Brazil; in the United States the price starts around USD 5,000.

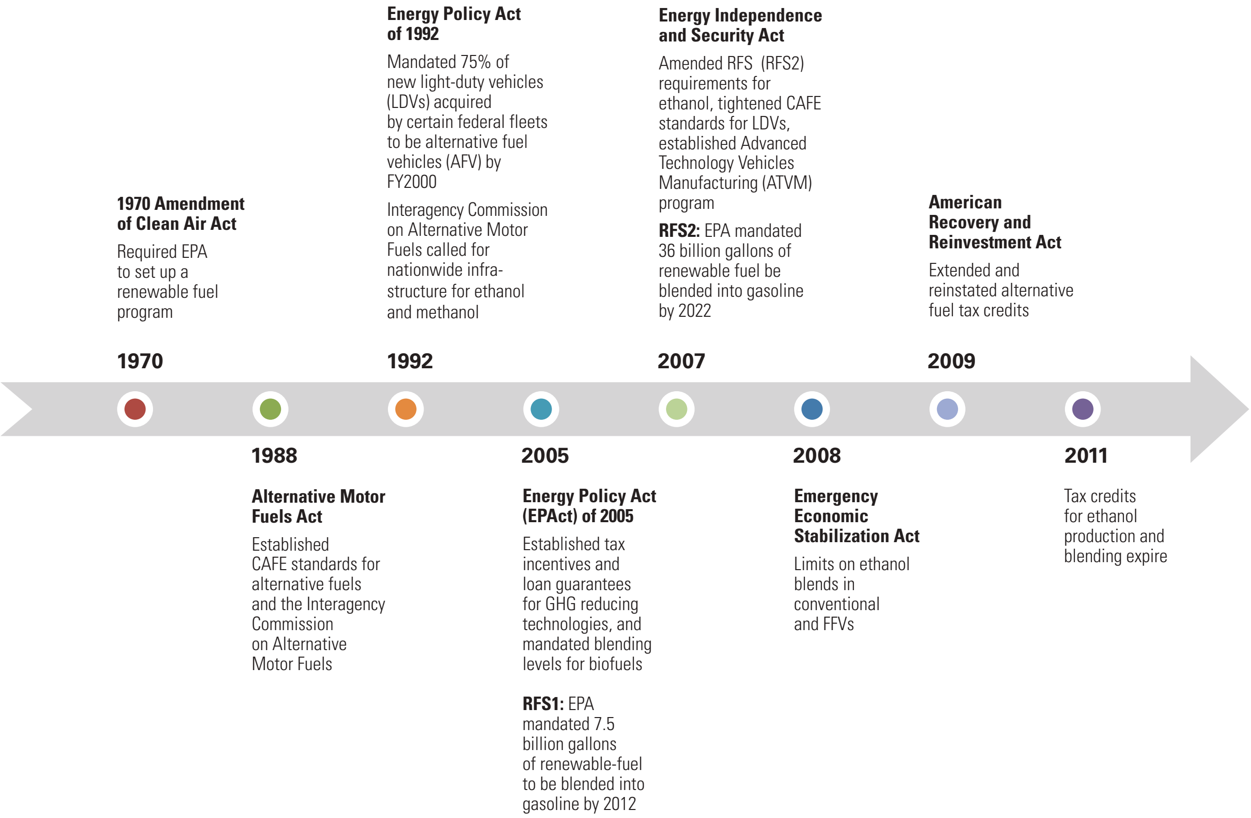
These tri-flex fuel vehicles proved successful for some groups of drivers (e.g., taxi drivers and individuals with short daily travel ranges). However, due to the short fuel mileage, these vehicles have not been popular with long-distance drivers.

Symposium participants discussed the issue of whether governmental policy intervention was warranted to enable effective competition of alternative fuels in the LDV market. The discussion also addressed questions regarding market failures caused by externalities and imperfect information, and the potential role of various policy instruments (standards and regulation, financial incentives, and Research and Development (R&D) funding) in correcting the market imperfections.

Historical Evolution of Alternative Fuels Legislation

The federal government has intervened in alternative fuels issues in a significant way for a variety of different policy reasons for at least the past three decades. Prompted by the oil crises of the 1970s and the growing awareness of the energy security and environmental issues raised by oil, alternative fuels (specifically renewable fuels such as ethanol) were first advocated to reduce oil import dependence. In the 1980s, leading up to the enactment of the Clean Air Act of 1990, alternative fuels were advocated as a strategy to reduce urban air emissions. Over the past decade, there has been interest in the expanded use of alternative fuels derived from biomass as a measure to reduce net CO_2 emissions in the transportation sector. Figure 30 illustrates the enactment of statutory authority affecting alternative fuels.

Figure 30 – Timeline of Federal Alternative Fuels Legislation



1970

1970 Amendment of Clean Air Act

Required EPA to set up a renewable fuel program

1988

Alternative Motor Fuels Act

Established CAFE standards for alternative fuels and the Interagency Commission on Alternative Motor Fuels

1992

Energy Policy Act of 1992

Mandated 75% of new light-duty vehicles (LDVs) acquired by certain federal fleets to be alternative fuel vehicles (AFV) by FY2000

Interagency Commission on Alternative Motor Fuels called for nationwide infrastructure for ethanol and methanol

2005

Energy Policy Act (EPAct) of 2005

Established tax incentives and loan guarantees for GHG reducing technologies, and mandated blending levels for biofuels

RFS1: EPA mandated 7.5 billion gallons of renewable-fuel to be blended into gasoline by 2012

2007

Energy Independence and Security Act

Amended RFS (RFS2) requirements for ethanol, tightened CAFE standards for LDVs, established Advanced Technology Vehicles Manufacturing (ATVM) program

RFS2: EPA mandated 36 billion gallons of renewable fuel be blended into gasoline by 2022

2008

Emergency Economic Stabilization Act

Limits on ethanol blends in conventional and FFVs

2009

American Recovery and Reinvestment Act

Extended and reinstated alternative fuel tax credits

2011

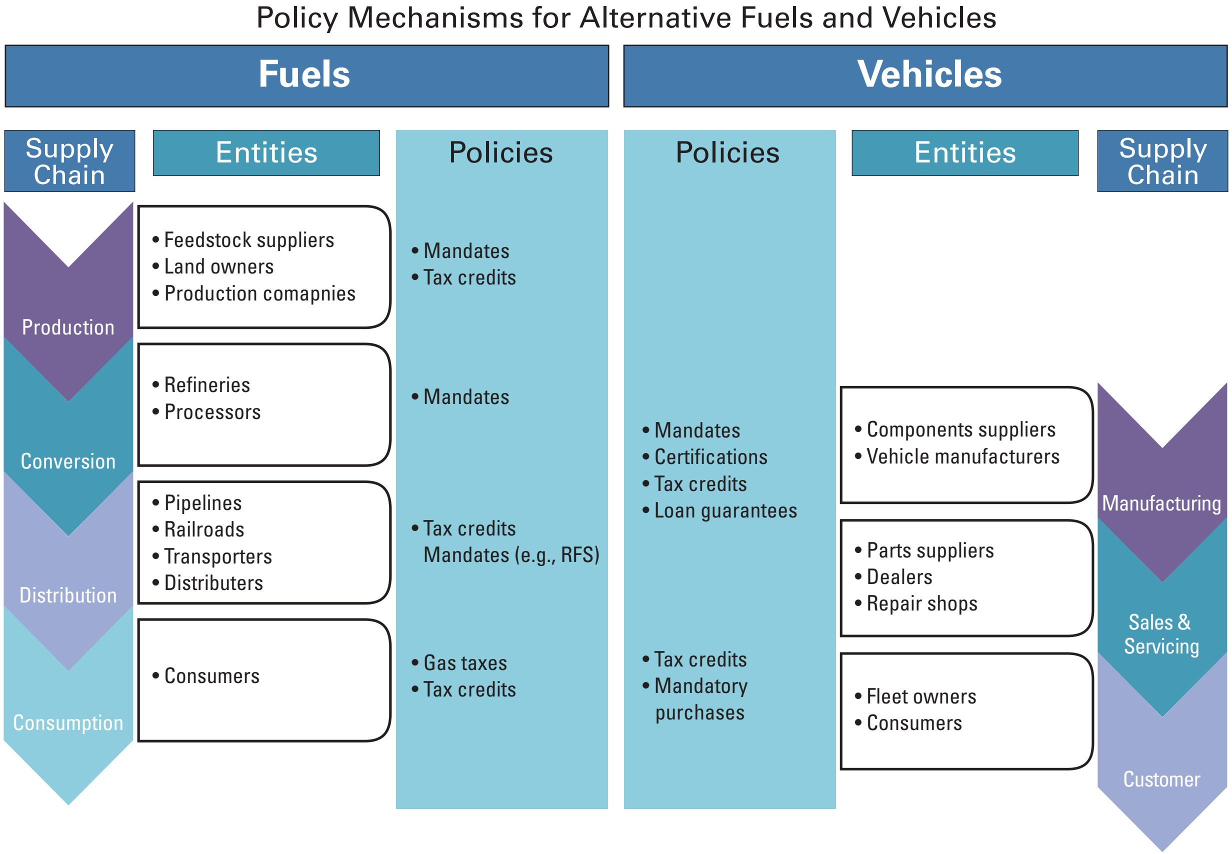
Tax credits for ethanol production and blending expire

Source: MITEI.

The United States has employed a variety of policy tools to stimulate the market for alternative vehicles and fuels, including incentives, mandates, tax credits, loan guarantees, and fleet demonstration programs. As illustrated in Figure 31, Government intervention has occurred in all stages of alternative fuel production and distribution as well as in AFV manufacturing and sales.

Policy mechanisms *stimulating production of alternative fuels* began with the Clean Air Act of 1970, which established the first renewable fuels program. The Energy Tax Act of 1978 created an excise tax credit for ethanol in gasoline, which was expanded several times in the 1980s and subsequently phased down beginning in the 1990s. In addition, legislation in the 1990s and early 2000s established a tax credit for ethanol producers, the VEETC, which expired at the end of 2011. Measures to mandate the use of alternative fuels began with the Clean Air Act of 1990, which established a minimum oxygen requirement for reformulated gasoline. Federal mandates were restructured and greatly expanded with the enactment of the Energy Policy Act of 2005, which established the RFS. The Energy Independence and Security Act of 2007 further expanded the RFS mandate.

Figure 31 – Policy Instruments Affecting All Elements of the Alternative Fuels Supply Chain



Source: MITEI.

Policy mechanisms stimulating production of AFVs by auto manufacturers began with the Alternative Motor Fuel Act of 1988, which authorized credits for AFVs with the CAFE program. In 1989, the federal government initiated purchases of AFVs for the federal fleet. The Energy Policy Act of 1992 mandated the purchase of AFVs by certain federal and state government fleets. The Energy Policy Act of 2005 added new provisions for AFV acquisition, tax incentives for the development of alternative fuel infrastructure, and mandated alternative fuel use in AFVs. The Energy Independence and Security Act of 2007 extended and expanded CAFE standards, including changes in the provisions for AFV credits.

Discussion of the Key Current Policies

Symposium participants discussed two policy measures in detail: credits for AFVs as part of the CAFE standards and the RFS programs.

Alternative Fuel Vehicle Credits in the Corporate Average Fuel Economy Program

Symposium participants focused on the role of CAFE standards in relation to alternative fuels and AFVs. In addition, there was some discussion as to provisions in the new CAFE standards that had the effect of encouraging the use of alternative fuels as a compliance option for meeting CAFE requirements.

Under the CAFE program, for vehicles through model year 2011, FFVs received special consideration that assisted manufacturers in meeting the CAFE goal of 27.5 MPG. For the purposes of calculating fuel economy, FFVs were assumed to operate on alternative fuels 50% of the time, and each gallon of alternative fuel was assigned a value equivalent to 0.15 gallons of gasoline. The combination of these two factors allowed the calculated MPG of a FFV (for CAFE compliance purposes) to be increased by a factor of 6.67 relative to its actual MPG value using gasoline 100% of the time. For example, a FFV at 15 MPG when operated with gasoline would be credited at 100 MPG for purposes of CAFE compliance.

Changes to the CAFE program in the 2007 Energy Independence and Security Act, as well as changes to harmonize CAFE with CO_2 tailpipe standards, have resulted in the phase-out of favorable conversion factors for FFVs. Beginning in model year 2016, manufacturers have to compute MPG for FFVs based on actual consumption of alternative fuels. Thus, vehicle manufacturers have a strong incentive to encourage owners of FFVs to actually use alternative fuel blends in those vehicles, in order to develop a database for future CAFE compliance purposes.

In May 2010, President Obama set goals for the next round of CAFE standards, affecting model year 2017–2025 LDVs. The proposed standard is much more stringent, calling on manufacturers to increase average efficiency to 54.5 MPG by 2025. To help manufacturers achieve these stringent standards, some flexibility for determining MPG values for FFVs will be reinstated.

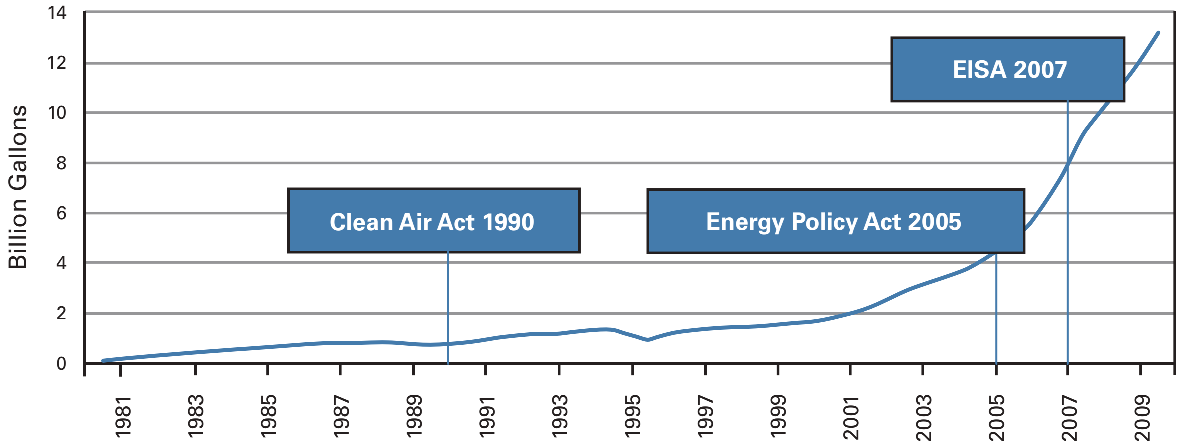
Participants noted that while the CAFE provisions for FFVs will become increasingly less favorable after model year 2012, CAFE provisions for EVs, PHEVs, and fuel cell vehicles are more favorable. For model years 2012 and beyond, these vehicles will be rated solely on the basis of downstream fuel use and emissions — essentially zero. The Obama Administration CAFE proposals for the 2017–2125 model years are more generous, allowing manufacturers to take credit for two vehicles for each EV or fuel cell vehicle produced, and credit for 1.6 vehicles for each PHEV produced. Several participants noted that these changes substantially tilt the policy playing field toward electrification of the LDV market relative to the use of alternative liquid fuels or CNG.

Alternative Fuel Mandates

Federal alternative fuel mandate have driven the growth of ethanol production over a 30-year period from nearly zero to almost 14 billion gallons annually, as illustrated in Figure 32.

The Energy Policy Act of 2005 included a Renewable Fuel Standard (RFS1), which mandated a minimum amount of alternate fuels to be blended into gasoline beginning in 2006. The Energy Independence and Security Act of 2007 extended and greatly expanded the RFS mandate to 36 billion gallons by 2022 (now known as RFS2). Total gasoline consumed in the US was approximately 133 billion gallons in 2011, thus the RFS mandate was equivalent to about 10% of total gasoline consumed in 2011, increasing to almost 27% by 2022.

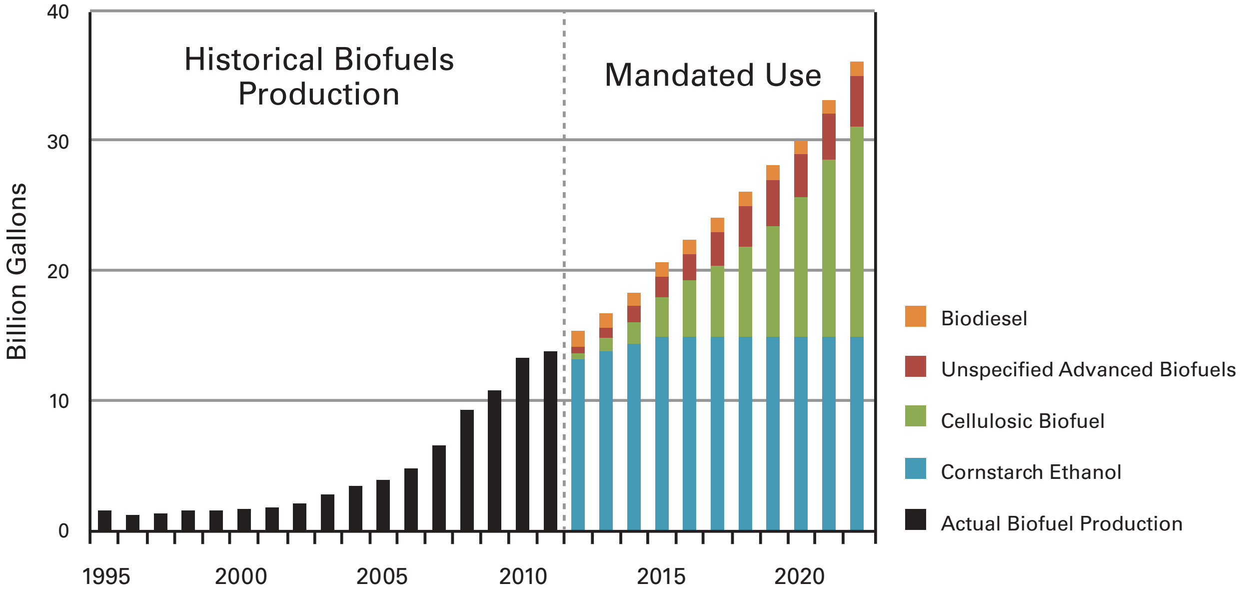
Figure 32 – Growth of US Ethanol Production in Response to Federal Mandates



Source: US Department of Agriculture, "US on Track to Become World's Largest Ethanol Exporter In 2011," http://www.fas.usda.gov/info/iatr/072011_ethanol_iatr.pdf

RFS1 also created an incentive for refiners to utilize cellulosic biomass, providing them with 2.5 renewable fuel credits for cellulosic ethanol. This means that each gallon of cellulosic ethanol counts as 2.5 gallons of renewable fuel toward the RFS mandate. RFS1 also set a floor on the quantity of cellulosic ethanol to be included in the overall RFS mandate, which could be adjusted based on EPA estimates of cellulose ethanol production and total gasoline demand. The cellulose ethanol floor in RFS1 was set at 250 million gallons in 2013. RFS2 substantially increased the mandated floor for cellulose ethanol so that by 2022, half of RFS requirement would be satisfied by cellulosic ethanol. The projected RFS2 mandate, along with its composition, is illustrated in Figure 33.

Figure 33 – RFS2 Mandate and Composition



Source: Congressional Research Service, January 2012. Available at http://www.nationalaglawcenter.org/assets/crs/R40155.pdf

Mandates are a hidden form of subsidy. In 2010 the Congressional Budget Office estimated that the costs of the RFS2 mandate ranged from $1.78/gal for corn ethanol to $3/gal for cellulosic ethanol, and that the implicit cost per ton of CO_2 reduced is $750/metric ton for ethanol and $275/ton for cellulosic ethanol.

The impact of the RFS on gasoline prices appears to be small, at least up to the date of the symposium. While some have speculated that the RFS increases average gasoline prices, EPA estimates that it has reduced average prices by about 2.5 cents/gal, the equivalent of $10.25/yr for an average vehicle owner (i.e., a 20-MPG vehicle driven 10,000 miles/yr).

Symposium participants discussed the fact that ethanol did not have a clear fuel advantage over other available biofuels based on its chemical properties. Rather, its primary advantage was in having a more developed fuel production infrastructure resulting from its history of receiving federal financial incentives as well as the RFS mandate. However, the prospects for further expansion of ethanol supply are being challenged by the possibility of limitation on the degree of ethanol blending with gasoline.

The Unsuccessful Effort to Incentivize the Introduction of Methanol Fuel

The focus on ethanol as the principal alternative liquid fuel ignores the history of efforts by the federal government to incentivize the introduction of methanol fuel. This effort originated in 1989, when the George H.W. Bush Administration, as part of a comprehensive Clean Air Act rewrite, proposed to establish a mandatory methanol vehicle program in the most polluted cities. The president also signed an Executive Order to mandate the purchase of methanol vehicles for the federal fleet.

The Clean Air Act of 1990, enacted by Congress one year later, established a reformulated gasoline program with a 2% oxygen requirement in lieu of the methanol vehicle mandate. Nonetheless, it was assumed at the time that the oxygenate would be either methanol or ethanol, and notwithstanding the tax incentives for ethanol production, the cost of methanol was highly competitive with ethanol.

In the implementation of the oxygenate requirement, refiners opted to use MTBE as the oxygenate of choice. In order to comply with the 2% oxygen requirement, refiners blended 11% by volume of MTBE into gasoline. Refiners and fuel distributors preferred MTBE because it did not have certain problematic characteristics of ethanol and methanol, principally that is was not hydrophilic and was not corrosive. Thus, it could be blended into gasoline at the refinery, avoiding the need for a dual distribution system and splash blending at storage terminals.

Environmental issues arose when spills of reformulated gasoline led to migration of MTBE into groundwater. MTBE is highly miscible with water and malodorous. This issue caused a number of states to ban the use of MTBE. Even so, the federal oxygenate requirement remained in statute, and refiners turned to ethanol as the oxygenate of choice. Finally, the Energy Policy Act of 2005 repealed the oxygenate requirement in favor of mandated use of renewable fuels (i.e., the RFS mandate currently in place).

Methanol remains as an EPA-approved additive to gasoline, but has not achieved significant penetration because it does not qualify under the RFS mandate. Under EPA rules, methanol and ethanol are considered to be fuel additives, and must have a waiver to be permitted in gasoline blends. Methanol currently has a fuel additive waiver from the EPA so that it can be used (with a co-solvent) in up to 5% blends with gasoline. However, the waiver for methanol cannot be used in addition to the waiver for up to 10% ethanol blends in gasoline. Since the RFS essentially requires 10% ethanol in all gasoline, and since methanol does not qualify for RFS compliance purposes, the use of methanol in gasoline currently is effectively blocked.

Thus, the most plausible scenario for introduction of large quantities of methanol fuel into the LDV market is through the introduction of dedicated methanol mono-fuel vehicles or the introduction of FFVs capable of utilizing methanol-rich blends, such as M85. The idea of the “GEM” fuel blend presented to symposium participants represents a novel option for introducing methanol into existing FFVs currently on the road.

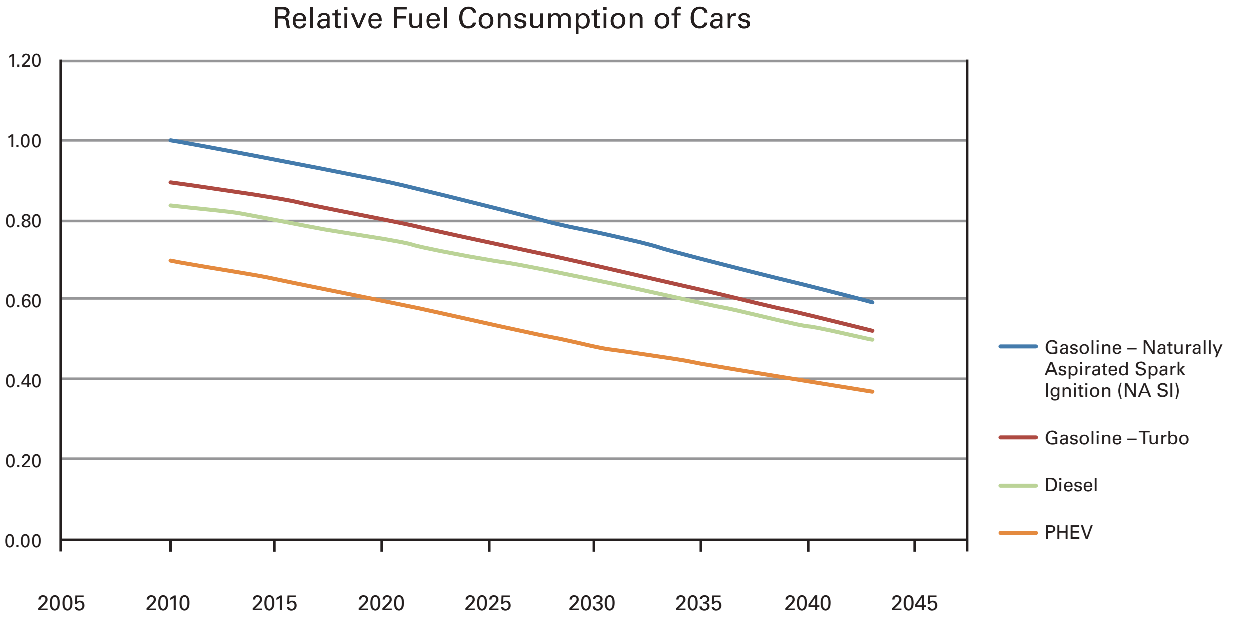
Are Alternative Fuels Needed in the US Transportation Fuel Market?

The discussion of various new policy measures to support the deployment of alternative fuels raised a more fundamental question by some symposium participants, namely, whether the United States should seek to develop an alternative fuels market for LDVs. These participants noted that new CAFE standards, combined with further advances in LDV technology, have the potential to bring about substantial reductions in the demand for liquid fuels. This reduction in demand provides an alternative policy approach to addressing energy security, national security, and environmental objectives established at the outset of the symposium.

Several participants noted that conventional vehicles are expected to experience gradual vehicle size and weight reduction of up to 15% by 2030 as a result of changes in vehicle design and the use of lighter materials, which will directly impact projected fuel consumption and will improve vehicle acceleration performance (projected to be a 10% increase). Based on current estimates — where a 10% reduction in vehicle weight gives a 6% reduction in fuel consumption — the 15% weight reduction by 2030 is projected to produce an 8% reduction in fuel consumption.

One of the participants, MIT Professor John Heywood, presented some projections from his research team on the demand for different transportation fuel and the relative shares of different types of vehicles. Figure 34 shows the volume of each fuel for a 100km-travel for different types of fuel. A similar trend is expected for light-duty trucks except for a 30%–40% higher amount of fuel consumption due to the particular vehicle's higher weight.

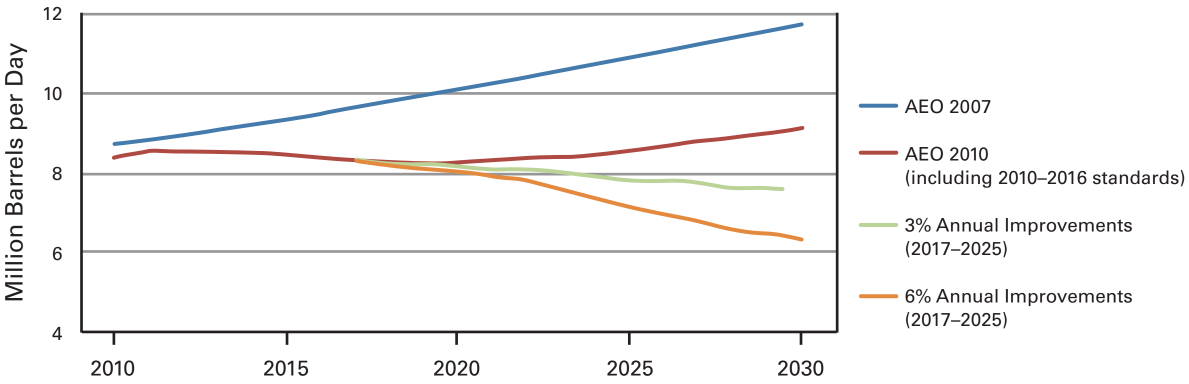
Figure 34 – Fuel Consumption Forecast of the Average Car for Different Powertrains over Time to 2050



Source: Bastani, Heywood, Hope, 2012.

The impact of fuel efficiency on total demand is illustrated in Figure 35. The figure shows that by 2030, fuel economy could potentially reduce oil consumption by nearly half. Most participants agreed that all available alternative fuels had reasonably similar trade-offs; reducing oil consumption by improving fuel economy provided a reasonably stable interim solution in addressing the oil security problem.

Figure 35 – Impact of Fuel-Economy Standards on Light-Duty Oil Demand



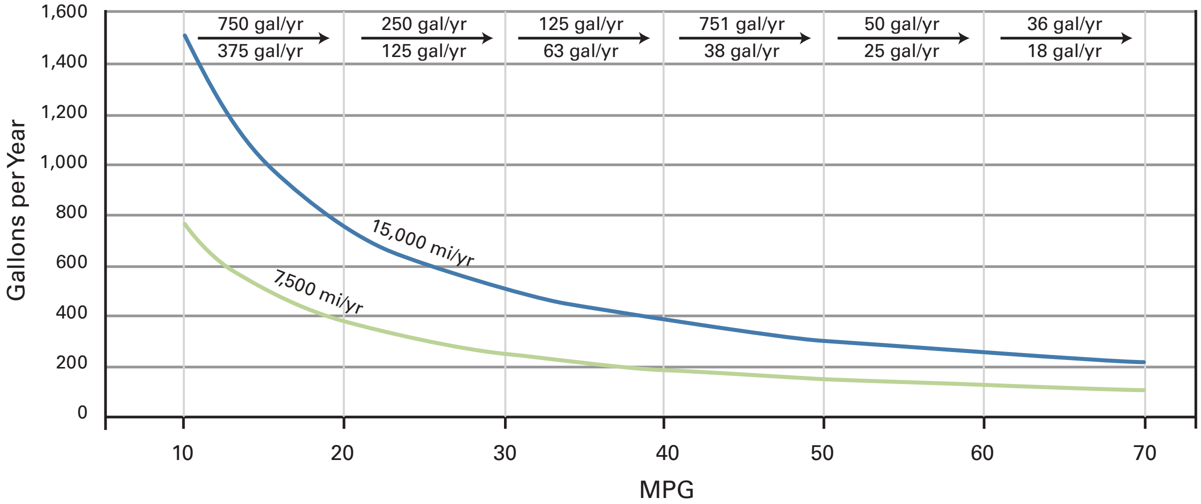
Source: DOE, EIA, SAFE Analysis.

There was some debate on the extent of the progress that has been made as a result of CAFE standards, noting that it was often masked by higher oil prices. Participants also discussed the fact that reliance solely on CAFE standards as the mechanism to reduce petroleum demand had significant limitations. Two issues — the rebound effect and new source bias — were identified in the discussion. The rebound effect is the tendency for individuals to drive more due to cheaper operating costs, as increased fuel efficiency reduces the effective price per mile. This effect has been estimated to be anywhere between 4.5% and 31%, and can offset efficiency gains. New source bias refers to reduced purchases of new vehicles due to the higher vehicle prices associated with more stringent efficiency regulations; the net result is that older, less-efficient vehicles tend to stay on the roads longer. National Highway Traffic and Safety Administration (NHTSA) and EPA estimates in support of the new CAFE standards assume a 10% rebound effect and a -1 price elasticity of demand for vehicles. Some participants noted that this analysis does not fully account for the impact on the used vehicle market or scrappage (though the negative price elasticity picks up some of the reduced demand for these vehicles given higher prices).

Participants reviewed analysis indicating that a policy solely focused on increasing fuel efficiency has diminishing returns. For example, replacing a sedan in the fleet with a hybrid equivalent costs the manufacturer around $3,000 given current hybrid technology (although exact costs are unknown, the difference in price between a hybrid car and its non-hybrid counterpart is approximately this amount). On the other hand, replacing an efficient non-hybrid vehicle with an electric vehicle costs anywhere between $10,000 and $30,000, mostly due to the cost of the battery (which, based on warranty information, is projected to need to be replaced more frequently than the battery in a hybrid due to its usage and cycles). Yet, reductions in gasoline consumption are much larger from replacing the sedan with the hybrid than replacing the efficient vehicle with an electric. Consider two vehicles: a 12-MPG vehicle and a 30-MPG vehicle. Increasing the 12-MPG vehicle by 2 MPG would result in fuel savings of 1.19 gallons per 100 miles driven. On the other hand, increasing the 30-MPG vehicle to 40 MPG would result in 0.08 gallons of fuel saved per 100 miles (assuming no change in Vehicle Miles Traveled (VMT) — if the rebound effect occurs, then the 40-MPG vehicle will be driven more than the 30-MPG vehicle, thus reducing even further the amount of gasoline saved).

Figure 36 demonstrates graphically the downward slope of these returns. This figure shows gasoline savings by increases in fuel efficiency (under assumed VMT of 15,000 or 7,500). For example, replacing a 20-MPG conventional gasoline vehicle with a 40-MPG hybrid vehicle would save 375 gallons (at 15,000 VMT) at a cost of $3,000, while replacing it with a 100-MPG electric vehicle would save 600 gallons at an average cost of $20,000. This implies marginal costs of $8/gal reduced vs. $33/gal reduced, demonstrating that although total gallons reduced are higher, it is less efficient (in an economic perspective) to replace a conventional gasoline vehicle with an EV compared to replacing it with a hybrid. An even larger number of gallons could be saved by replacing a 10-MPG vehicle with a traditional gasoline 20-MPG vehicle — and without spending thousands of dollars to do so.

Figure 36 – Annual Fuel Savings with Higher CAFE Standards



Source: William Chernicoff, Energy & Environmental Research Group Manager, Toyota Motor North American, Inc.

Possible Additional Areas for Government Intervention

A number of participants strongly supported the policy objective of achieving a substantial market penetration for alternative fuels in the LDV market. Participants discussed additional measures to complement existing policies that aim to address externalities created by oil dependency, create a controlled environment to test new technologies, support greater investment in R&D, and better inform consumers of alternative fuels and vehicle choices.

This discussion was framed by two concerns:

- The chicken and egg problem associated with what comes first: increasing alternative fuel production and building fuel distribution infrastructure or promoting the manufacturing of increased numbers of bi-fuel and flex-fuel vehicles. Vehicle manufacturers argue that there are an insufficient number of refueling stations, which deters consumers from investing in the vehicle, while fuel suppliers argue that there is insufficient demand for fuel to justify building refueling stations. While not fully resolved, participants believed that an Open Fuel Standard for vehicles may be the appropriate path forward to resolve this dilemma.

- The tendency to gravitate toward low-hanging fruit policies in which only fuel and vehicle technologies that are currently economically viable are incentivized, to the detriment of developing advanced technologies that may prove superior. Participants generally believed that a mix of policies was appropriate, with strong emphasis on R&D and technology advancement.

The principal alternative policy mechanisms discussed by the participants included the following:

Open Fuel Standard

A key regulatory option discussed by participants was the proposed Open Fuel Standard. The Open Fuel Standard is a mandate that OEMs manufacture FFVs capable of operating on a variety of fuels and fuel mixtures without the need for aftermarket adjustments. An Open Fuel Standard is a broad-based mandate that avoids the issue of picking winners and losers among particular combinations of alternative fueled vehicles, but rather would allow the market to decide the economically viable options. Requiring flex-fuel capability on OEM vehicles also facilitates consumer acceptance because consumers would be able to purchase vehicles with confidence that they meet all applicable environmental emissions standards and certifications.

The Open Fuel Standard Act of 2011 provides one possible blueprint for an Open Fuel Standard. As proposed, the proposed legislation would require each OEM to manufacture a minimum proportion of vehicles meeting the standard, on a mandated schedule of:

- 50% qualified vehicles in model year 2014;

- 80% qualified vehicles in model year 2016; and

- 95% qualified vehicles in model year 2017 and each subsequent year.

The legislation defines a “qualified vehicle” broadly to include:

- A vehicle that operates solely on natural gas, hydrogen, or biodiesel;

- An FFV capable of operating on gasoline, E85, and M85;

- A PEV; or

- A vehicle propelled solely by fuel cell or by a technology other than an ICE.

Participants noted that the rapid phase-in schedule in the proposed legislation would favor vehicle options that are developed and have sufficient production and distributional infrastructure in place.

Fuel Tax

While fuel economy standards could help stabilize domestic oil demand, the presence of a rebound effect — the tendency for people to drive more when they have a more efficient vehicle — could further negate its benefits. Some participants proposed implementing a fuel tax to curb demand and directly holding consumers responsible for reducing their fuel consumption. However, this could reduce the benefit of using alternative fuels and create long-term issues with replacing lost revenue from reduced fuel consumption.

Government Fleet Programs

Federal, state, and local governments can take the lead with respect to government-owned and operated LDV fleets. A controlled fleet program can provide a useful demonstration to test the technical performance and economic competitiveness issues regarding alternative fuels. For example, participants discussed a new initiative starting in Oklahoma and Colorado that is supported by 13 governors to help CNG vehicles gain market traction as well as consumer acceptance. The proposal commits the governors to transitioning their state fleet vehicles to run on CNG and work with auto manufacturers to help drive down the vehicle price point. Proponents note that this initiative parallels policies for EVs, and is not meant to pick a winner.

Better Informing the Public

Some participants argued that rather than help a particular technology become commercially viable, the government's role is in educating consumers and in making consumers internalize the externalities associated with gasoline consumption to change their behavior. In doing so, the most efficient vehicle would emerge naturally. Participants noted that certain alternative vehicle technologies, namely methanol and CNG-powered vehicles, were more impacted by negative consumer and public attitudes that sometimes could be attributed to sensationalized news.

Federal R&D Support

Federally funded R&D through agencies, including the National Science Foundation and US DOE, such as ARPA-E, is critical in discovering newer and/or more affordable technologies.

CNG Refueling Programs

One often overlooked but important aspect of using CNG-powered vehicles is the refueling process itself. As a compressed gas, CNG would require specific refueling tools that often require proper training or otherwise could lead to dangerous leakages. Government could provide a useful role in setting specific standards on this process, so as to minimize potential technology incompatibilities.

Another option discussed by the participants is the possibility of financial incentives for purchasing a CNG home-refueling device, which would help reduce the cost barrier as well as mitigate some of the problems with fuel accessibility.

Vehicle and Fuel Certification Process

Fuel certification and emission standards should be developed for this new type of tri-flex-fuel by the EPA. This might be a very complex or time-consuming process for this kind of a complex blend fuel.

ENDNOTES

1 MITEI, “Electrification of the Transportation System,” Symposium Report, April 2010.

2 MITEI, “Electrification of the Transportation System,” Symposium Report, April 2010.

3 US Energy Information Administration, Annual Energy Review 2011, published September 2012.

4 US Energy Information Administration, Annual Energy Review 2011.

5 Steven E. Koonin, “The Evolving Fuels Context for Light-Duty Vehicles, MITEI Symposium White Paper, April 2012.

6 Steven Koonin, Symposium White Paper.

7 Testimony of Dr. Gal Luft, Executive Director, Institute for the Analysis of Global Security, presented before the House Committee on Foreign Affairs, December 16, 2011.

8 Steven Koonin, Symposium White Paper.

9 Steven Koonin, Symposium White Paper.

10 www.autoalliance.org/auto-economics, and www.api.org/policy-and-issues/policy-items/jobs/energy-works

11 Ulrich Kramer and James E. Anderson, Ford Motor Company, “Prospects for Flexible- and Bi-Fuel Light-Duty Vehicles: Consumer Choice and Public Attitudes,“ Symposium White Paper, April 2012.

12 US Energy Information Administration, Annual Energy Review 2011.

13 US Energy Information Administration, Annual Energy Review 2011.

14 MITEI, “The Future of Natural Gas: An MIT Interdisciplinary Study,” 2011.

15 MITEI, “Electrification of the Transportation System,” Symposium Report, April 2010.

16 Fuels and vehicles that were not discussed in the symposium, and are not further discussed in this report, include butanol, coal-to-liquids, hydrogen, dual-fuel vehicles, dedicated vehicles, and biodiesel/diesel.

17 Dual-fuel vehicles are another type of alternative vehicle in which there are two independent fuel systems that can run on both fuels simultaneously or on one fuel alone.

18 Others have defined drop-in fuel as not only being compatible with vehicles, but also with current infrastructure.

19 Recently, the EPA has tested and approved E15 for use in vehicles from model years 2001 and newer. However, “GreenWire” reported on Jan 29, 2013, that a study conducted by the Coordinating Research Council (CRC) found gasoline with 15% ethanol by volume (E15) damages critical fuel components in an automobile fuel system. In their study, researchers used several car models — the 2007 Nissan Altima, 2001 Chevrolet Cavalier, 2004 Ford Focus, 2003 Nissan Maxima, and 2004 Ford Ranger. The fuel components used in this study represent 29 million vehicles that are currently on the road. The study found that E15 could completely fail fuel systems in some cars. Based on this result, the American Petroleum Institute argues that the testing on E15 by EPA and DOE was not correct and that the Renewable Fuel Standard should be repealed. Biofuels groups showed their disagreement with the result of the study. “The CRC study by contrast doesn’t reflect a single mile driven, but rather, car components tested in isolation. By researchers’ own admission, testing also included an ‘aggressive’ E15 blend that includes more water and acid than what consumers would use in their cars,” said Fuel America, a coalition of biofuels supporters.

20 Ulrich Kramer and James Anderson, Symposium White Paper.

21 David J. Ramberg and John E. Parsons, “The Weak Tie Between Natural Gas and Oil Prices,“ *The Energy Journal*, Vol. 33, No. 2, 2012.

22 Michael D. Jackson, “The Case for Bi-fuel Natural Gas Vehicles,” Symposium White Paper, April 2012.

23 Oak Ridge National Laboratory, Transportation Energy Data Book, 30th Edition, 2011.

24 US Energy Information Administration, Annual Energy Review 2011.

25 Paul Jarod Murphy, “The Role of Natural Gas as a Vehicle Transportation Fuel,” Master’s Thesis, Massachusetts Institute of Technology, June 2010.

26 Natural Gas Vehicle Association, http://www.ngvc.org/gov_policy/index.html

27 Energy Policy Act of 1992 — Fleet Program, NGVAMERICA, http://www.ngvc.org/gov_policy/fed_regs/fed_EPAFleetPrg.html

28 Fact Sheet: Converting light-duty vehicles to natural gas,” NGVAMERICA, http://www.ngvc.org/pdfs/FAQs_Converting_to_NGVs.pdf

29 Fact Sheet, converting light-duty vehicles to natural gas, NGVAMERICA, http://www.ngvc.org/pdfs/FAQs_Converting_to_NGVs.pdf

30 US Department of Energy, Alternative Fuels Data Center.

31 Michael Jackson, Symposium White Paper.

32 Michael Jackson, Symposium White Paper.

33 Michael Jackson, Symposium White Paper.

34 Michael Jackson, Symposium White Paper.

35 Ulrich Kramer and James Anderson, Symposium White Paper.

36 Fact Sheet: Converting light-duty vehicles to natural gas, NGVAMERICA, http://www.ngvc.org/pdfs/FAQs_Converting_to_NGVs.pdf

37 Paul Jarod Murphy, "The Role of Natural Gas as a Vehicle Transportation Fuel," Massachusetts Institute of Technology, June 2012.

38 Ulrich Kramer and James Anderson, Symposium White Paper.

39 This discussion is adapted from E-85 and Flex-Fuel Technology, Blaine M. Heisner, Southern Illinois University Carbondale, 2008.

40 From Flexible Fuel Vehicles, Alternative Fuels Data Center (AFDC), http://www.afdc.energy.gov/vehicles/flexible_fuel.html

41 Ulrich Kramer and James Anderson, Symposium White Paper.

42 Roberta J. Nichols, "The Methanol Story: A Sustainable Fuel for the Future," *Journal of Scientific and Industrial Research*, Vol. 62, January–February 2003.

43 Roberta J. Nichols, op. cit.

44 Roberta J. Nichols, op. cit.

45 Vehicle changes for E85 Conversion, Coleman Jones, Clean Cities Webcast.

46 Elisheba Spiller, "Regulations and Incentives for Alternative Fuels and Vehicles," Symposium White Paper, April 2012.

47 MITEI, "The Future of Natural Gas: An Interdisciplinary Study," 2011.

48 L. Bromberg and W.K. Cheng, "Methanol as an Alternative Transportation Fuel in the US: Options for Sustainable and/or Energy-Secure Transportation," Sloan Automotive Laboratory, Massachusetts Institute of Technology, November 2010.

49 Steven Koonin, Symposium White Paper.

50 Roberta J. Nichols, op. cit.

51 US Energy Information Administration, Annual Energy Review 2011.

52 Ulrich Kramer and James Anderson, Symposium White Paper.

53 Molly F. Sherlock, "Energy Tax Policy: Historical Perspectives on and Current Status of Energy Tax Expenditures," Congressional Research Service, May 2011.

54 US Energy Information Administration, Annual Energy Review 2011.

55 US Energy Information Administration, Annual Energy Review 2011.

56 MITEI, "The Future of Natural Gas: An MIT Interdisciplinary Study," 2011.

57 Steven Koonin, Symposium White Paper.

58 Steven Koonin, Symposium White Paper.

59 US Department of Energy, Clean Cities, Vehicle Technologies Program, http://www.afdc.energy.gov/uploads/publications/clean_cities_overview.pdf

60 http://www.afdc.energy.gov/fuels/natural_gas_cng_stations.html#fastfill

61 Bromberg and Cheng, op. cit.

62 M.A. Weiss et.al., "On the Road in 2020," MIT Energy Laboratory Report MIT EL-00-003, October 2000.

63 R. Abbott et. al., "Evaluation of Ultra Clear Fuels from Natural Gas," Conoco Phillips, Nexant and Pennsylvania State University, Final Report for the US Department of Energy, 2006.

64 MIT, "The Future of Natural Gas."

65 Bromberg and Cheng, op. cit.

66 Nichols R J et al., Cold Start Studies, Canadian Flexible Fuel Vehicle Program, Final Report, Ontario Ministry of Energy, March 31, 1987.

67 Roberta J. Nichols, op. cit.

68 S. Yeh, "An Empirical Analysis on the Adoption of Alternative Fuel Vehicles: The Case of Natural Gas Vehicles," *Energy Policy*, 35(11):5865-5875.

69 MITEI, "The Future of Natural Gas: An Interdisciplinary MIT Study," 2011.

70 X-Prize Foundation, "National Household Travel Survey Data Summary for X-Prize," http://www.progressiveautox-prize.org/files/downloads/auto/AXP_FHWA_driving_stats.pdf. March 2007.

71 Michael Jackson, Symposium White Paper.

72 Michael Jackson, Symposium White Paper.

73 Ulrich Kramer and James Anderson, Symposium White Paper.

74 Ulrich Kramer and James Anderson, Symposium White Paper.

75 China: The Leader in Methanol Transportation, Methanol Institute http://www.methanol.org/Methanol-Basics/Resources/China-Methanol.aspx

76 Natural Gas "Flex" Cars in Brazil, Anna Fitzpatrick, April 12, 2011, *The Rio Times.*

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GLOSSARY OF TERMS

Vehicle Terms

Battery electric vehicle (BEV): A vehicle that uses batteries to store the electrical energy that powers the motor.

Bi-fuel vehicle: A vehicle that is capable of operating on and switching between two fuels — generally gasoline or diesel and an alternative fuel — that are stored in separate tanks. Unlike a flex-fuel vehicle, a bi-fuel vehicle engine runs on one fuel at a time and the fuels are not mixed.

Conventional gasoline vehicle: A vehicle that runs on conventional gasoline fuel.

CNG-dedicated vehicle: A vehicle that runs on only compressed natural gas.

CNG/Gasoline Bi-fuel vehicle: A vehicle that is capable of operating and switching between CNG and gasoline that are stored in separate tanks.

Dedicated or mono-fuel vehicle: Any vehicle engineered and designed to be operated using a single fuel.

Dual-fuel vehicle: A type of a FFV in which there are two independent fuel systems that can operate on both fuels simultaneously or on one fuel alone.

Electric vehicle (EV): An electric vehicle (EV), also referred to as an electric drive vehicle, uses one or more electric motors <http://en.wikipedia.org/wiki/Electric_motor> or traction motors <http://en.wikipedia.org/wiki/Traction_motor> for propulsion <http://en.wikipedia.org/wiki/Ground_propulsion>. Three main types of electric vehicles <http://en.wikipedia.org/wiki/Vehicle> exist, those that are directly powered from an external power station, those that are powered by stored electricity originally from an external power source, and those that are powered by an onboard electrical generator, such as an ICE (a hybrid electric vehicle) or a hydrogen fuel cell.

Flex-fuel vehicle (FFV): A vehicle designed to run on more than one fuel, usually gasoline blended with ethanol or methanol. The most common FFVs in the world use ethanol as their alternative fuel source. Unlike bi-fuel vehicles, FFVs store two fuels in the same tank.

Heavy-duty vehicle: An on-road vehicle with a gross vehicle weight rating equal to or greater than 26,001 pounds. Transit buses and large delivery trucks fall into this category.

Hybrid electric vehicle (HEV): A vehicle powered by 1) an ICE or other propulsion source that can be run on conventional or alternative fuel and 2) an electric motor that uses energy stored in a battery. Hybrid electric vehicles combine the benefits of high fuel economy and low emissions with the power and range of conventional vehicles.

Light-duty vehicle (LDV): An on-road vehicle with a gross vehicle weight rating equal to or less than 8,500 pounds. Automobiles, motorcycles, minivans, SUVs and other small pickups fall into this category.

Medium-duty vehicle: An on-road vehicle with a gross vehicle weight rating between 8,501 and 26,000 pounds. Some larger cargo vans, pickup trucks, and maintenance trucks fall into this category.

Natural gas vehicle (NGV): A natural gas vehicle (NGV) is an alternative fuel vehicle <http://en.wikipedia.org/wiki/Alternative_fuel_vehicle> that uses compressed natural gas (CNG) <http://en.wikipedia.org/wiki/Compressed_natural_gas> or liquefied natural gas (LNG) <http://en.wikipedia.org/wiki/Liquefied_natural_gas> as a cleaner alternative to other fossil fuels <http://en.wikipedia.org/wiki/Fossil_fuel>. Natural gas vehicles should not be confused with vehicles powered by propane <http://en.wikipedia.org/wiki/Autogas> (LPG) <http://en.wikipedia.org/wiki/Liquefied_petroleum_gas>, which is a fuel with a fundamentally different composition. Worldwide, there were 14.8 million natural gas vehicles by 2011.

Plug-in hybrid electric vehicle (PHEV): A plug-in hybrid electric vehicle (PHEV), plug-in hybrid vehicle (PHV), or plug-in hybrid is a hybrid vehicle <http://en.wikipedia.org/wiki/Hybrid_electric_vehicle> which utilizes rechargeable batteries <http://en.wikipedia.org/wiki/Rechargeable_battery>, or another energy storage device, that can be restored to full charge by connecting a plug to an external electric power <http://en.wikipedia.org/wiki/Electric_power> source (usually a normal electric wall socket <http://en.wikipedia.org/wiki/AC_power_plugs_and_sockets>). A PHEV shares the characteristics of both a conventional hybrid electric vehicle, having an electric motor <http://en.wikipedia.org/wiki/Electric_motor> and an internal combustion engine (ICE) <http://en.wikipedia.org/wiki/Internal_combustion_engine>; and of an all-electric vehicle <http://en.wikipedia.org/wiki/All-electric_vehicle>, having a plug <http://en.wikipedia.org/wiki/AC_power_plugs_and_sockets> to connect to the electrical grid <http://en.wikipedia.org/wiki/Electrical_grid>. Most PHEVs on the road today are passenger cars, but there are also PHEV versions of commercial vehicles and vans, utility trucks, buses, trains, motorcycles, scooters <http://en.wikipedia.org/wiki/Scooter_(motorcycle)> , and military vehicles.

Tri-flex fuel vehicle: A vehicle that is capable of operating on a blended mixture of gasoline and two alternative fuels in a single tank. In the symposium, primarily gasoline/ethanol/methanol vehicles were considered.

Fuel Terms

Alternative fuel: Any fuel material that is not conventional fuel. Alternative fuels for transportation include methanol, denatured ethanol, compressed or liquefied natural gas, liquefied petroleum gas (propane), hydrogen, coal-derived liquid fuels, cellulosic biofuel, and electricity.

Biodiesel: Vegetable oil or animal fat–based diesel fuel. Biodiesel can be used alone or as a mixture with diesel fuel in any diesel engines.

Conventional (traditional) fuel: Fuel that is petroleum-based (e.g., gasoline and diesel).

Drop-in fuel: Fuel that can currently be blended with conventional petroleum-based fuel (gasoline, diesel) and used in conventional gasoline- or diesel-powered vehicles without requiring vehicle modifications (e.g., E5-E15, M5, and biodiesel).

Drop-out fuel (non-drop-in fuel): Fuel that is not drop-in fuel. There are two types of drop-out fuels:

- **Blendable drop-out fuel:** Fuel that can be blended with gasoline but requires vehicle and/or infrastructure modifications for use (e.g., E85, M85).

- **Physical drop-out fuel:** Fuel that cannot be blended with conventional petroleum-based fuel (e.g., electricity, CNG).

Ethanol blend fuel: A mixture of liquid ethanol and gasoline in various ratios. “E” numbers describe the percentage of ethanol fuel in the mixture by volume. For example, E15 is 15% anhydrous ethanol and 85% gasoline by volume.

Methanol blend fuel: A mixture of liquid methanol and gasoline in various ratios. “M” numbers describe the percentage of ethanol fuel in the mixture by volume.

Tri-flex fuel: A fuel mixture of gasoline and two alternative fuels in a single tank. In the symposium, a tri-flex fuel composed of gasoline, ethanol, and methanol was discussed.

XTL: Any alternative liquid fuel produced from conversion of a solid or gaseous feedstock. This includes, Coal-to-Liquids (CTL), Gas-to-Liquids (GTL), and Coal/Biomass-to-Liquids (CBTL).

ABBREVIATIONS / ACRONYMS

AFDC	Alternative Fuels Data Center
AFV	Alternative Fuel Vehicle
AKI	Anti-Knock Index
ARPA-E	Advanced Research Projects Agency – Energy
BEV	Battery Electric Vehicle
CAFE	Corporate Average Fuel Economy
CBL	Coal/Biomass-to-Liquids
cf	Cubic Feet
CNG	Compressed Natural Gas
CTL	Coal-to-Liquids
DME	Dimethyl Ether
DOE	Department of Energy
DOT	Department of Transportation
E10	Low-level Blend, 10% Ethanol, 90% Gasoline
E85	Ethanol Fuel Blend
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EU	European Union
EV	Electric Vehicle
FFV	Flex-Fuel Vehicle
gal	Gallon
GDP	Gross Domestic Product
GEM	Gasoline/Ethanol/Methanol
GGE	Gallon of Gasoline Equivalent
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GTL	Gas-to-Liquids
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
LDV	Light-Duty Vehicle
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
M5	Methanol with Gasoline
M100	Pure Methanol
mcf	Thousand Cubic Feet
MON	Motor Octane Number
MPG	Miles Per Gallon
MTBE	Methyl-Tertiary-Butyl-Ether
NA SI	Naturally Aspirated Spark Ignition
NEVC	New England Vehicle Council
NGV	Natural Gas Vehicle
NHTSA	National Highway Traffic Safety Administration
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
OPEC	Organization of the Petroleum Exporting Countries
PCM	Powertrain Control Module
PHEV	Plug-in Hybrid Electric Vehicle
psi	Pounds per square inch
R,D,&D	Research, Development, and Deployment
R&D	Research and Development
RFS	Renewable Fuels Standard
RON	Research Octane Number
SUV	Sport Utility Vehicle
tcf	Trillion Cubic Feet
USDA	US Department of Agriculture
VEETC	Volumetric Ethanol Excise Tax Credit
VMT	Vehicle Miles Traveled

COMPREHENSIVE SUMMARY OF VEHICLE-FUEL OPTIONS

This section provides a comprehensive summary of possible alternative fuels and vehicles options. These options include all the ideas proposed by the participants from the symposium as well as those reflected in the discussions after the symposium. The options are listed below, in Table 22 and then discussed in more detail.

Table 22 – Summary of Vehicle-Fuel Combinations

Option #	Fuel Options		Vehicle Options
1	Increase Vehicle Energy Efficiency		Conventional gasoline vehicle
Drop-in Fuels			
2	E5–E15		Conventional gasoline vehicle
3	M5 (maximum volume allowed, from 1986)		Conventional gasoline vehicle
4	Biodiesel up to 100%		Conventional diesel vehicle
Drop-out Fuels			
5	Blendable drop-out fuels	Ethanol (E16-E85)	FFV
6		Methanol (M6-M85)	FFV for methanol
7		Tri-flex fuel (Gasoline + ethanol + methanol)	Tri-flex fuel vehicle
8	Physical drop-out fuels	CNG	CNG-dedicated vehicle
9			Bi-fuel vehicle
10		Electricity	Electricity-dedicated vehicle
11			Hybrid electric vehicle

Source: MITEI.

Except for the biodiesel option in the Drop-in Fuels category, the other two fuel options (E5-E15 and M5) cannot achieve gasoline price decoupling from the price of corresponding alternative fuels. This is because at E15 and M5 level, the total supply of either ethanol or methanol is too small so that the demand and the supply curve of both ethanol and methanol intersect at points where the price of either the two fuels is higher than the price of gasoline.

However, it is important to remember that those two options are still beneficial to the society, since they diversify fuel options for consumers. The existence of an alternative fuel compared with the gasoline-only situation creates 1) consumer surplus (until the point when the methanol supply curve is smaller than the world gasoline price) and 2) fuel arbitrage.

Option 1. Increase Vehicle Energy Efficiency

Compression-ignition engine with diesel fuel operates with about 20% higher efficiency compared to non-turbocharged gasoline engines on an energy-equivalent basis and about 30% higher efficiency on a fuel-volume basis. Efficiency of diesel engines will gradually improve but the increase will not be as high as the increase gain in gasoline engines. Transmission efficiency of diesel vehicles will improve by about 10% as powertrain incorporates more efficient shifting mechanisms. Currently the United States does not extensively use diesel and on a fuel-volume basis, diesel is more expensive than gasoline.

Vehicles for Drop-in Fuels

Option 2. E5-E15 Fuel + Conventional Gasoline Vehicle

Currently up to E15 (15% of ethanol by volume) can be used for conventional gasoline vehicles without vehicle modifications. It was the general view of participants that at this maximum level of ethanol blend, ethanol price is coupled with the gasoline price since the ethanol supply is not large enough.

Option 3. M5 + Conventional Gasoline Vehicle

In the United States, the maximum level of methanol that can be blended with gasoline for conventional gasoline vehicles is set at 5% by volume. Again, the amount of total methanol supply is restricted at a certain level such that the price of methanol in the market is determined at a point higher than the price of gasoline. Therefore, the methanol price is coupled with the gasoline price.

Option 4. Biodiesel up to 100% + Conventional Diesel Vehicle

Biodiesel refers to a vegetable oil or animal fat–based diesel fuel and it can be used with and without petro-diesel. In other words, biodiesel can be used from 0% to 100% by volume for conventional diesel vehicles without vehicle modification. In this sense, biodiesel is a perfect drop-in fuel.

For biodiesel to bring about price decoupling with diesel price, the supply curve of biodiesel should intersect with the demand curve at a price lower than the price of diesel. For this scenario to happen, the number of diesel vehicles needs to substantially increase in the United States.

Vehicles for Drop-out (Non-Drop-in) Fuels

According to the definition of a drop-in fuel, there exist two different types of drop-out fuels. First, fuels that can be blended with gasoline but require vehicle modifications are classified as drop-out fuels. This includes ethanol (E16-E85), methanol (M6-M85), and tri-flex fuel (mixture of gasoline + ethanol + methanol). Second, fuels that are not physically blendable with gasoline are another type of drop-out fuels. Compressed natural gas and electricity are the examples.

A. Blendable Drop-out Fuel Options

Option 5. Ethanol (E16-E85) + Current FFV

Current FFVs can run on ethanol and gasoline blend up to 85% of ethanol by volume (E85). Ethanol price decoupling with the price of gasoline can occur when the demand curve and the supply curve of ethanol intersect at a point where the ethanol price is lower than the price of gasoline. This scenario requires a wider distribution of FFVs, an increase in ethanol production.

Option 6. Methanol (M6-M85) + FFV for Methanol

Current FFVs are designed and certified to run on ethanol blends but not on methanol blends. Methanol fuel is corrosive to engines and fuel lines in vehicles, therefore, high levels of methanol as fuel requires vehicle modifications. Methanol price decoupling with the price of gasoline occurs when the demand curve and the supply curve of methanol determine the methanol price that is lower than the gasoline price. For this to be realized, both the number of FFVs for methanol and the production of methanol fuel need to be increased substantially.

Option 7. Tri-Flex Fuel (Gasoline + Ethanol + Methanol) + Tri-Flex Fuel Vehicle

Tri-flex vehicles are capable of operating on a fuel mixture of gasoline and two other alternative fuels in a single tank. At the symposium Turner et al. from Lotus Engineering argued that a fuel blend of gasoline, ethanol and methanol (called GEM blend) can be produced in a way that the blend has the same stoichiometric property as that of E85 and as a result, the difference between this new blend and E85 is invisible to a current FFV. They also argued that producing vehicles that can run on the GEM blend is not highly challenging since current FFVs have been already tested with M100. In addition, since there are three fuel sources, the opportunities for fuel arbitrage are maximized.

B. Physical Drop-out Fuels Options

Option 8. CNG + CNG-Dedicated Vehicle

CNG-dedicated vehicles run on only CNG. Compressed natural gas requires high compression (typically at 3,000–3,600 psi) for storage, which makes it more expensive to operate refueling stations. In 2009, the United States had 114,270 CNG vehicles and most of them were buses. Although CNG is a physical drop-out fuel, whether its price can be easily decoupled with the price of gasoline is less certain because of the historical link between the price of natural gas and the price of oil in the United States. There is no fuel arbitrage opportunity since CNG is the only fuel source.

Option 9. CNG / Gasoline + Bi-Fuel Vehicle

CNG/Gasoline bi-fuel vehicles are capable of operating and switching between CNG and gasoline that are stored in separate tanks. Many gasoline-powered vehicles can be converted to bi-fuel vehicles in the aftermarket. Due to the same reason mentioned in the previous case, the price decoupling effect is not certain. Fuel arbitrage opportunities exist since there are two fuel options.

Option 10. Electricity + Electricity-Dedicated Vehicle (BEV)

Battery electric vehicles use batteries to store the electrical energy that powers the motor. Battery electric vehicles rely solely on electricity. Since electricity is a physical drop-out fuel and the overlap between the electricity market and the gasoline market is minimal, the price decoupling is naturally achievable. Fuel arbitrage opportunities do not exist since electricity is the only fuel source.

Option 11. Electricity/Gasoline + Hybrid Electric Vehicle

Hybrid electric vehicles are powered by 1) an ICE or other propulsion source that can be run on conventional or alternative fuel and 2) an electric motor that uses energy stored in a battery. Due to the same reasons mentioned in the BEV case (Option 10), price decoupling is easily achievable. There is fuel arbitrage opportunity since there are two fuel options. However, the benefit is limited because HEVs cannot only rely on electricity due to their small battery capacity.

SYMPOSIUM AGENDA

2012 MITEI Symposium

Prospects for Bi-Fuel and Flex-Fuel Light-Duty Vehicles

Boston Marriott Cambridge
Two Cambridge Center, 50 Broadway, Cambridge, MA
April 19, 2012

8:30–9:00 **Breakfast**

9:00–10:30 **Framing the Issues**
Policy Overview
White Papers/Speakers:
Dr. Steven E. Koonin, Institute for Defense Analysis
Prof. John Heywood, MIT
Discussant #1: Prof. Bruce Dale, Michigan State University
Discussant #2: Dr. Gal Luft, Institute for the Analysis of Global Security

10:30–10:45 **Morning Break**

10:45–12:45 **Vehicles**
Bi Fuel
White Paper/Speaker:
Mr. Michael D. Jackson, TIAX LLC
Discussant #1: Prof. William Green, MIT
Discussant #2: Mr. Richard Kolodziej, NGVAmerica
Discussant #3: Mr. Kevin Stork, US DOE

Tri-Flex Fuel
White Paper/Speaker:
Dr. James Turner, Lotus Powertrain
Discussant #1: Dr. José Coelho Baeta, Fiat South America
Discussant #2: Mr. Norman Brinkman, General Motors
Discussant #3: Dr. Daniel Cohn, MIT

12:45–1:30 **Lunch Break**

1:30–2:30 **Consumer Choice and Public Attitudes**
White Paper/Speaker:
Dr. Ulrich Kramer and Dr. James E. Anderson, Ford Motor Company
Discussant #1: Dr. Alicia Birky, TA Engineering, Inc.
Discussant #2: Prof. Stephen Ansolabere, Harvard University

2:30–2:45 **Afternoon Break**

2:45–4:00 **Policy & Regulation**
White Paper/Speaker:
Dr. Elisheba Beia Spiller, Resources for the Future
Discussant #1: Prof. Christopher Knittel, MIT
Discussant #2: Mr. Ronald Minsk, Securing America's Future Energy
Discussant #3: Mr. Jay Albert, Deputy Secretary of Energy, State of Oklahoma
Discussant #4: Mr. Michael Carr, Senior Counsel, Senate Committee on Energy and Natural Resources

4:00–4:30 **Closing Discussion**
Chair: Prof. Ernest Moniz, MIT Prof. John Deutch, MIT

SYMPOSIUM PARTICIPANTS

Prospects for Bi-Fuel and Flex-Fuel Light-Duty Vehicles

Boston Marriott Cambridge
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The Evolving Fuels Context for Light-Duty Vehicles

Steven E. Koonin

April, 2012

Abstract

This paper discusses the evolving fuels context for light-duty vehicles, with an emphasis on supply and infrastructure. Key points of techno-economic analyses of diverse liquid hydrocarbons (crude-derived, XTL, and biofuels) and non-liquid fuels (natural gas, hydrogen, and electricity) are compared. The challenges in effecting a transition to any alternative fuel are discussed.[1]

1. Introduction

The 240 million light duty vehicles (LDVs) in the US are powered almost exclusively by crude-derived gasoline-like fuels. These passenger cars and light trucks consume some 130 billion gallons of fuel annually and account for 8.7 million barrels per day (Mbpd) of liquids[2] consumption (45% of the US total).

Gasoline has dominated US LDVs for several reasons: its high energy density (some 30 times greater than batteries), its convenience, safety, and historical low cost, the interdependence among fuel production/distribution/vehicles, as well as consumer expectations and incumbent business interests. Yet present circumstances have drawbacks, mostly importantly that the US imports about 45% of the liquids it consumes (Figure 1).

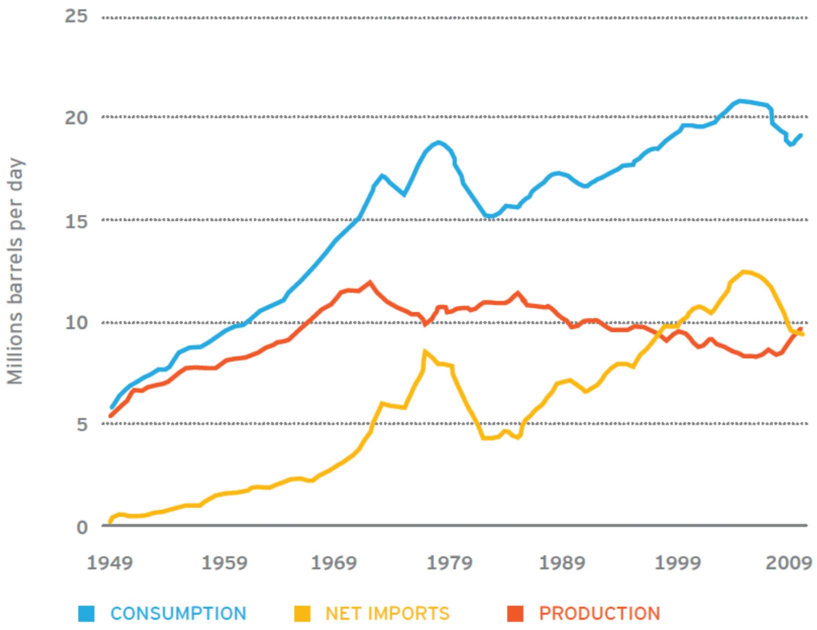

Figure 1: US Liquids History, 1949-2010. Source: EIA

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[1] Much of the material in this paper derives from the recent DOE Quadrennial Technology Review (QTR). A report on that process can be accessed at http://energy.gov/sites/prod/files/ReportOnTheFirstQTR.pdf and the companion Technology Assessments are expected to be released in the future.

[2] Liquids include crude oil, natural gas liquids, and biofuels

Indeed, concerns about “foreign oil” and a quest for “energy independence” have garnered the resolve of every president for the past four decades, as illustrated in Figure 2.

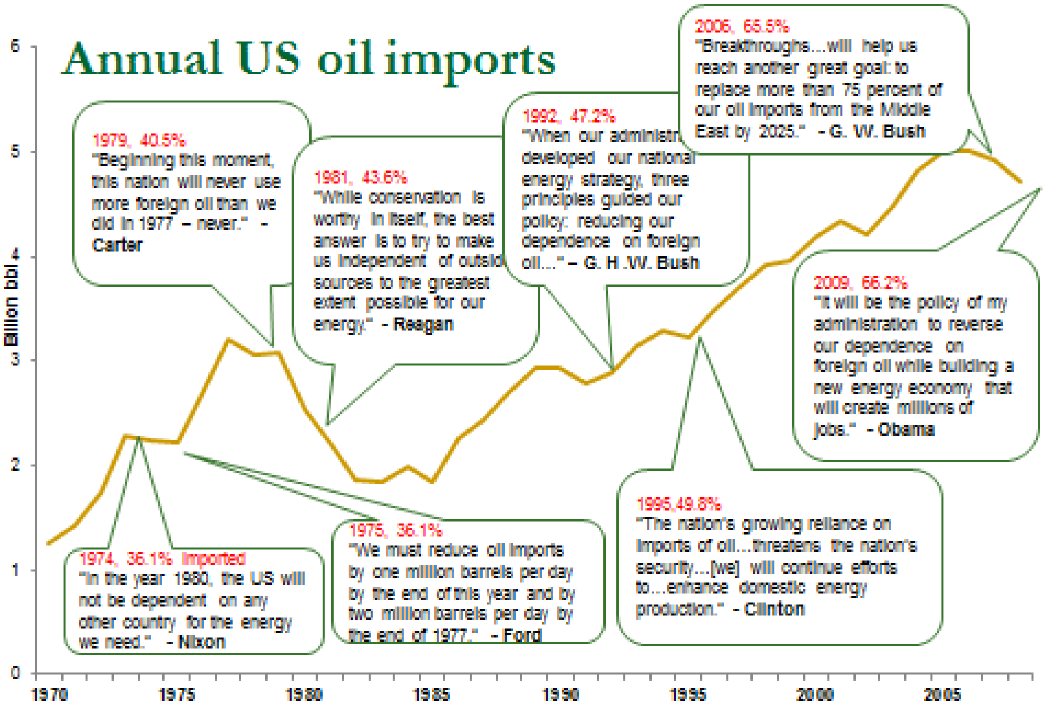

Figure 2: US liquids imports. Import fraction is given at the time of each presidential quote.

Today’s “oil problem” can be parsed into several related but distinct sub-problems:

- **Physical security:** While roughly half of US imports come from the Western Hemisphere (most importantly Canada, Mexico and Venezuela), the other half arrives via longer and less secure routes (Figure 3). Any extended physical interruption of supply would have severe consequences for the Nation; the Strategic Petroleum Reserve stores 700 M bbl (70 days of imports) against such contingencies.

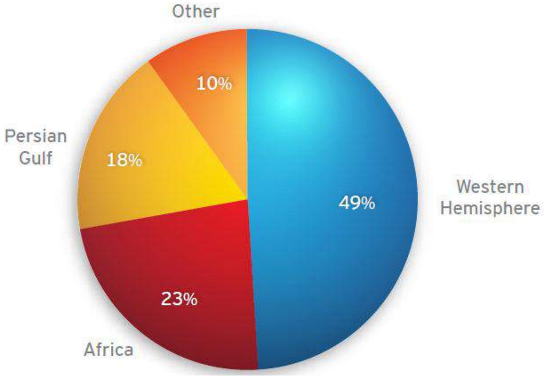

Figure 3: Origin of US petroleum imports, 2010. Source: EIA, Petroleum Supply Monthly

- **Trade deficit:** At a price of $100/bbl, US oil imports debit the balance of trade by almost $1B/day. In 2010, US exports were $1.8T, while imports were $2.3T, for a

$500B trade deficit, of which oil-related imports were half, the largest single debit item.

- **Price volatility:** Gasoline is one of the few globally-traded commodities that US consumers purchase directly, keeping its price in the public consciousness. That price, driven by the underlying crude price, has risen dramatically in the past decade and remains volatile, as shown in Figure 4.

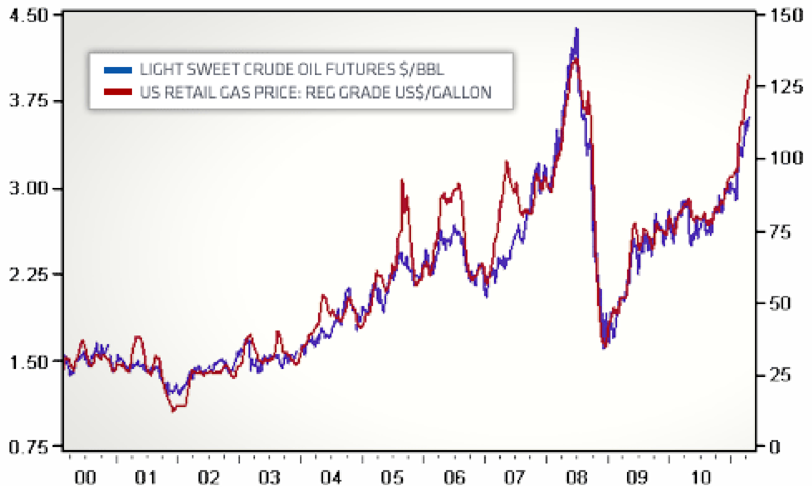

Figure 4: US retail gasoline price and light sweet crude price. Abscissa is year, left ordinate $/gal, right ordinate $/bbl Source: CNBC, derived from EIA/DOE/WSJ/Haver data. Accessed at http://media.cnbc.com/i/CNBC/Sections/News_And_Analysis/__Story_Inserts/graphics/__CHARTS_SPECIAL/MISCELLANEOUS/CNBC_US_RETAIL_GASOLINE_PRICE_520.gif

- **Greenhouse gas emissions:** LDVs account for about 1/3 of US energy-related emissions. Although the stationary energy sector (heat and power) has larger and more price-sensitive[3] opportunities for mitigation, any serious commitment to reduce emissions will entail changes to the LDV sector.

"Demand-side" measures that reduce oil use, such as price signals, regulations (*e.g.,* the recently strengthened CAFE standards), and behavior (*e.g.,* shifts to public transport) offer some of the most timely, material, and cost-effective solutions to *all* of the oil sub-problems. But there are also "supply-side" actions that can be categorized as:

- Increased domestic production of crude
- Increased production of alternative liquid fuels (XTL[4], biofuels)
- Transition to a non-liquid fuel, such as natural gas, electricity, or hydrogen

Each of these measures must be judged in terms of its technical feasibility, materiality, timeliness, economics, and the varying proportions in which it addresses the different sub-problems.

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[3] For example, a carbon price of $40/t CO_2 would be sufficient to induce a shift away from coal-fired power to low-GHG generation technologies. Yet it corresponds to only a $0.35 increase to the price of gasoline.

[4] Thermochemical processes that convert coal, gas, or other organic feedstocks into liquid hydrocarbon fuels

After a review of relevant aspects of the oil scene, this paper considers each of the LDV supply-side options in turn, with an emphasis on the fuels and infrastructure. The companion white paper by John Heywood emphasizes vehicle issues.

2. Liquid fuels

A "holy grail" supply-side solution to all of the oil sub-problems would be a low-cost, low-carbon, liquid fuel compatible with existing infrastructure and vehicles ("drop-in") that could be produced domestically at scale. Unfortunately, technology, economics, and politics conspire to make such a solution currently unimaginable, so that trade-offs will be necessary. A brief synopsis of the current oil scene is an important prelude to discussions of specific solutions.

2.1 Today's oil scene

Crude oil[5] has been produced and consumed for more than 150 years. It is a finite resource traded on a global market with one price (varying somewhat with quality and location) set by demand and supply, the latter modulated by the OPEC cartel.

World liquids demand, currently about 87 Mbpd, is projected to rise by almost 1 Mbpd *every year*, driven largely by economic development in Asia, as shown in Figure 5. EIA projections, necessarily an imprecise art, show the OPEC cartel continuing to satisfy about 40% of that demand for the next 25 year, and a growing wedge of unconventional production (tar sands, tight oil).

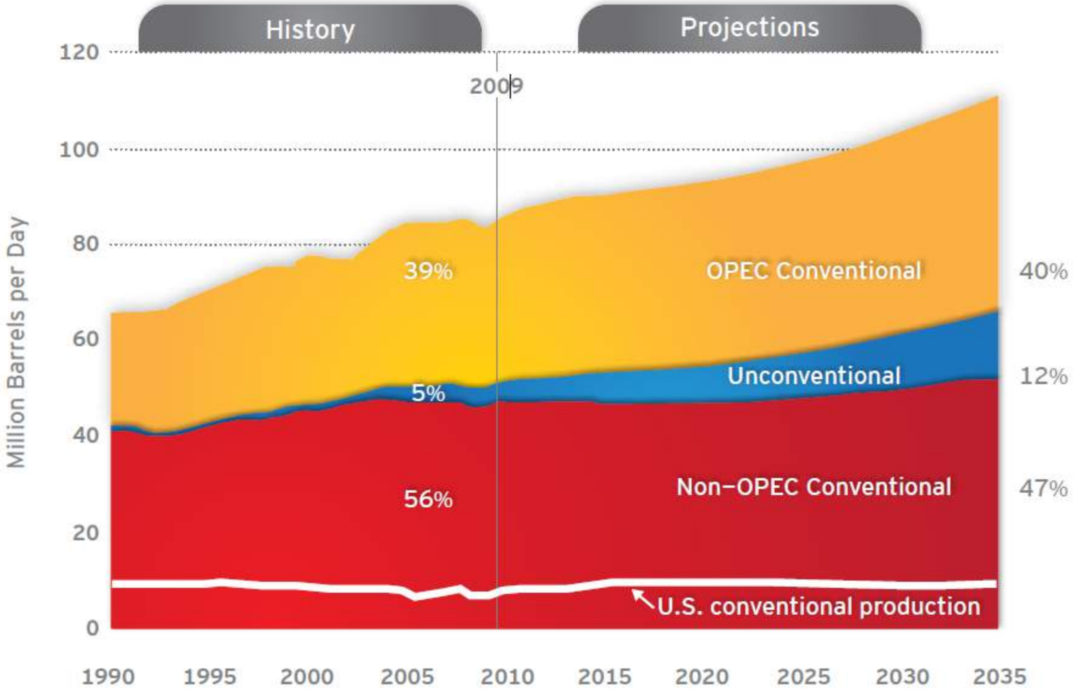

Figure 5: Global liquids production, 1990-2035. Source: EIA

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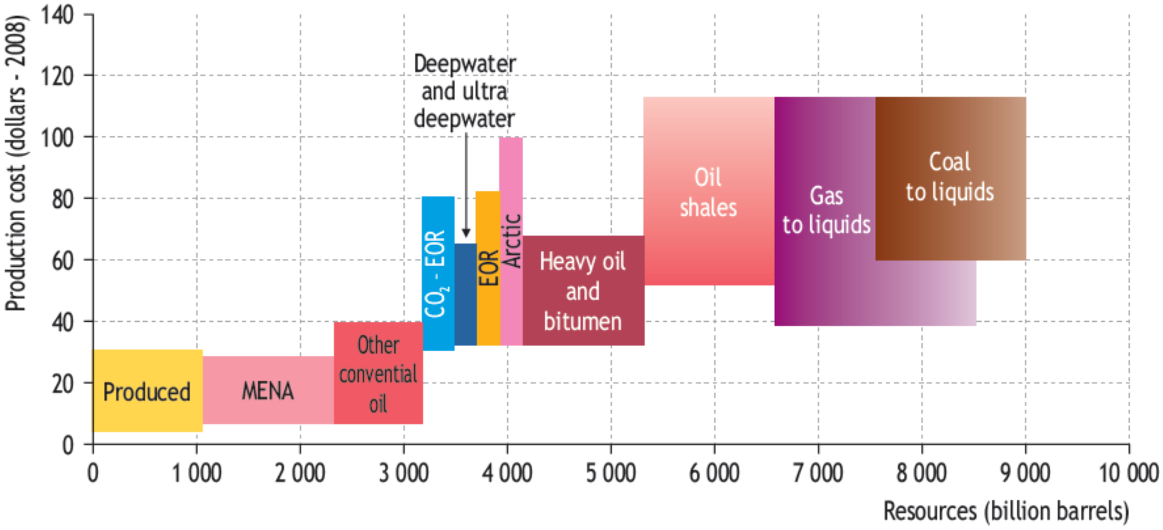
[5] The terms "oil" and "liquids" are used interchangeably for convenience; a note will be made where the distinction is important

High oil prices invariably increase the volume of an on-going discussion best paraphrased as “we’re running out!” But an average global consumption of 100 Mbpd over the next 25 years requires 1,000 B bbl (about what the world has consumed over the past century), easily accommodated at reasonable cost by the supply curve shown in Figure 6. However, the substantial investment to produce that increasingly difficult oil will require new technology, access to resource, and favorable business cases.



Note: The curve shows the availability of oil resources as a function of the estimated production cost. Cost associated with CO_2 emissions is not included. There is also a significant uncertainty on oil shales production cost as the technology is not yet commercial. MENA is the Middle East and North Africa. The shading and overlapping of the gas-to-liquids and coal-to-liquids segments indicates the range of uncertainty surrounding the size of these resources, with 2.4 trillion shown as a best estimate of the likely total potential for the two combined.

Figure 6: Long-term oil-supply cost curve. Shale oil is an additional significant resource that is not included on this four-year-old chart. Source: IEA WEO 2008, p. 220

Although there is more than enough hydrocarbon in the ground, the “easy” oil reserves (those with a low cost of production) are increasingly concentrated in the hands of a few countries, as shown in Figure 7.

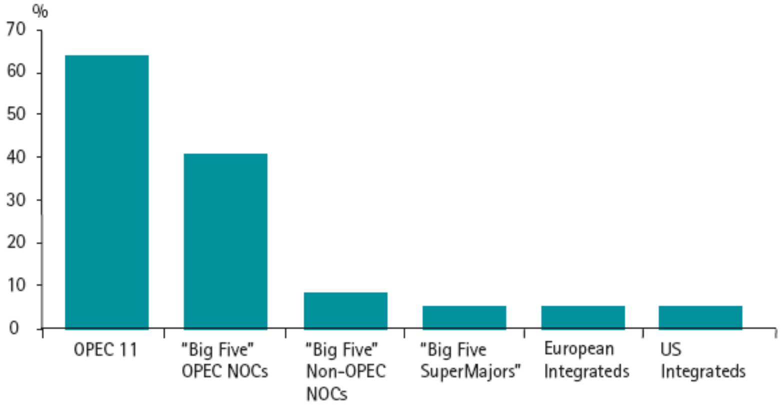


Figure 7: Percentage of conventional reserves in key NOC (National Oil Company) hands. Source: Morgan Stanley

The decisions and fates of countries like Venezuela, Saudi Arabia, Iran, and Russia are therefore important elements in thinking about security of supply. More costly, but more significant, opportunities are distributed differently around the globe. Of particular interest for the US are the North American tar sands and oil shales.

Figure 8 below shows the history and projections of US liquids supply. Total consumption is expected to be essentially flat, as improvements in vehicle efficiency are offset by growing vehicle miles travelled[6]. Biofuels and Natural Gas Liquids (NGLs) are expected to grow as imports decline modestly. Most surprising is how little change is projected over 25 years, but EIA projections, by design, make conservative technology and regulatory assumptions.

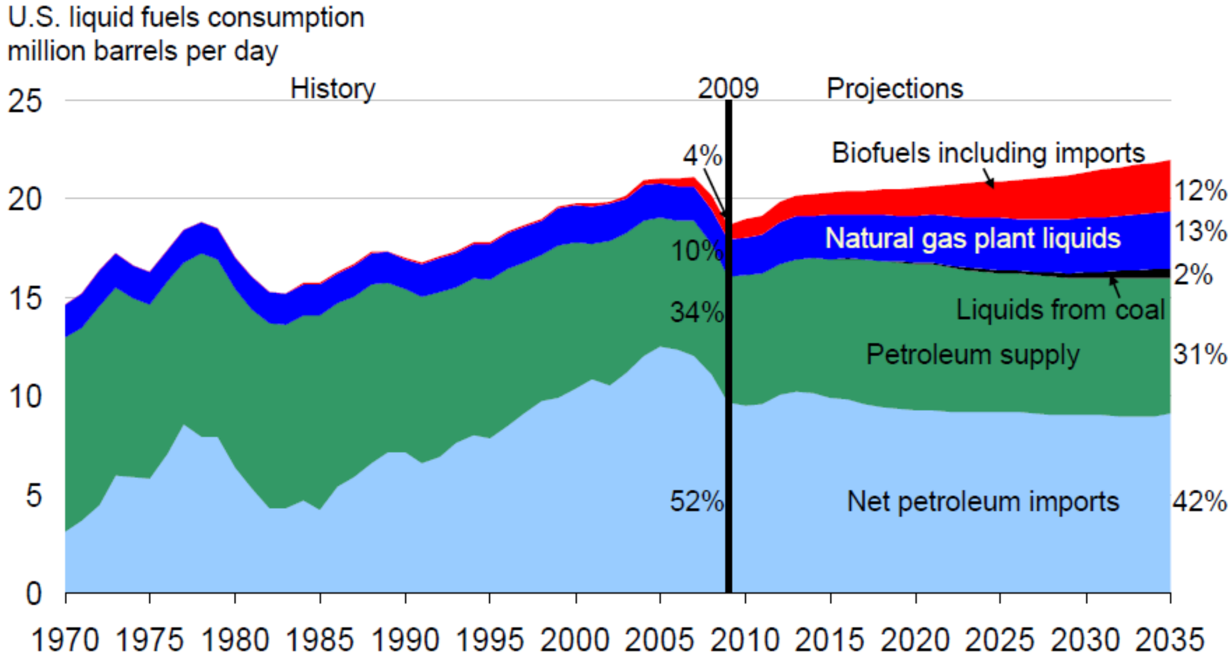


Figure 8: History and projection of US liquids consumption and sources. Source: EIA

2.2 Increased domestic crude production

The US is the world's largest consumer of oil (22%), but even as the world's third largest producer (after Saudi Arabia and Russia), it provides only 11% of global supply. The security and balance of trade impacts of increased domestic production are scaled by US imports (9 Mbpd), but as oil is a freely-traded global commodity, the price impact must be judged against the global 87 Mbpd, growing 1 Mbpd each year (white line at the bottom of Figure 5.) There is no GHG benefit of increased domestic production, and likely a slight drawback, as the production, refining, and use of more difficult oils generates at least 10% more life-cycle GHGs than conventional crude.

A convenient threshold of materiality for increased US production is 1 Mbpd. Figure 1 shows that, following a more rapid run-up before 1970, changes of that magnitude have taken about a decade. More detail can be seen in Figure 9, which shows that, even with great effort, it has taken a decade to bring on 1 Mbpd production in either the Gulf of

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[6] US population is projected to increase at 1% per annum through mid-Century.

Mexico or through corn ethanol (energy equivalent). It is sobering to view these histories against the much larger and more rapid changes in Saudi production also shown.

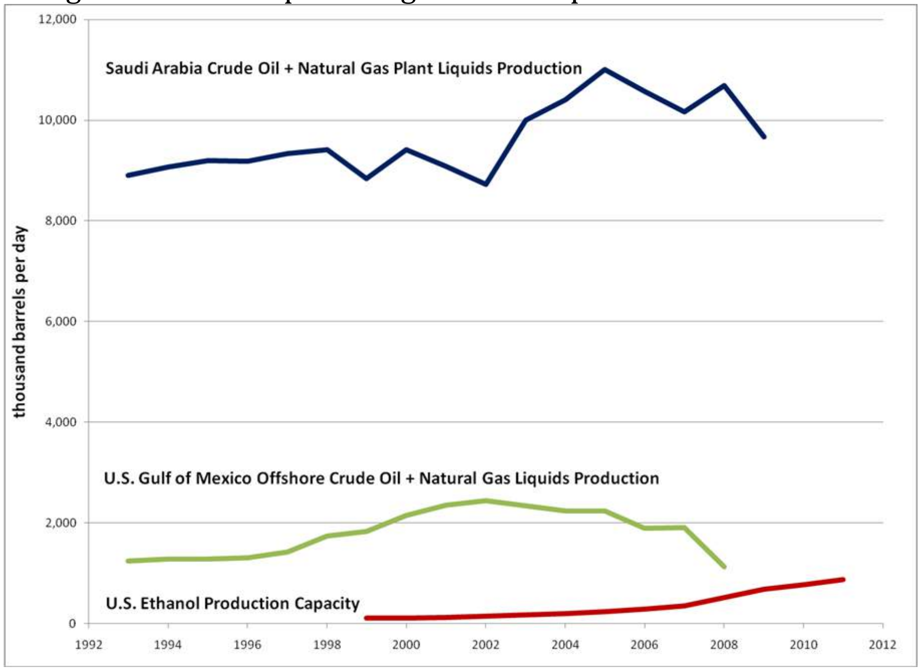
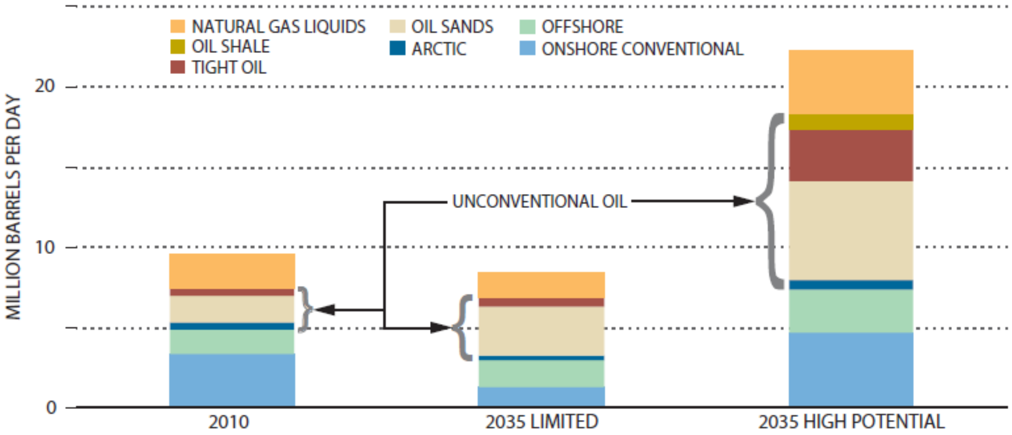


Figure 9: **Saudi, US Gulf of Mexico, and corn ethanol production, 1993-2011.** Source: EIA

A 2011 National Petroleum Council study[7] attempted to quantify the potential for increased North American production. The "2035 High Potential" case shown in Figure 10



Note: The oil supply bars for 2035 represent the range of potential supply from each of the individual supply sources and types considered in this study. The specific factors that may constrain or enable development and production can be different for each supply type, but include such factors as whether access is enabled, infrastructure is developed, appropriate technology research and development is sustained, an appropriate regulatory framework is in place, and environmental performance is maintained.

Source: Historical data from Energy Information Administration and National Energy Board of Canada.

Figure 10: Limiting projections for NA liquids production. Source: NPC NARD report, Figure 1-5. p. 49

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[7] *Prudent Development: Realizing the Potential of North America's Abundant Natural Gas and Oil Resources*, (NARD) available at http://www.npc.org/. Given the general alignment and tight coupling of the North American economies, it is not unreasonable to treat them as a unit when discussing security and balance of trade.

compounds favorable assumptions about technology, access, infrastructure, and regulation. Oil sands, NGLs, and tight oil are the largest contributors to a dramatically increased production. None of these sources are without its drawbacks, although all three are currently growing rapidly [tight oil production has almost already hit this projection]. While US (or North American) production during 1950-1970 grew at a rate comparable to that implied by the High Potential case (more than doubling over 25 years), it has declined slightly at a much slower rate during the past 40 years. If realized, the High Potential case would improve security, balance of trade, and is material enough to impact global price, but would deteriorate progress on GHG emissions.

2.3 XTL[8]

Various thermochemical and biological processes can be exploited to turn *any* carbonaceous material into a liquid fuel, as shown in Figure 11. As with increased oil domestic production, the desideratum of a "drop in" product fully compatible with gasoline vehicles and fueling infrastructure means that 1 Mbpd-scale deployment can improve security and trade, but will not lower price and will not necessarily reduce GHG emissions. This section covers thermochemical processes that convert coal, gas, and biomass to fuel, while biological processes are covered in the following section.

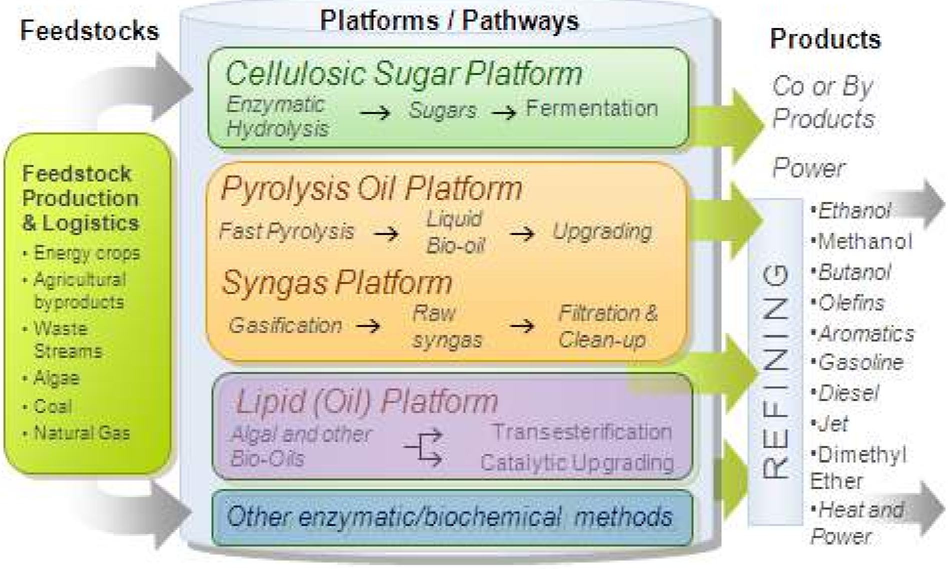

Figure 11: Summary of feedstocks, pathways, and products for alternative hydrocarbon fuels

Viable domestic deployment of Coal-to-Liquids, Gas-to-Liquids, or Coal/Biomass-to-Liquids (respectively CTL, GTL, and CBTL, and collectively XTL) requires a material and economic domestic carbonaceous feedstock. Figure 12 shows annual US carbon flows in various streams. Assuming a 50% carbon efficiency, the nominal 1 Mbpd, requires about 100 MtC/yr, which could be accommodated by modest increases in the coal, natural gas, or biomass streams.

The GHG impacts of various XTL schemes are shown in Figure 13. Apart from unsequestered CTL, life-cycle emissions are comparable to, or smaller than, crude-derived

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[8] Material in this section is reproduced or adapted from the QTR and its forthcoming Technology Assessments.

gasoline. As gasification produces relatively pure CO_2 streams, the incremental costs of Carbon Capture and Storage (CCS) in an XTL process are only those of compression, transportation, and storage.

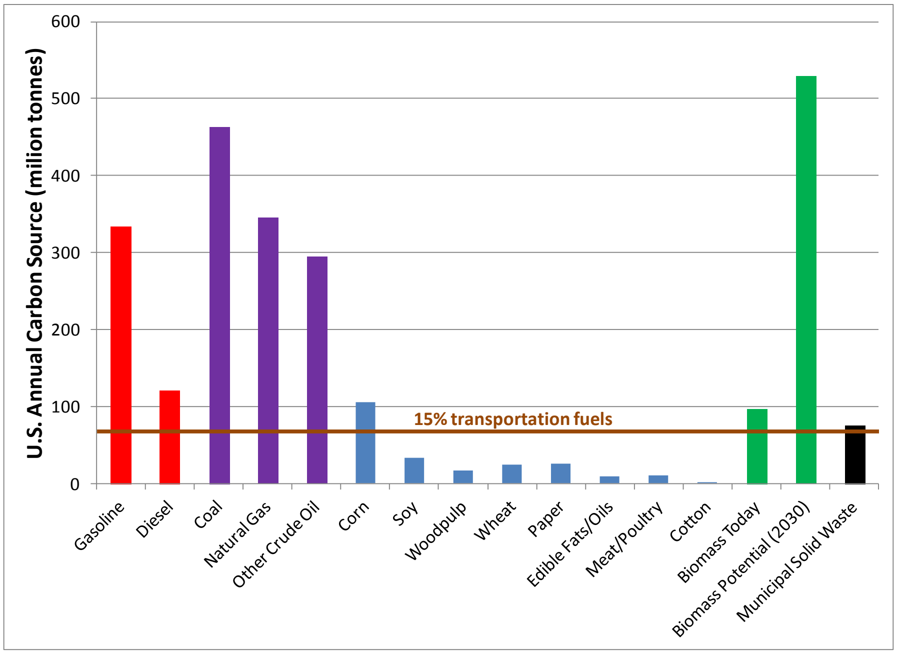

Figure 12: Annual U.S. carbon flows (in MtC). As shown by the height of the brown line, some 70 Mt of carbon in non-oil feedstocks would be required to replace 15% of current transport fuels if no carbon were lost in the conversion process.

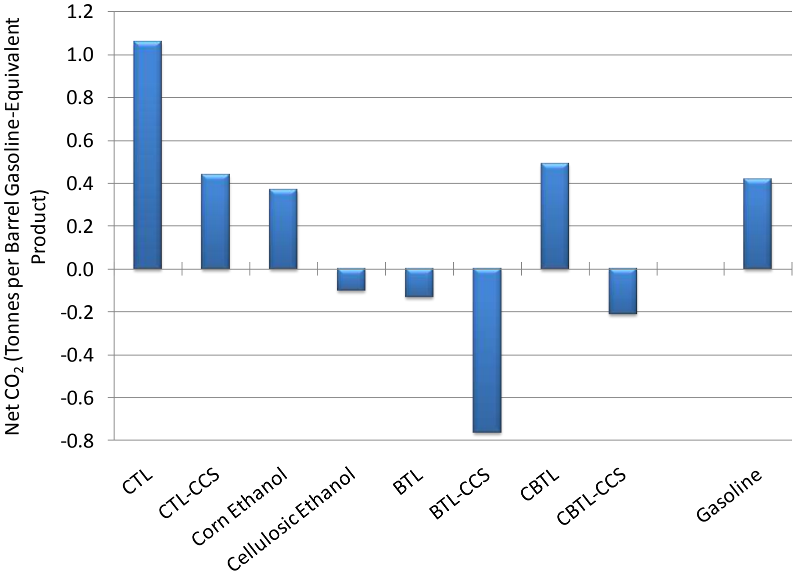

Figure 13: **Life Cycle Carbon Emissions for Various Transportation Fuels.** The greenhouse gas emissions from some alternative fuels are less than those from conventional fuels, while others are higher. Source: *America's Energy Future Panel on Alternative Liquid Transportation Fuels***,** accessed at: http://www.nap.edu/openbook.php?record_id=12620&page=250

XTL processes currently produce over 370 kbpd of liquid fuels and specialty chemicals, some 0.4% of global liquids production. The most common product is diesel fuel via Fischer-Tropsch (F-T) synthesis; GTL facilities deployed in the last 10 years are responsible for most of the synthetic fuel production and utilize the newest F-T technologies. The syngas product of gasification (a mixture of CO and H_2) can also be converted to methanol, which can then be converted to gasoline via the Mobil MTG process. CTL and GTL F-T facilities without CCS have been deployed at the 150 kbpd scale but a CBTL facility has yet to be deployed. The largest GTL methanol plants deployed are less than 50 kbpd.

Current studies suggest that GTL can be economically viable at crude oil prices above $80/bbl[9], while CTL w/ CCS can be viable at crude oil prices above $97/bbl. The large capital outlays associated with CTL, CBTL, and GTL facilities—normally built at 50 kbpd or greater to maximize economies of scale—present a significant risk to potential investors, especially given oil price volatility. At capital costs of some $150k and $80k per daily barrel for CTL/CBTL and GTL, respectively, a 150 kbpd CTL plant with CCS is a $22B bet that crude prices will average above $97/bbl over the amortization period.

The CO_2 from an XTL plant can be used for enhanced oil recovery (EOR), thereby improving the fuel production economics. Current annual U.S. use is some 60 MT of CO_2, mostly from natural sources (e.g., natural gas separation plants). At a typical 50% carbon efficiency, the current CO_2 usage for EOR would be met by 300 kbpd of synthetic fuel production.

While there is some potential for incremental technical improvements, the greatest hurdles to deploying XTL are economic, not technical. Relative to other methods for producing fuels, thermochemical conversion has both higher production and capital costs. Industry understands the risks and is well-poised to deploy should economic conditions warrant.

2.4 Biofuels[10]

Federal policies have encouraged the domestic production of biofuels through fuel standards, blender subsidies, and import tariffs. Corn ethanol production now exceeds more than 14 B gallons annually, amounting to more than 10% of the US gasoline pool on volume basis (7% energy basis); more than half of the US corn crop is now devoted to ethanol production.

Corn ethanol addresses the security and trade subproblems, but not the GHG issue; direct life-cycle emissions from corn ethanol are only slightly less than conventional gasoline. Brazilian cane ethanol could be imported on material scales. Doing so would improve security by diversifying supply and reduce direct GHG emissions, but would not improve the trade balance. If the cost of ethanol production from whatever source is less than the cost of gasoline, as is currently the case, fuel prices could be reduced and stabilized if penetration levels were significantly greater than today's.

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[9] Assumes a a 12% Internal Rate of Return on Equity, gas prices of $5-10 mmBTU, and a 10% Capital Charge Factor.

[10] Material in this section has been reproduced or adapted from the QTR Section 7 and its companion Technology Assessments

Unfortunately, neither the "corn" nor the "ethanol" in "corn ethanol" is optimal. Resource requirements and the interactions with food and feed make crop-based biofuels problematic and it is difficult to imagine corn production growing substantially beyond current levels. The Energy Independence and Security Act of 2007 therefore mandates that by 2022 the US produce annually 16 billion gallons of cellulosic biofuels (made from the structural material of plants), together with 15 billion gallons of corn ethanol. While the corn ethanol target will be achieved easily, there are no commercial scale cellulosic biofuels plants in the US today and 2011 production of cellulosic biofuels was no more than 7 million gallons.

Cellulosic ethanol production is hindered by economics. Feedstocks from food-crop residues, dedicated energy crops, forest materials, and municipal solid waste are collectively ample to make a material impact (Figure 12). Gathering and processing costs are the barrier. Feedstock transport costs limit the size of an economic processing facility to some 10 kbpd, preventing economies of scale. Processing costs are currently too high by about a factor of two, as the lignocellulose must be decomposed into lignin (generally burned for power) and sugars (both C5 and C6) which are then fermented to ethanol.

Ethanol is not an optimal motor fuel. Its energy density is only 70% that of gasoline, and it is hydroscopic and corrosive. Low blends (perhaps to 15 volume percent, or E15) can be accommodated by the existing infrastructure and vehicles, but E85 requires an upgraded fueling infrastructure and flex-fuel vehicles (the latter at only a $300 premium). Research has been underway for some years to develop organisms that will ferment sugars to higher alcohols (most famously butanol), which have a higher energy density and are more compatible with the gasoline system.

High-value coproducts (i.e., chemicals for the pharmaceutical, cosmetic, and food science markets) can augment the economics of early-stage biofuel production. But the coproduct market will saturate as fuel production is taken to materiality.

3. Non-liquid fuels

The liquid fuel solutions discussed above directly address the security, trade, and perhaps GHG sub-problems, but would not materially impact price except at the most aggressive levels of deployment. Indeed, any drop-in product that is a minority[11] of the US gasoline pool will continue to sell at the global crude derived price.[12] In other words, "energy independence" will not guarantee "price independence". That point is vividly illustrated by noting that:

- Fuel riots in the UK in 2000 protested fuel price increases driven by a rising global crude price. Yet at the time the UK was more than energy independent, exporting half of its 3 Mbpd production (largely from the North Sea).
- After correcting for taxes and exchange rate, the price of gasoline in the US is, to within a few percent, the same as it is in Germany, even though the US produces 200 times as much crude.

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[11] If the product cost were less than the crude-derived price, manufacturers would not leave money on the table, while if it were greater, a mandate or subsidy would be required for a viable business. The minimum penetration required for a drop-in to set the market price remains a point of discussion.

[12] Short term, infrastructure constraints can cause a violation of this general rule.

The impact of price volatility is most directly addressed by improved vehicle efficiency. A supply side measure toward that same end is a shift to a source of LDV energy not fungible with gasoline (ie, a "drop-out" fuel rather than "drop-in"). We review in this section the three major drop-out possibilities: natural gas, electricity, and hydrogen. Figure 14 shows the impact that additional transport demand might have on each of these alternative energy sources, while the damping of price volatility enabled by "drop outs" is illustrated by Figure 15.

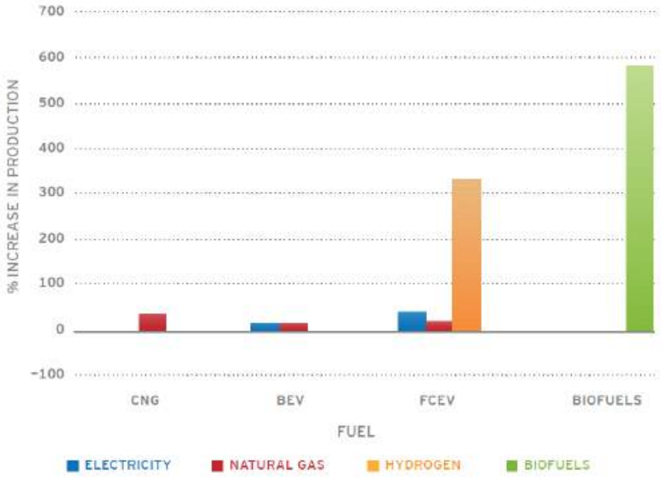

Figure 14: Estimated supply impacts of satisfying 50% of today's LDV demand by various "drop out" fuels. Running half of today's LDVs on Compressed Natural Gas (CNG) would increase current NG demand by about 1/3. Running those same vehicles entirely on electricity (BEVs) would increase electricity demand by 1/6 and, if all that electricity were generated from natural gas, gas demand would increase by the same fraction. If Fuel Cell Vehicles (FCEVs) powered by hydrogen were deployed, hydrogen production would need to increase by more than a factor of three, and either electricity demand would increase by 1/3 or natural gas demand would increase by 1/5, depending upon how the hydrogen were produced. Finally, for comparison, biofuel production would have to increase six-fold from today's corn ethanol volume. Source: QTR, Section 6.

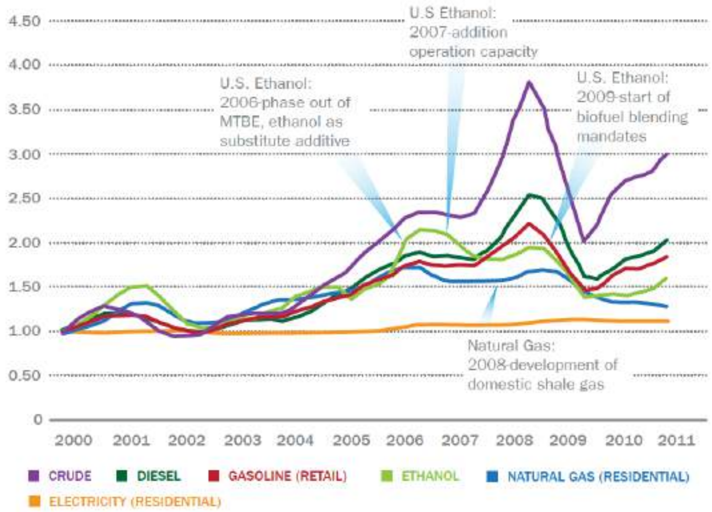

Figure 15: Relation of Fuel Prices to Crude Oil Price, 2000-2011. Data from EIA and Nebraska Energy Office

The price of residential electricity is quite stable because of regulation and because the cost of fuels is only one component of the total cost. The price of natural gas in the US has decoupled from that of oil and dropped to extraordinarily low levels because of booming shale gas production, as shown in Figure 16. On an energy-equivalent basis, wholesale gas is now only 1/8 the cost of crude oil.

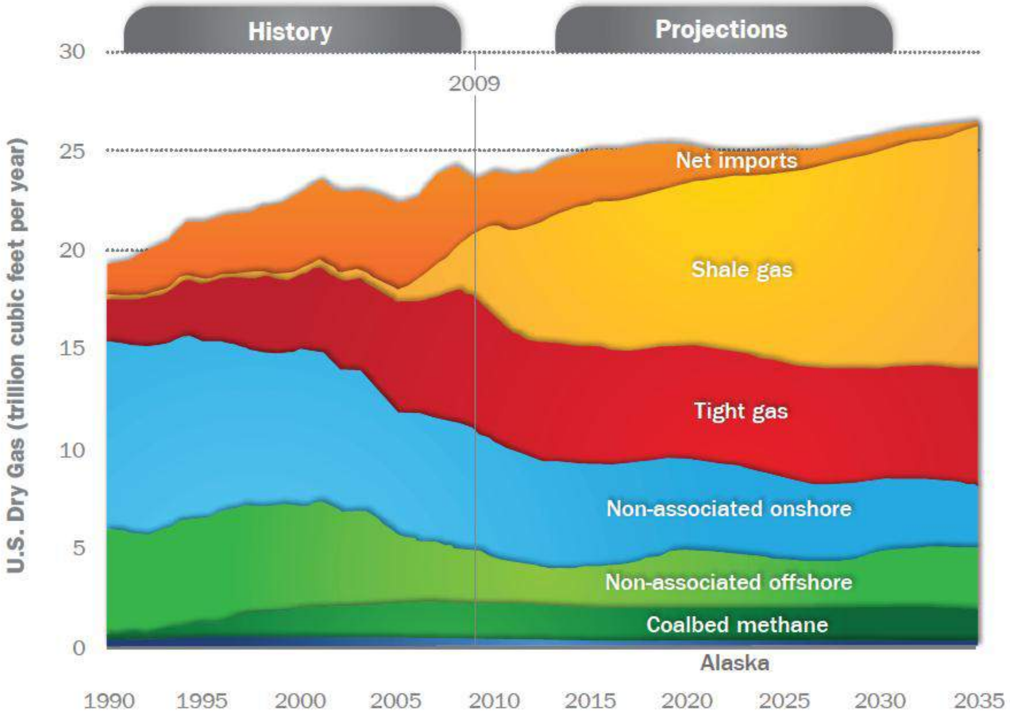

Figure 16: Historic and projected sources of US natural gas. Source: EIA

3.1 Natural gas[13]

In 2008, 150,000 of the Nation's 250 million road vehicles (less than 0.1%, mostly buses and corporate-fleet vehicles) were powered by compressed natural gas (CNG); About 20% of transit buses in use (and 20% of bus sales) are fueled by natural gas. Advantages of CNG as a substitute for liquid fuels include a lower and more stable fuel price, GHG reduction of up to 10% compared to gasoline, and the existing natural gas distribution infrastructure: the U.S. has more than 210 natural gas pipeline systems totaling over 300,000 miles of transmission pipelines and 1.9 million miles of distribution lines. However, this infrastructure is optimized to supply power plants and commercial and residential end users, not to fuel vehicles - natural gas must be compressed (typically to 3500 psi) to meet the volume requirements of mobile applications.

The barriers to natural gas deployment for LDVs include:

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[13] Material in this section is reproduced or adapted from the QTR, Section 7.2 and its Technology Assessments

- Limited availability of CNG refueling stations (the closest to the author's home is 14 miles distant, although its fuel prices are half that of gasoline on an energy-equivalent basis). Fewer than 1% of U.S. fueling stations supply CNG.
- High capital cost ($5,000) and long fueling times (overnight) for home refueling
- Vehicle price premium of $2,000-4,000 relative to gasoline-fueled
- Limited vehicle range and smaller trunk space (each about about half that of gasoline fueled) due to lower fuel density; the density issue would be alleviated by developing in-tank methane-absorbing materials such as metal-organic frameworks.

These barriers are well-described in a recent Consumer Reports article, http://www.consumerreports.org/cro/2012/03/the-natural-gas-alternative/index.htm .

Globally, propane is the most widely used drop-out fuel. Outside of the United States, propane—or liquefied petroleum gas (LPG)—is commonly referred to as "autogas" when used as an automotive fuel. EIA estimates that roughly 147,000 vehicles operate in the U.S. using 130 million gasoline-equivalent gallons of propane fuel a year (a bit more than 0.1% of gasoline use). Propane vehicles in the U.S. are primarily used in fleet or rural (e.g., farming) applications. Propane fueling stations, though the most numerous of all drop-outs, are unevenly distributed around the country.

Virtually all propane is produced as a co-product of natural gas processing or an oil refinery product. US production in 2010 was about 20 billion gallons. Hence, a 4-fold increase in production would be required to meet 50% of today's LDV demand and continue to satisfy other uses. US propane production could increase strongly as economics of shale gas production drive interest toward "wet gas"..

3.2 Hydrogen[14]

Research on fuel cells has led to significant progress in recent years, helping to reduce their cost by a factor of five and on-vehicle hydrogen storage has improved to acceptable ranges for an LDV. But significant further improvements in key technologies remain to be demonstrated to create a viable LDV system. Further progress could well bring the cost of driving (vehicle plus fuel) for FCEVs within the range of other drop-out technologies. However, those other technologies are currently economically superior and will continue to improve rapidly.

Although the projected cost of hydrogen (dispensed to the vehicle) via some production pathways is less than $5/gge (gasoline gallon equivalent, roughly 1 kg of hydrogen), given the higher vehicle cost, $2–4/gge is required for FCEVs to be competitive. Reforming natural gas is the most mature and lowest cost method to produce hydrogen; it

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[14] Most of the material in this section has been reproduced or adapted from QTR (Section 6 and the Technology Assessments).

is used to produce over 90% of the 9 million tons of merchant hydrogen annually in the U.S. (equivalent to about 7% of today's U.S. gasoline supply). R&D has advanced the state of hydrogen production from distributed natural gas so that it could be technically possible to achieve high volume production costs of approximately $3/gge, but industry estimates indicate a more realistic high-volume cost of $7/gge over the near-term. Production of hydrogen from renewable sources (biomass, algae, solar, etc.) offers lower GHG emissions, but is less mature and more costly today; there are also serious scaling issues in some of these sources.

3.3 Electricity[15]

Degrees of electrification for electric drive vehicles range from mild and strong hybrid electric vehicles (HEVs), through plug-in hybrid electric vehicles (PHEVs), to pure electric vehicles powered by batteries (all-electric vehicles, or AEVs). HEVs and PHEVs offer increased fuel economy but still require some liquid hydrocarbons, while AEVs do not require liquid hydrocarbons, and thus fully decouple transport from oil.

The vehicle industry is more than a decade into the commercial deployment of electric powertrains in HEVs, and is generating expertise in integrating conventional and electric powertrains. Although HEVs are currently only 3% of new LDV sales, market penetration is increasing. General Motors, Nissan, and Toyota have undertaken mass-production of plug-in vehicles, so expertise in the next generation EV powertrains is growing.

PHEVs and HEVs are more energy-efficient than conventional vehicles because electric motors are four times more efficient than today's ICEs, hybridization of the powertrain allows for use of more efficient ICEs than conventional powertrains, and because regenerative braking allows energy to be recovered and reused.[16] PHEVs further reduce oil consumption by replacing liquid fuels with electricity. As shown in Figure 17, a PHEV with a 40 mile all-electric range would replace at least 2/3 of gasoline consumption with electricity. This modeling is in accord with the real-world experiences of Chevy Volt owners.

HEVs have a price premium of $2,000-$4,000, which offers an attractively short payback period in an era of $4 gasoline price. The premium for a PHEV40 is three two fours times larger and such vehicles are not now an economic proposition; with declining battery costs and/or rising gasoline price, they would become so.

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[15] Most of the material in this section is reproduced or adapted from the QTR, Section 6.

[16] Typical efficiencies for a PHEV and AEV are 2.5 mi/kWh and 4 mi/kWh, respectively, corresponding to a fuel costs of $0.06mi and $0.04/mi if electricity is $0.15 /kWh. At $4 gasoline, the fuel cost for a 40 mpg ICE is $0.10/mi.

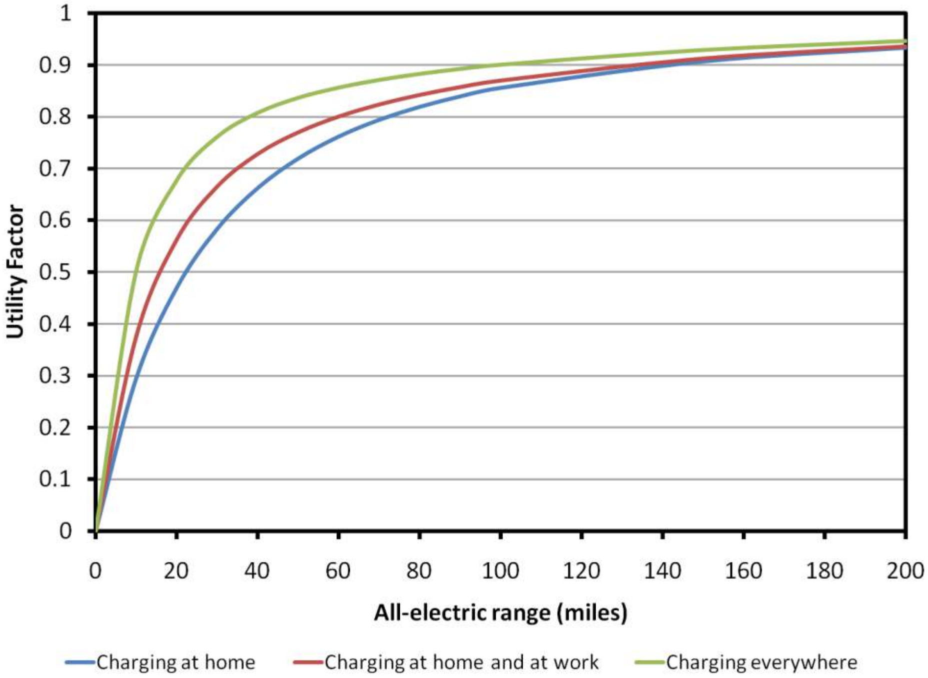

Figure17: Impacts of plug-in hybrid electric range and charging infrastructure. Utility factor is the fraction of vehicle miles that would be driven on electric power without recharging. Different charging scenarios are shown. The benefit of ubiquitous charging becomes smaller as the all-electric range increases; for most applications, home charging is sufficient. From a forthcoming EPRI report, "Understanding the Effects and Infrastructure Needs of Plug-In Electric Vehicle (PEV) Charging."

There is more than enough electrical generation capacity to power the LDV fleet. As shown in Figure 14, only 15% more electricity would be required to fully power half of today's LDV fleet. Since the average capacity factor of installed generation is less than 50% due the diurnal load variation and inability to store large amounts of electrical energy, charging at night will not be an energy issue. But it could be a power issue, as discussed in the following section.

The GHG impact of LDV electrification will, of course, depending upon the carbon intensity of grid power. With the current average US carbon intensity of power, they would reduce GHGs by about 1/3, a figure that would improve as the grid decarbonizes and/or PHEVs are fueled with low-carbon biofuels.

3.4 Effecting a transition

It is plausible that technical advances and/or rising gasoline prices will make the driving costs per mile (vehicle + fuel) of any or all of the drop-out fuel possibilities economically attractive. But a large-scale transition of LDVs to any dropout fuel will not be simple, as vehicles, fuel production, and fueling infrastructure, each separate industries, must shift simultaneously while maintaining a “fuel anywhere” capability. Further, it seems likely that at most one drop-out fuel system would be supported to supplement the current gasoline system. Important questions then are: Should a drop-out system be deployed? Which one? and How would the transition be effected?

New LDV technologies will be deployed most rapidly and seamlessly if they can integrate with the existing energy infrastructure. The fueling patterns of on-road transport require extensive infrastructure (Figure 18). The U.S. has 55,000 miles of crude oil pipeline feeding 150 refineries and another 95,000 miles of refined product pipelines and many local delivery trucks supplying 160,000 gas stations.

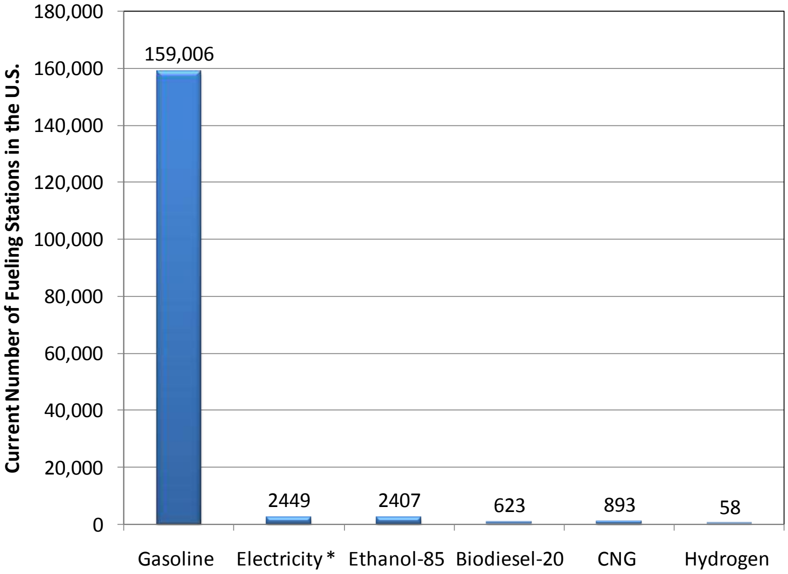

Figure18: Current fueling stations in the United States. There are many more fueling stations for gasoline than for other fuels. *Electricity stations are the publicly available stations only. Not shown are the millions of existing locations for home charging. Source: DOE EERE (for alternative fueling stations) and EIA (for gasoline stations).

Among the drop-out possibilities, electricity is most favored in these considerations because the LDV transition to it can be gradual and graceful. The existing grid infrastructure can accommodate significant immediate deployment of HEV and PHEV vehicles, and could eventually support full electrification of the light-duty vehicle fleet with some upgrades and modifications. There are 11 million miles of electrical distribution circuits that can, today, accommodate virtually unconstrained residential 120V wall outlet charging of plug-in hybrid electric vehicles (Level 1, ~2 kW, equivalent to a hair dryer). Ubiquitous charging does not significantly increase the utility factor of a PHEV with an electric range greater than 40 miles (Figure). Among the drop-out possibilities, PHEVs will therefore see fastest deployment and can have the greatest near-term impact on oil consumption.

Charging time is a potential barrier to further electrification; ten hours are required to fully charge a PHEV with a 40 mile electric range from a 120V charger. Vehicles with longer electric ranges will require faster charging, which would eventually require grid upgrades. While the household circuits necessary for 240V Level 2 chargers (>3 kW) are commonly used for appliances, obtaining vehicle access to those circuits may require specialized wiring and could affect grid distribution circuits if deployed in clusters. Fewer than 2% of U.S. fueling stations currently offer 240V charging for EVs (Figure 18). Direct current "fast" charging (Level 3, 480V DC, 50kW) would stress today's grid and would require special infrastructure and power management for widespread deployment.

As the market progresses from HEVs to PHEVs of various ranges to AEVs, the demands on the electric charging infrastructure will gradually increase. These increases can be accommodated as they occur, allowing for a smooth path toward greater electrification.

In contrast, the U.S. hydrogen fueling infrastructure is extremely limited. Fewer than 0.05% of U.S. fueling stations supply hydrogen. Hydrogen can be centrally generated and distributed in the U.S. by truck or through the 1,200 miles of pipelines mostly in Illinois, California, and along the Gulf Coast. Mass-market FCEVs would therefore require vastly expanded hydrogen generation, distribution, and fueling infrastructure, which will hinder, if not limit, their impact in the transport sector.

Infrastructure requirements vary across application. Vehicle fleets with their own fueling infrastructure could benefit from specialized fuels. Examples include overhead electrification for designated public transportation routes and hydrogen or CNG fueling at fleet depots. However, these are specialized applications, and technology pathways that leverage existing infrastructure are more likely to succeed in mass markets. Because of their infrastructure requirements, AEVs and FCEVs are most easily introduced into vehicle fleets with a captive fueling infrastructure.

Steven E. Koonin was the second Under Secretary for Science at the US Department of Energy, serving from May 2009 thru November 2011. In that capacity, he was oversaw technical activities across the Department's science, energy, and security activities and led the Department's first Quadrennial Technology for energy, from which some of the material in this paper is drawn. Prior to joining the government, Koonin spent 5 years as Chief Scientist for BP, plc. where he played a central role in establishing the Energy Biosciences Institute. Koonin was a professor of theoretical physics at Caltech from 1975-2006 and was the Institute's Provost for almost a decade. He is a member of the U.S. National Academy of Sciences and the JASON advisory group. Koonin holds a BS in Physics from Caltech and a PhD in Theoretical Physics from MIT (1975) and is currently an adjunct staff member at the Institute for Defense Analyses. He will take up an academic position in 2012.

Light-Duty Vehicles: A Discussion of the Evolving Engine, Vehicle and Fuel Requirements Context

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Abstract

This paper discusses the evolving vehicle context within which assessments and choices of alternative fuels for transportation should take place. The focus is on anticipated engine, powertrain, and other propulsion system improvements (especially their average efficiency) in the context of steadily reducing vehicle driving resistances, and especially weight. The fuel requirements of spark-ignition, diesel, and hybrid engines are discussed and connected to the supply, distribution, and refueling requirements of alternative fuels. An illustrative scenario of alternative fuels is described and used to indicate likely future fuel demand.

1. Background

As the price of oil continues to rise, and the potential for growth of petroleum-based transportation fuel in the longer-term is uncertain, the question of other energy sources and fuels is obviously important. An awareness of the vehicle context, especially the engines or other propulsion system changes in progress, is a necessary preliminary to developing effective alternative fuels strategies. This paper addresses the question of how this engine and vehicle context is likely to evolve over the next twenty years especially in relation to fuel requirements. The focus is on the current state of the in-use light-duty vehicle fleet (cars and light-trucks) in the United States and how, as new and more fuel efficient technology and propulsion systems enter and leave the vehicle fleet or parc through sales and scrappage, the fuel demand and greenhouse gas emissions of this critical component of the total U.S. energy sector will change.

The current U.S. transportation fuels situation from an energy perspective is as follows. Ethanol, made from corn grain is approaching 10 percent of the gasoline market. It is largely blended with and sold as "gasoline." There are some 2500 refueling stations where ethanol fuel (as E85) can be purchased: there are close to 120,000 re-fueling stations nationwide. A modest amount (or order 1 percent) of biodiesel fuel is blended with regular diesel fuel. In the total in-use fleet of 260 million vehicles there are about 10 million flexible-fuel vehicles in use that can satisfactorily use gasoline, E85, or any mixture of the two. Vehicle models that can use electricity directly (plug-in hybrids, PHEVs, battery electric vehicles, BEVs) are entering the market but as yet sales volumes are very small. There is also modest use of natural gas in vehicles in the U.S.—in buses, and in a small number of dual-fuel and dedicated NG vehicles.

In terms of mainstream technology the dominant propulsion systems are gasoline-fueled spark-ignition engines and diesel engines. While the light-duty vehicle market in Europe is about half gasoline/petrol and half diesel, in the U.S. gasoline engines dominate. The performance and fuel consumptions of these engines has and continues to steadily improve. Table 1 lists the primary nearer-term opportunities for improving the efficiency of gasoline-fueled engine vehicles. They are, in order of importance:

- Turbocharging naturally-aspirated gasoline engines which constitute some 90% of the market, with direct injection of fuel into the cylinder, and significant engine downsizing since the torque per unit of engine displaced volume is substantially increased.

- Improving the base engine efficiency through variable valve timing/control, increasing engine compression ratio, and reductions in powertrain friction, trends that are already underway.

- Introducing engine shut down at idle: so-called engine stop/start. In urban driving this reduces average fuel consumption by up to 5%.

- Steadily reducing the weight of vehicles through substitution of lighter materials, vehicle redesign, and shifting the vehicle size distribution downwards.

Beyond 2016, the auto manufacturers are likely to use these technologies more widely in their sales mix to meet the 2025 CAFE mpg targets now being finalized, step up the pace of ongoing incremental improvements, take additional weight out of vehicles beyond the 5 – 10% reduction expected by 2016, increase the percentage of hybrids, and introduce some electrified vehicles (PHEVs and BEVs) to gain the miles-per-gallon credits these alternative energy vehicles are being awarded.

Table 1: Opportunities for Improving Powertrain Efficiency

Technology	Compared with	% Gain in MPG
Diesel engine	Gasoline engine	25 – 30%
Gasoline direct injection + Turbo	Multiport fuel injection	Up to 12%
Dual-clutch transmission	Automatic transmission	Up to 10%
Cylinder deactivation	Using all cylinders	6%
Cont. variable valve timing	Fixed valve settings	5%
Stop-start system	Idling	5%
5 or 6-speed transmission	4-speed	3 – 5%

Source: Automotive News, May 25, 2009

2. Evolving Vehicle Context for Alternative Fuels

To assess the roles that alternative transportation fuels might play in the U.S., we need to extend our planning timeframe form the above nearer-term where impacts will largely come from improvement that can be made in mainstream spark-ignition and diesel engines, and expanding hybrid use, over the next 20 or more years. This evolving powertrain, vehicle, and fuels-requirement context involves both the quantitative performance and efficiency gains that improved mainstream and new technology could provide (at the vehicle level), and the deployment potential over time of these technology changes so their impacts on fleet fuel consumption (and other issues such as greenhouse gas (GHG) emissions) can be assessed.

As described above, in the powertrain arena, we expect that spark-ignition engines (largely gasoline fueled) will improve their efficiency through many advances in their component technologies, and through better optimization. By 2030 it is anticipated that a significant fraction (some 50% ore more) of these spark-ignition engines will be direct-injection, turbocharged, and downsized engines. This improves engine part-load efficiency significantly, largely by reducing the relative (and negative) impact of engine friction. Also, through turbocharging, automakers can continue to offer both enhanced (increasing) vehicle performance and higher fuel economy at the same time. There is a negative trade-off between performance and fuel consumption (1): thus this increased vehicle performance does decrease the fuel economy benefit by some 10-15%.

In terms of engine fuel requirements, this turbocharging trend, and the increasing efficiency trend it enables, is constrained by the abnormal engine combustion phenomenon of knock—the rapid spontaneous release of a portion of the fuel-air mixture's chemical energy inside the engine cylinder towards the end of the normally continuous mixture burning process. This knock constraint depends on the fuel's spontaneous ignition characteristics and is quantified by the fuel's octane number. Use of direct fuel-injection in these turbocharged engines helps with this knock constraint because as the in-cylinder fuel spray evaporates, it cools the unburned mixture and the temperature of that mixture which is a critical controlling variable.

What this says is that alternative liquid fuels with high knock resistance—high octane number—are most desirable. Note that interest is growing in increasing the octane rating of current gasolines, if it can be shown that the higher efficiency of the higher compression ratio gasoline engines these better fuels would enable more than offsets the additional energy used in the production of these higher octane gasolines.

Note also that the volatility—ease of vaporization—of spark-ignition engine fuels is a key characteristic in achieving fast and repeatable engine starting and realizing the very low emission levels of hydrocarbons required now (and more stringent levels in the future). This is another major constraint on the properties of alternative fuels.

Diesel engines will steadily improve also, but their efficiency will not increase as much as gasoline engine efficiency will increase. However, diesels, already some 20% more efficient than non-turbocharged gasoline engines on an energy consumption basis (some 30% more efficient on a fuel volume basis—gallons per 100 miles, liters per 100 km). This gap is expected to narrow over time. However, in the U.S. there is no tradition of extensive diesel use in light-duty vehicles, fuel costs are still relatively low, and diesel (per gallon) is more expensive than gasoline. So, the diesel sales fraction in U.S. is not expected to exceed 5-10% of vehicle sales over the next couple of decades. Hybrid vehicles (see below) appear to be a more attractive option. Also, transmission efficiencies will improve by about 10% as powertrain and vehicle designers incorporate more gears and more efficient shifting mechanisms, or continuously variable transmissions.

Alternative propulsion systems are already in production though still at modest levels. Hybrid sales (HEVs) are expected to grow steadily from today's 3% level to 10-20% of new vehicles in 2030, as the HEV cost premium above a conventional engine vehicle is reduced. Use of electricity in light-duty vehicles, in PHEVs and BEVs, will grow more slowly. Sales of such vehicles in 2030 might reach 10% if the battery cost premium falls sufficiently, though there is a growing consensus that the necessary cost reductions will need the successful development of new battery chemistries, a research and development task that would take at least 15 years.

From 2020 to 2030, the use of natural gas as a vehicle fuel may well grow, but prospects are uncertain. In the light-duty vehicle area its use is likely to be largely confined to localized fleets. Natural gas vehicles, either as single-fueled vehicles or as dual fuel—with both natural gas and gasoline fuel systems on the vehicle—are significantly more costly and a readily and broadly available distribution and refueling system for natural gas does not yet exist. Thus, at present the use of natural gas as a vehicle fuel is "inconvenient" though natural gas per unit energy content is significantly cheaper than petroleum-based fuels and is expected to remain so.

Fuel-cell hybrid systems, which many view as a promising longer-term option for the larger end of the light-duty vehicle size distribution, will continue to be developed and tested under real world conditions essentially as "production prototypes." Sales volumes in the 2020-2030 timeframe might be several percent. The deployment of a widespread hydrogen distribution system will be a critical constraint, and at best will take time to develop. However, the cost premium of the fuel-cell propulsion system has been substantially reduced, and that cost reduction trend continues.

There will be vehicle changes, too. A steady reduction in vehicle weight, up to some 10-15% by 2030, from vehicle design changes and use of lighter-weight materials is anticipated. A comparable weight reduction (by 2030) is likely to occur in parallel due to downsizing of the U.S. new vehicle size distribution. This downsizing is starting as gasoline prices steadily rise, and due to consumer's caution in the current economy. A 10% reduction in vehicle weight results in about a 6% reduction in fuel consumption.

An important "less obvious" trend is the ongoing negative impact of increasing vehicle performance on fuel consumption. An average vehicle acceleration performance escalation of some 10% where it eventually levels out by about 2030 is anticipated for an average car value of about 9 seconds today to about 8 seconds). Some 15% degradation of the anticipated potential 2030 fuel consumption benefit will result as a consequence. Note that smaller lighter vehicles with less powerful engines may compromise vehicle drivability, performance up a grade, vehicle towing capability, load-carrying capacity, etc., especially in certain important categories of vehicles where one or more of these capabilities is critical.

What will be the fuels requirements of these evolving future vehicles? Multi-component hydrocarbon fuels closely comparable to what we have today would be the "best solution." Such fuels would have a high octane rating and appropriate wide volatility range: liquid fuels are obviously the most desirable. It will be challenging to replace petroleum-based fuels as their supply, though pulled by increasing demand, over time will become limiting. Oil sands and heavy oil are a growing source of liquid fuels: currently supplying some 10% of demand in the U.S. Global supply projections of petroleum and oil sands/heavy oil based fuels, out to 2030, suggest modest growth of order 1% (at best) with a gradual leveling-off and then decline thereafter.

Ethanol, which at present is an easier end-product to produce than many of the alternatives, is about 7% (on an energy basis) of U.S. transportation fuel supply. 10% corn-based ethanol is a likely upper bound in the U.S. Other biomass sources and fuel production approaches are moving toward pilot production but are not yet at that stage. Currently, plausible best fuel choices from biomass are unclear.

Methanol, from energy density (half that of gasoline) and toxicity perspectives, is not an ideal end product, and the broader motivation in the U.S. for methanol, beyond its potential for lower cost, is unclear.

While we are steadily learning about the environmental and other potential impacts of large-scale use of biomass for transportation, the likely magnitude of these impacts is often uncertain. The issues are: competition with food in agricultural land use, the ecological impacts of large scale biomass production for fuel, the greenhouse gas emissions impacts of increasing and changing land use patterns to produce fuels from biomass, water impacts—the amounts required for this agricultural expansion and the amounts used in biomass processing, and the environmental consequences of increased use of fertilizer, etc.

Increasingly, many professionals in this area, are recognizing the real challenges involved in setting up new fuel distribution and vehicle refueling infrastructures for alternative fuels such as ethanol and methanol, for natural gas, and for hydrogen, and in parallel implementing at scale the propulsion system and on-vehicle fuel storage technology needed to use these fuels. As a consequence, attention at least for the nearer-term, is shifting to whether "drop-in" fuels that are compatible with existing fuels—gasoline and diesel—and thus do not require any major changes on the fuel side and the vehicle side, are a realistic alternative. Given this difficult choice with substantial uncertainty, it is not surprising that the major growing non-petroleum based fuel supply is "gasoline and diesel" from Canadian tar/oil sands.

3. Illustrative Demand Scenarios

A second part of this evolving context is the anticipated U.S. demand for transportation fuel and how that will change over time. This has been an important focus of my MIT team's research. Here, I will summarize one of our recent assessments (2). Many others, of course, are active in this area. While different groups make different assumptions, especially about the rates at which we progress to lower fuel-consuming vehicles technology, the general trends in these studies are similar.

Figure 1 shows our recent projections of vehicle fuel consumption (in liters/100 km) of different powertrain technology vehicles into the future. Light-trucks show similar trends but with fuel consumptions some 30-40% higher due primarily to their higher weight. Figure 2 shows the assumed market shares of the various powertrains as a percentage of new vehicle sales in each year, out to 2050. Note that in this study (2), assumed values for the some 40 input parameters required for each simulation were specified by a minimum and maximum value, and a modal value for each triangular distribution. These figures show mean values. A steady transition over time to more efficient propulsion systems (and increasingly lighter vehicles) is assumed. (We update these assumptions periodically. With the 2025 CAFE targets now part of a NHTSA/EPA rulemaking, we are assuming a higher proportion of gasoline engines is likely to be turbocharged (increasing that percentage from 20 or so to approaching 50%. The net impact of this change on fleet fuel consumption and GHG emissions is modest.) Many other assumptions related to the in-use fleet size and turnover, vehicle kilometers traveled, sources of alternative fuels to petroleum-based gasoline and diesel, any electricity and hydrogen used, extent of vehicle performance escalation, are required: see reference (2). Also, a Monte Carlo probabilistic methodology is used to generate a distribution of outputs form the input distributions specified as assumptions (3).

The results for the LDV U.S. in-use fleet's fuel consumption (in billion liters of gasoline equivalent per year), is shown in Fig. 3. We see that the mean projected fuel consumption changes little over the next decade, and then decreases at some 1 to 1.5 percent per year. By 2040 fleet fuel consumption would be down by about 20% from its 2010 to 2020 value. The U.S. in-use fleets GHG emissions decrease from 2010-2020 levels also by about 20% (note these are life-cycle emissions, and several other fuel-related factors come in). The dashed lines in Fig. 3 show the 75% and 25% probability pathways (one standard deviation), and 95% and 5% probability pathways (two standard deviations) in this calculation, which embodies uncertainty. These scenario analyses give us a useful sense of what future demand for transportation fuels is likely to be.

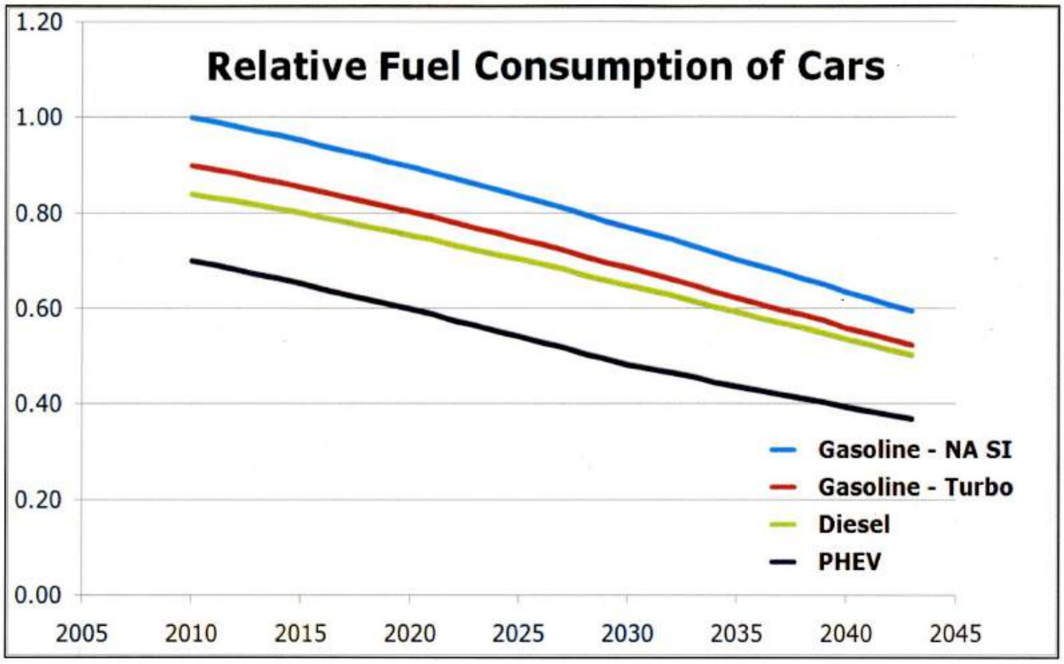

Figure 1. Relative fuel consumption of the average car for the different powertrains, assumed scenario input, over time to 2050. Hybrids and plug-in have the same fuel consumption for liquid-fuel driven miles. (2)

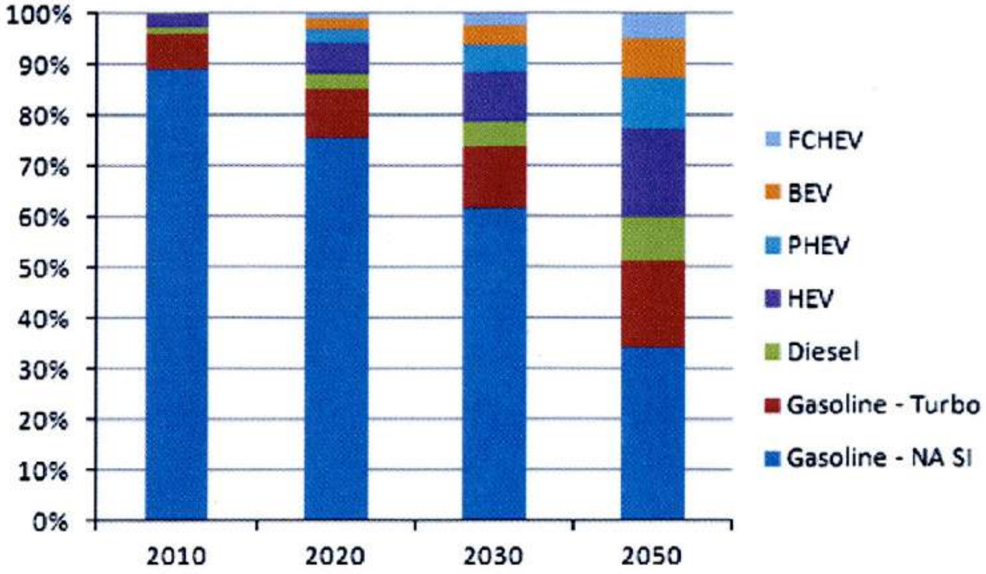

Figure 2. Powertrain new vehicle market share, mean input values 2010-2050. (2)

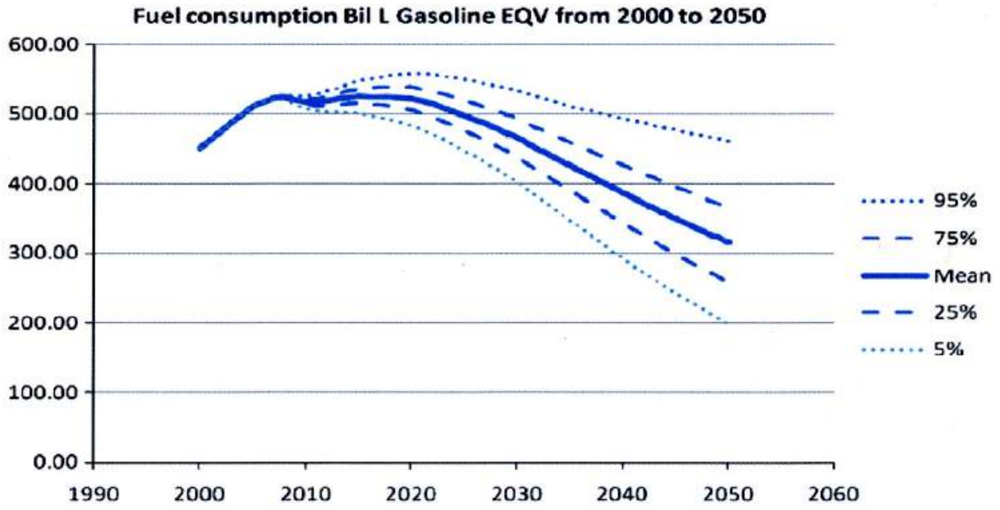

Figure 3. U.S. light-duty fleet fuel use (billion liters gasoline equivalent/year) over time out to 2050. (2)

4. Alternative Fuels: Overall Objectives

Our overall objectives are to displace a significant fraction of the petroleum and oil-sands based fuels we are using at roughly equivalent cost, and do this in ways that also reduce the LDV fleet's greenhouse gas emissions. Both these objectives are furthered if the powertrain that use these alternative fuels are of equal or higher fuel efficiency than the steadily improving gasoline engine. It is clearly beneficial if vehicle engines can operate satisfactorily on both the alternative fuel and gasoline. Higher compression ratios, higher turbocharger boosting levels and thus greater engine downsizing, all improve powertrain-in-vehicle efficiency. Thus alternative liquid fuels should match or exceed the anti-knock rating (octane number) of gasoline.

Light-duty vehicles must, of course, meet current and future vehicle air-pollutant requirements. Future standards will be lighter than today's requirements and, the most demanding requirement, the HC emission standards (emissions must be less than 1/10,000 of the vehicle's fuel usage), are expected to be further reduced. Thus the volatility/evaporation characteristics of alternative fuels will need to be comparable to those of gasoline (which also need to be tightly controlled as well), to ensure very clean engine start-ups. Note that deployment of engine start/stop technology makes this even more important.

Obviously, a high specific energy density (per unit mass and per unit volume) is important in fuel production, distribution, storage, and refueling at the service station, and for fuel storage on the vehicle. Here the alcohols, ethanol and methanol, are at a disadvantage because they are partly oxidized already (they have specific chemical energy densities of 0.7 and 0.5 relative to gasoline, respectively).

The above summary indicates that drop-in fuels—hydrocarbons with properties little different from petroleum-based gasoline, maybe with higher octane ratings, are an attractive option if the availability of primary energy sources of such fuels and their processing technology indicates their potential for large-scale production at marketable prices. If alternative fuels can be produced that are fully miscible with gasoline or diesel, and could even enhance the characteristics of these petroleum-based fuels (for example through higher octane) they would have a significant advantage.

Alternative fuels that would need a separate (and therefore new) supply, and distribution, and refueling system, and which would need vehicle modifications to use these fuels would be disadvantaged.

The anticipated future prices of these different alternative fuels relative to the prices of petroleum-based gasoline and diesel, is clearly a major factor in choosing among the alternatives.

5. Vehicle and Fuel Options

Here I list and briefly describe our vehicle and fuel options, with the next 20 years as the timescale. Table 2 summarizes the several alternatives.

We can blend these new fuels with conventional fuels. We are already doing this with ethanol as E10 and we may move to E15. With ethanol and methanol, which is not fully miscible, there is an upper bound on the amount that can be absorbed by blending.

Thermochemical conversion of biomass and other sources to gasoline-and diesel-like fuels has the potential for producing drop-in fuels—end products fully miscible with gasoline and diesel. As discussed previously, should the cost of producing these fuels prove to be competitive, their development and use would be an especially attractive option because propulsion system and vehicle technology changes, and fuel distribution and refueling infrastructure changes would be minimum.

Flex-fuel vehicles that can operate with any mixture of gasoline and ethanol have been brought into the vehicle fleet over the past decade or so. The auto manufacturer's incentives were the government's CAFE credit incentive that this approach (with its low costs—some $100 per vehicle) could open the LDV fuel market to growing ethanol use, and There are currently about 10 million flex-fuel vehicles in use in the U.S., about 4% of the in-use fleet. E85 refueling stations have spread and there are now about 2500 such stations, about 2% of the 120,000 U.S. refueling stations. Only about 500,000 of the 10-million flex-fuel vehicles regularly use E85. Barriers to increased ethanol use are the fuel's cost, its availability (production and retailing are currently concentrated in the U.S. Midwest) and limited supply (most of the available ethanol is blended).

Table 2: Vehicle/Alternative Fuels Options

(a) Blend new fuels with existing fuels: e.g., E10, maybe E15. Upper bound on penetration.

(b) Produce new fuels that are fully miscible with gasoline and diesel.

(c) Expand production of flex-fuel vehicles; achieve adequate distribution of alternative-fuel refueling stations.

(d) Produce dedicated optimized alternative-fuel-vehicles: e.g., natural-gas vehicles.

(e) Dual-fuel vehicles: e.g., both gasoline and natural gas fuel tanks and fuel-injection systems on the vehicle.

(f) More focused approaches: Separate on-board tank for "anti-knock" fuel (e.g., ethanol): suppresses knock with gasoline and increases gasoline engine efficiency.

An approach to expand this ethanol path under consideration is to require all vehicles sold be made bi-flex-fuel (gasoline and ethanol) or tri-flex-fuel (gasoline, ethanol, and methanol). Thus, over time, use of these alcohol fuels—which do have attractive combustion and knock-resisting characteristics—could then expand. An important question is whether uncertainly as to the long-term potential for these two alcohol fuels relative to other options such as producing drop-in fuels thermochemically from biomass and other sources, makes it premature to attempt a mandate.

Development and limited production of dedicated fuel vehicles is occurring. Honda is selling a natural-gas-fueled LDV. Also, in other parts of the world (Sweden, Brazil) E100, ethanol-fueled vehicles, have been offered. The latter usually require a small gasoline tank on-board to achieve adequate low-emissions engine starting.

Another option is dual-fuel vehicles such as natural gas and gasoline. These vehicles require two on-board fuel storage systems and fuel injection systems. Dual fuel vehicles, as with the flex-fuel vehicles, may not be able to get the optimum use out of each of the two fuels due to their different characteristics. Each of the fuels in these two pairs—natural gas and gasoline, or gasoline and ethanol—has different knock resistance and thus octane rating. The engine compression ratio is fixed by the basic geometrical design of the engine, so it has to be set (more or less) at a value determined by the lower octane rating fuel (gasoline, compared to natural gas; gasoline, compared with ethanol). So optimum efficiency in the absence of variable compression ratio engines is not obtained with each fuel. Variable valve control can help here but at a loss in power. The added costs of dual-fuel spark-ignition engines involving natural gas are substantial.

In addition to the broader options outlined above, there are some more specific engine-fuels opportunities. One concept that I, with Dan Cohn and Leslie Bromberg here at MIT are exploring uses direct-injection of ethanol (or methanol) into the cylinders of a gasoline engine when that engine (with gasoline) is about to knock. Thus the major efficiency constraint on compression ratio and high turbocharger boost pressures is removed, the engine can be downsized substantially, and its efficiency significantly increased (doubling the benefits that a direct-injection, turbocharged and downsized standard gasoline engine achieves). This can be done with modest amounts (5% or less) of ethanol but a small additional tank and fuel pump for this anti-knock fuel are required. This approach to constraining or removing knock is also applicable to flex-fuel vehicles and natural gas vehicles to optimize their operation and performance. It can utilize more than a modest amount of the "alternative fuel," if more is available. This concept is being explored by some industrial groups. There are several potential refueling options: one is to distribute the anti-knock fuel (say ethanol plus some water) in a manner analogous to how windshield washer fluid is distributed.

6. Key Questions

This Symposium is taking place because developing a significant supply of alternative fuels is important as the cost of petroleum-based transportation fuels rises, and (in due course) their availability becomes a serious constraint. Our discussions today are also important because we have yet to identify clearly the most advantageous and viable path towards this goal—a substantial supply of one or more alternative fuel that is cost effective as it is used in light-duty vehicles. We need to acknowledge that our knowledge base for identifying the more promising fuel options (along with the vehicle propulsion systems these fuels require) is currently insufficient.

The challenge of building-up significant supply of these fuels can usefully be separated into two steps. First, how can we best "get started" on exploring the various options in ever-greater depth and thus narrowing our many possible choices in a rational way? Second, we need to explore how to grow the supply of the most promising of these options, to significant scale, as we steadily become "wiser." A key piece of these questions is what the appropriate role of our Federal Government in this process should be. The basic question is how do we break out of the "chicken and egg" constraint circle—fuels first or vehicles first: how can we best grow both together?

One approach to moving us forward would be to identify the (limited number of) promising options, gaining real-world experience with the required vehicle technology, fuel supply and distribution, in a step-by-step manner. Some of this is already happening with limited fleet studies that are "localized" so that fuel supply and distribution, and actual vehicle use, are not severely constrained. A steadily expanding set of fleet studies, which may well need to be incentivized by Federal funding, may be a promising way to get us started more seriously towards our broader goal. At present, our progress is limited.

References

1. Cheah, L.W.B., A.P., Bodek, K.M., Kasseris, E.P., Heywood, J.B. 2009. The Trade-off between Automobile Acceleration Performance, Weight, and Fuel Consumption, SAE paper 2008-01-1524, *SAE International Journal of Fuels and Lubricants,* 1, 771-777.

2. Bastani, P., Heywood, J.B., Hope, C., 2012. The Effect of Uncertainty on the U.S. Transport-Related GHG Emissions and Fuel Consumption Out to 2050. *Transportation Research Part A: Policy and Practice,* 46, 517-548.

3. Bastani, P., Heywood, J.B., Hope, C., 2012. A Forward-Looking Stochastic Fleet Assessment Model for Analyzing the Impact of Uncertainty on Light-Duty Vehicles Fuel Use and Emissions, SAE paper 2012-01-0647, SAE World Congress, April 24-26, 2012, Detroit, MI.

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The Case for Bi-Fuel Natural Gas Vehicles

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April 14, 2012

A Position Paper for the 2012 MITEI Symposium
Prospects for Flexible- and Bi-Fuel Light Duty Vehicles

Summary

The purpose of this paper is to examine the feasibility of a bi-fuel natural gas vehicle for the U.S. light duty retail market. Although both dedicated and bi-fuel natural gas vehicles (NGVs) have been marketed in the U.S., the vehicles have been designed to maximize compressed natural gas storage within constraints of costs and volume.

Throughout the world bi-fuel NGVs are the predominate design. In developing countries most bi-fuel vehicles are converted from existing gasoline vehicles. Costs of conversion kits including storage tanks (mostly Type I steel tanks) are relative low as are installation costs. Coupled with high gasoline prices and low CNG prices, these bi-fuel conversions continue to capture market share. Fueling infrastructure is being built to meet customers demand for the cheaper natural gas fuel. The bi-fuel concept allows for some leeway in station build-out, since gasoline can still be used if needed in these vehicles.

Automakers marketing vehicles in Europe have further evolved the bi-fuel concept to take advantage of the relatively high gasoline and low CNG prices. CNG prices in Europe are 30 to 50 percent of gasoline prices. Automakers are providing bi-fuel vehicles with underfloor CNG storage so as to not compromise vehicle functionally. They are also optimizing fuel consumption and performance. Automakers are offering enough storage to provide good range on CNG and have maintained a somewhat smaller gasoline storage tank. This strategy is aimed at mostly CNG use and therefore requires the investment and built-out of CNG stations. Bi-fuel vehicles are more expensive than gasoline counterparts, but the price of CNG makes reasonable paybacks possible.

In the U.S. the NGV strategy for light-duty vehicles has been to maximize CNG range of either dedicated or bi-fuel NGVs. Typically, however, dedicated vehicles have reduced range compared to their gasoline counterpart due to limited vehicle space available for CNG storage tanks. Similarly, for bi-fuel options vehicle space is further limited by the retained gasoline fuel tank. In either design, the CNG tanks are often mounted in the vehicle’s trunk or pickup bed, thus reducing storage space or payload. The current designs really address the commercial light duty market for those users that can justify

the higher upfront costs based on their duty cycle. With U.S. fuel prices, this usually means that NGVs are only economical for fleets that use a lot of fuel/drive a lot of miles.

This design philosophy effectively excludes the light duty retail market where the average annual mileage is 12,000 and the average annual fuel use is less than 500 gallons. At these low utilization rates, it is hard to payback the higher upfront costs of NGVs fast enough to interest consumers. However, if storage could be reduced, costs could be lowered enough to possibly interest consumers. Two thirds of all drivers travel 40 miles or less per day which means depending on vehicle that CNG storage of 1 or 2 gallons gasoline equivalent could be sufficient. Home refueling would most likely also be needed to eliminate daily CNG refueling trips. A simple analysis indicates that the combination of reduced vehicle costs and additional costs for home fueling appliance may be attractive to consumers.

Additionally, with small natural gas storage volumes it may be possible to further reduce system complexity and costs by lowering the storage pressure. This would need to be investigated further.

Introduction

In the world today, there are over 12.7 million natural gas vehicles (NGVs) operating.[1] Most of these vehicles are light-duty (passenger and light commercial) vehicles and are largely converted from gasoline to natural gas.   Table 1 shows the world’s distribution of light, medium and heavy duty natural gas vehicles in 2010. Almost all the light duty conversions retain the gasoline fueling system and are then capable of operating on natural gas and gasoline—so called bi-fuel vehicles. The majority of heavy duty applications using natural gas are buses due to the emissions benefits of natural gas compared to uncontrolled or minimally controlled diesel technologies in developing countries. Except for buses, there is little penetration of natural gas technologies in the heavy duty sector; the U.S. is the exception and this discussed further below.

Table 1. World NGV Population by Vehicle Class

Total NGV population - Cars, Buses and Trucks				
LD+MD +HD Vehicles	**LD Cars and Commercial Vehicles**	**MD+HD Buses**	**MD+HD Trucks**	**Others**
11,931,328	**11,236,843**	**400,370**	**206,789**	**87,326**

Source: Gas Vehicles Report, October 2010

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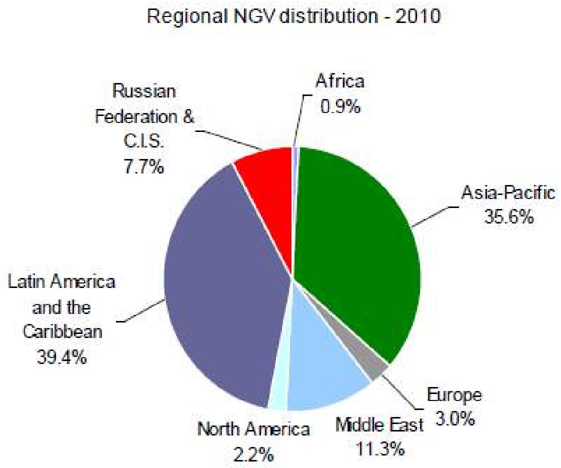
[1] http://en.wikipedia.org/wiki/Natural_gas_vehicle

Figure 1 shows the distribution of NGVs by country. The majority of NGVs are concentrated in Latin America and Asia Pacific regions. Most of these vehicles in these regions are converted gasoline vehicles. Conversion costs in these countries are low due to low cost conversion kits (less sophisticated gasoline technologies), low cost CNG cylinders (steel), and low cost labor. These regions also have reasonably high gasoline prices and natural gas costs are often 30% to 50% cheaper. Low conversion costs coupled with fuel savings—and often government incentives—results in quick payback periods.



Source: J. Seisler, Clean Fuels Consulting working paper to TIAX on "International Perspective NGV Market Analysis: Light- and Medium-Duty Vehicle ownership and Production," April 2011.

Figure 1. Regional Distribution of NGVs throughout the World

Key to the penetration of NGVs worldwide has been the installation of CNG fueling stations to meet vehicle fueling demands. Even thought the vehicles are capable of gasoline or natural gas operation, the low cost of natural gas in comparison to gasoline has lead to the demand for natural gas and the build-out of natural gas fueling infrastructure. As shown in Table 2, the number of vehicles per station varies from 112 for the U.S. to 1,890 for India. The U.S. number is biased by more heavy duty applications that use more fuel per vehicle. The average of this data set is 840 vehicles per station. This is consistent with station costs and a reasonable rate of return based on economic analysis performed by TIAX.

The purpose of this paper is to examine the viability of light-duty NGVs for the U.S. retail market. As indicated most of the NGVs operating in the world are bi-fuel vehicles that have been converted to natural gas. European automakers have been introducing many new bi-fuel models into the market place and the next section reviews this experience. How the world and European experience are related to U.S. conditions is then discussed. Finally, the paper ends with proposed bi-fuel approaches for the U.S. light-duty retail market.

Table 2. 2010 Fueling Infrastructure for Selected Countries

Country	NGVs	Fueling Stations	Vehicles per fuel station
India	1,080,000	571	1,891
Iran	1,954,925	1,574	1,242
Egypt	122,271	119	1,027
Argentina	1,901,116	1,878	1,012
Kyrgyzstan	6,000	6	1,000
Brazil	1,664,847	1,725	965
Italy	730,000	790	924
Bolivia	140,400	156	900
Pakistan	2,740,000	3,285	834
Peru	103,712	137	757
Bulgaria	60,270	81	744
Ukraine	200,000	285	702
Myanmar	22,821	38	601
Colombia	340,000	614	554
Thailand	218,459	459	476
Uzbekistan	47,000	133	353
China	450,000	1,350	333
United States	112,000	1,000	112
Totals	11,893,821	14,201	838

Source: http://www.iangv.org/tools-resources/statistics.html

European Development of NGVs

Like the developing countries today, Europe NGV development started with conversions or retrofits of existing gasoline vehicles. Italy, for example, started with conversions of gasoline vehicles to NGVs in the 1930s. NGV technology has vastly improved since these early conversions mostly due to the substantial improvements in gasoline technologies over the last 20 years. Early conversions were performed on carbureted gasoline vehicles without emissions controls. As emission controls were phased in carburetors gave way to closed loop carbureted technologies which then gave way to close loop fuel injection systems. Aftertreatment catalyst also became much more efficient driving gasoline emissions to extremely low levels. Natural gas technologies kept up with the advances in gasoline technology with multi point sequential injection, engine controls, and exhaust aftertreatment.

Gaseous storage technology also evolved. Natural gas has a low energy density compared to petroleum fuels and can be improved by compression. This however requires high pressure storage containers which are more costly than gasoline or diesel fuel tanks. Four types of storage cylinders are now manufactured:

- Type I all steel cylinder
- Type II fiberglass, hoop wound aluminum cylinder
- Type III fully wrapped metal liner cylinder

- Type IV 100% full composite cylinder—liner and wrapping

Type I steel cylinders are the least expensive but weigh the most. Type IV cylinders are the most expensive—due mostly to the cost of carbon fiber—and weigh the least. For light duty vehicles every 3 percent increase in weigh reduces fuel consumption by 0.6 to 0.9 percent.[2] Pressure has also changed over the years from 2400 psi in some of the earlier applications to 3000 psi used in Europe today to 3600 psi used in the U.S. Higher pressure allows for more storage of natural gas and longer vehicle range.

European vehicle manufacturers are now offering a variety of natural gas bi-fuel models for the retail light-duty market. According to NGVA, auto manufacturers including Fiat, Mercedes Benz, Opel, Seat, Scoda, VW, Audi, Volvo, and Saab now offer 22 passenger car models. Table 2 provides examples of OEM offerings for small and medium size NGVs. All these models meet Euro V emission standards. A distinction is now be made between NGVs with smaller gasoline tanks (<15 L) and those with larger gasoline tanks. The former are referred to as mono-fuel and the latter as bi-fuel.

Table 2. Example of OEM Vehicles Available in Europe

OEM	Model	Power (hp)	CNG storage kg	Gasoline storage (L)[1]	Range (km)	CO2 g/km[2]
Fiat	Panda 1.2 8V	69	15	30	800	107
Fiat	Punto Evo 1.4 8V	70	15	45	1000	115
Fiat	Qubo 1.4 8V	70	15	45	950	114
Fiat	Fiorino 1.4 8V	70	15	45	960	119
Mercedes Benz	B 180 NGT					
Mercedes Benz	E 200 NGT	163	19.5	54	1070	149
Opel	Zafira Tourer 1.6 CNG Turbo ecoFlex	150	25	14	680	129
Opel	Comobal 1.4 CNG Turbo ecoFLEX	120	16-22	22	750	134
VW	Up!CNG	68	11			79-86
VW	Passat 1.4 TSI EcoFuel	150	21	31	940	117
VW	Touran 1.4 TSI EcoFuel	150	18-21	11	650	128
VW	Caddy 2.0 EcoFuel	109	37	13	760	156

Source: www.ngvaeurope.eu/cars

1. According to Directive 2007/46/EC concerning type approval of vehicles, all petrol/gas vehicles having a petrol tank not exceeding 15 liters should be classified as “mono-fuel”, beyond 15 liters petrol tank size, the classification would be “bi-fuel”.
2. Regulation (EC) No 443/2009 says that "in the case of bi-fuelled vehicles (petrol/gas) the certificates of conformity of which bear specific CO2 emission figures for both types of fuel, Member States shall use only the figure measured for gas".

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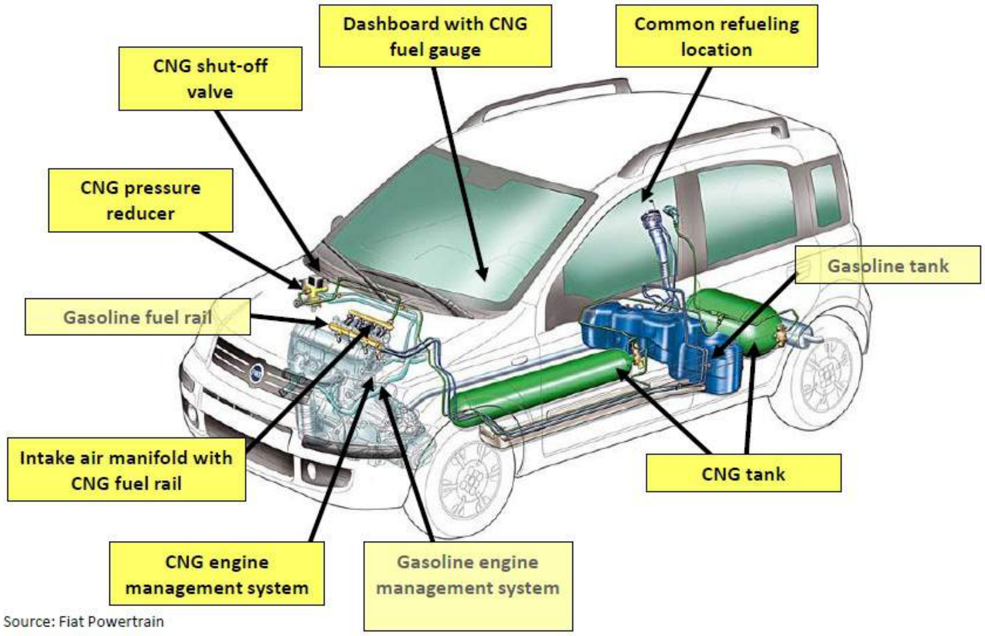
[2] “Assessment of Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles,” with Matthew A. Kromer and Wendy W. Bockholt, Final Report prepared for the National Academy of Sciences, Washington, DC, November 3, 2009.

European auto manufacturers have also introduced a number of vans that have applications from commercial to private use. These manufactures and models include Iveco Daily, Fiat Ducato, Mercedes Benz Sprinter, Fiat Dobolo cargo, Fiat Fiorino, and VW T5.[3] Clearly, either in the passenger car segment or the van segment European auto manufacturers are now providing products instead of the previous retrofits/conversion companies. Some conversions are still being done, but primarily through a qualified vehicle manufacturing (QVM) program like Volvo's V70 CNG bi-fuel vehicle. This is a result of the more complicated emissions and engine/powertrain controls and aftertreatment on modern gasoline vehicles. Integrating natural gas technologies to these very complex gasoline technologies requires close interaction with the automakers.

An example of the packaging of natural gas components in these European NGVs is shown in Figure 2. In this bi-fuel example, Fiat has located the CNG tanks underfloor along with the gasoline tank. Fueling for gasoline or CNG is in a common vehicle location as shown in the figure. Locating the fuel tanks underfloor does not compromise the space in the vehicle as has been the practice in most NGVs to date.

Keeping the gasoline fuel system has several advantages. Key advantage is that the vehicle is not solely dependent on CNG fueling infrastructure. Gasoline can be used in cases where CNG fueling is not available or to extend the driving range. Operating on gasoline can also be used to help to meet the very tight emission standards. For example, auto makers are adopting the strategy of starting up on gasoline and then switching to



Source: Fiat Powertrain

Figure 2. Example of European NGV Packing

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[3] http://www.ngvaeurope.eu/vans

natural gas to minimize methane emissions during cold starts with natural gas. Of course, there are also disadvantages of bi-fuel operation since the engine can not necessarily be optimized for natural gas operation. Higher compression ratio associated with 130 octane rating of natural gas is not possible with today's engine technology without affecting gasoline performance. Valves and valve seats have to be hardened for natural gas operation. Ignition systems also need to be evaluated including spark plug durability.

Also, aftertreatment systems need to be optimized for both gasoline and natural gas and methane emissions in natural gas operation need to be managed. European automakers are adding a catalyst to reduce methane emissions from bi-fuel vehicles. Off setting some of these issues, is that gasoline technology today is much more flexible than the mechanical systems of the past. Nevertheless, natural gas technology will have to keep up with the advancing improvements in gasoline technology aimed at improving fuel consumption and CO2 emissions.

European gasoline prices are quite high compared to U.S. prices. Some example prices for February 21, 2012[4] were:

Italy	1.80 €/L (8.98 $/gal assuming 1.32 €/$)
Germany	1.68 €/L (8.38 $/gal)
Sweden	1.63 €/L (8.13 $/gal)
France	1.60 €/L (7.98 $/gal)

CNG prices in these same countries range from 0.80 €/kg to 1.15 €/kg or on an equivalent gasoline energy basis (liter gasoline equivalent, Lge) 0.53 €/Lge to 0.77 €/Lge.[5] CNG is therefore 30% to 50% cheaper than gasoline. This fuel savings can be use to offset the higher costs of the CNG equipped vehicles. Figure 3 shows a simple payback analysis for the fuel prices in Italy. Average annual vehicle kilometers travel in the EU15 is 10,450.[6] Fuel consumption was assumed at 7.8 L/100km. With these assumptions nearly all incremental costs are within an acceptable 3 year payback. Lower fuel consumption increases the payback period.

A more specific analysis was also performed for the recently announced Opel Zafira Tourer. The CNG version of this vehicle has a best in class 530 km natural gas range with 25 kg CNG capacity and a 14 L auxiliary gasoline tank.[7] This vehicle is a multi passenger vehicle (MPV) with seating up to 7. Figure 4 shows a schematic of the vehicle with CNG tanks located underfloor. The CNG version of this vehicle which includes start stop technology is priced at € 27,950 (recommended price in Germany including VAT). A comparably equipped gasoline version of this vehicle (1.4 L turbo rated at 103 kW/140hp) retails for € 24,150 with fuel consumption of 6.3 L/100km slightly better than the CNG version.

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[4] http://www.drive-alive.co.uk/fuel_prices_europe.html

[5] http://www.cngprices.com/station_map.php accessed April 13, 2012

[6] J. Seisler, Clean Fuels Consulting working paper to TIAX on "International Perspective NGV Market Analysis: Light- and Medium-Duty Vehicle ownership and Production," April 2011.

[7] http://media.opel.com/content/media/intl/en/opel/news.detail.print.html/content/Pages/news/intl/en/2011/OPEL/12_08_opel_zafira_tourer_cng

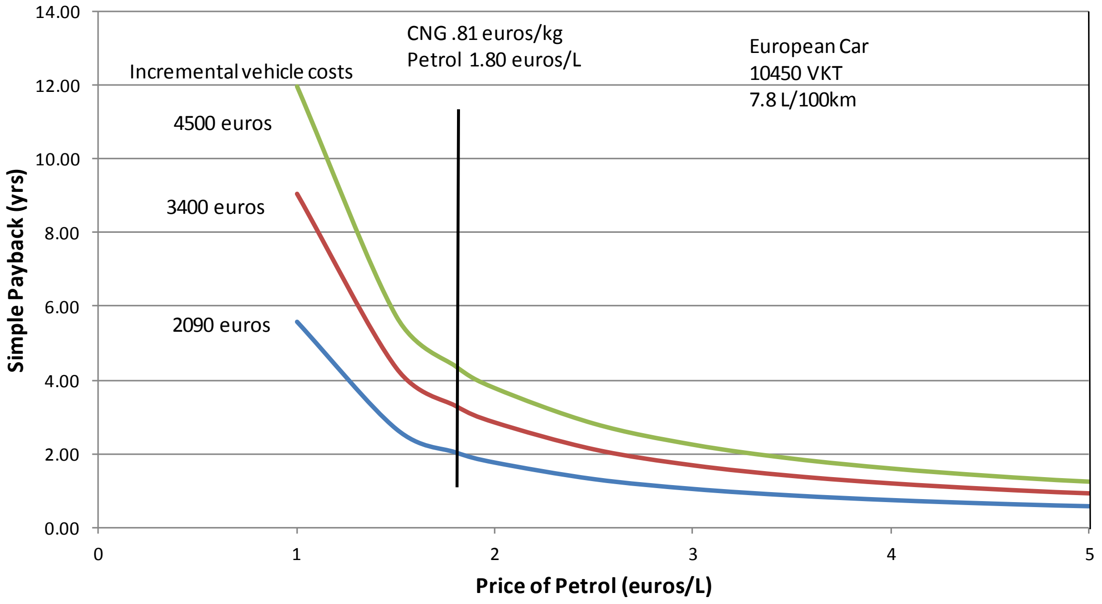

Figure 3. Payback in years for incremental vehicle costs decreases with higher gasoline prices

Source: Opel

Figure 4. Opel CNG Zafira Tourer 1.6 L Turbo ecoFLEX with 110 kW/150 hp. Natural fuel consumption 4.7 kg/100km

A simple payback analysis was performed for this vehicle using the gasoline fuel prices in Germany and a range of CNG prices. These results are shown in Figure 5. For gasoline at €1.68/L and CNG prices ranging from €0.80/kg to €1.15/kg, paybacks range from 4.4 to 5.75 years. Although outside the 3 year payback target, little changes in either CNG or gasoline pricing would potentially make a difference on consumer acceptance.

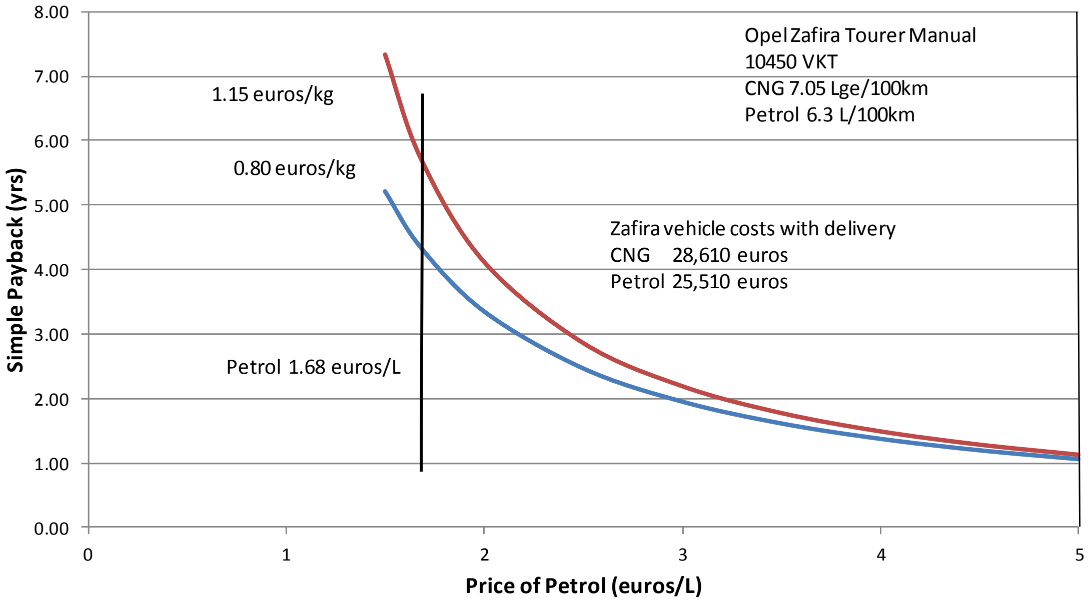

Figure 5. Simple payback analysis for recently introduced Opel CNG Zafira Tourer

European automakers are leading the world in the development and sales of CNG bi-fuel (and mono-fuel) vehicles. CNG bi-fuel vehicles sold in Europe to retail customers have integrated the CNG and gasoline storage tanks so as to not affect vehicle functionally. They have also designed these vehicles to have comparable attributes on vehicle range and performance. Retail customers are not sacrificing vehicle attributes with these offerings and — provided the customer has convenient access to CNG fueling — acceptable savings are possible if natural gas is used.

United States Development of NGVs

U.S. experience also paralleled Europe with the first NGVs converted gasoline vehicles using technology developed in Italy and the Netherlands. This was followed by companies offering conversion systems and subsequently by the U.S. automakers developing dedicated and bi-fuel technology in the late 1980s and early 1990s. Although conversions were favored initially, the development of sophisticated light-duty emission controls in the 1990s made it difficult for the conversions to meet emission levels achieved by the gasoline vehicles without substantially more integration with the OEM (original equipment manufacturer) engine and emissions systems. In fact some retrofit and conversion systems actually increased tailpipe emissions, leading the U.S. EPA and California ARB to require conversion and retrofit suppliers to emission certify their systems. Ultimately, this increased the cost of the retrofit systems since the certification costs are amortized over a small number of vehicles.

Energy legislation in the U.S. required government and fuel provider fleets to purchase light duty alternative fuel vehicles (EPAct 1992)[8] which help to develop the demand for NGVs in the late 1990s early 2000s. Alcohol flexible fuel vehicles were also introduced into the market in the mid to late 1990s. Automakers received CAFE (corporate average fuel economy) credits for manufacturing these alternative fuel vehicles.

Fuel use was not required by EPAct and many of the bi-fuel or FFVs used only gasoline. This was a result of very sparse or non-existing fueling facilities for alcohol fuels (first methanol and then ethanol) and compressed natural gas. One exception was vehicles placed in many of the utilities around the U.S. (gas and/or electricity suppliers). Here the utilities built the infrastructure to supply high pressure natural gas (CNG) to their dedicated and bi-fuel light duty vehicles purchased to meet EPAct requirements. These stations were also used by other fleets to fuel their NGVs.

The second factor that hurt the penetration of alternative fuel vehicles and use of alternative fuels was the drop in oil prices after the first Gulf war (1992) and the relative stability of prices throughout the 1990s. Low oil prices drove down the price of gasoline and the lower the price differential between gasoline and natural gas. This made it particularly hard for natural gas to complete with gasoline, since fuel savings were insufficient to reasonably payback the higher upfront vehicle costs.

Unlike Europe and other regions in the world, U.S. gasoline prices are much lower due to higher taxing of gasoline in these other regions. As shown previously, these higher gasoline prices coupled with low CNG prices makes it possible to amortize the higher CNG vehicle costs over reasonable payback periods. For the U.S. market with low gasoline or diesel fuel prices, the primary factor affecting payback periods is the amount of fuel used. Figure 6 shows estimated average fuel economy and fuel use for various U.S. vehicle segments. The light duty segment fuel economy assumes full adoption of the recent fuel economy rule making (average fuel economy for MY 2016).[9] In this example, the high fuel use fleets are mostly heavy duty, but not illustrated are light-duty fleet applications like taxi cabs that can annually travel 70,000 miles or more.

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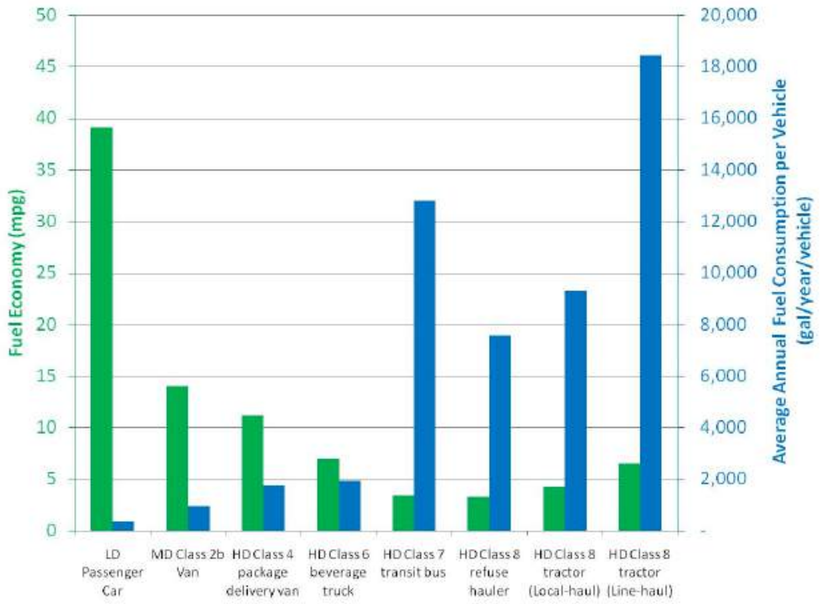
[8] Energy Policy Act of 1992. See for an overview of the alternative fuel requirements: http://www.afdc.energy.gov/afdc/laws/key_legislation

[9] NHTSA, “Corporate Average Fuel Economy for MY 2011 Passenger Cars and Light Trucks,” Final Regulatory Impact Analysis, March 2009



Source: TIAX estimates made in 2010

Figure 6. Fuel Use and Average Fuel Economy of U.S. Vehicle Segments

Figure 7 illustrates how effective fuel use is in paying back the higher upfront costs of NGVs. Shown in this figure are the incremental costs that can be amortized in 3 years (3 year payback) for two fuel price differentials. The discount rate in this analysis was 8 percent. Heavy duty vehicles using upward of 20,000 gallons per year (line haul tractor trailer) can afford incremental costs ranging from $50,000 to $110,000 depending on the price spread between natural gas and diesel. Conversely, with lower incremental costs the payback period would be reduced. Transit buses use 13,000 gallons of diesel fuel per year and can afford increased costs ranging from $34,000 to $69,000.

Transit buses and refuse applications have been very successful at converting from diesel to natural gas. This success has depended on a variety of factors:

1. reasonable vehicle payback periods or user economics
2. high enough fuel demand at return to base facilities to justify fueling infrastructure
3. economics of scale and reasonable fueling station costs to provide high fuel price differentials
4. little or no vehicle attribute differences between natural gas and diesel vehicles
5. lower local emissions (at least up until 2010 diesel technologies)[10]

Conversely, the penetration of NGVs into the tractor trailer truck segment has been much slower as a result of little or no fueling infrastructure and limited product from the engine and truck manufacturers. This is currently changing especially with the growing price differentials between diesel and natural gas.

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[10] Natural gas still has lower overall emissions of criteria or local emissions due lower upstream fuel cycle emissions.

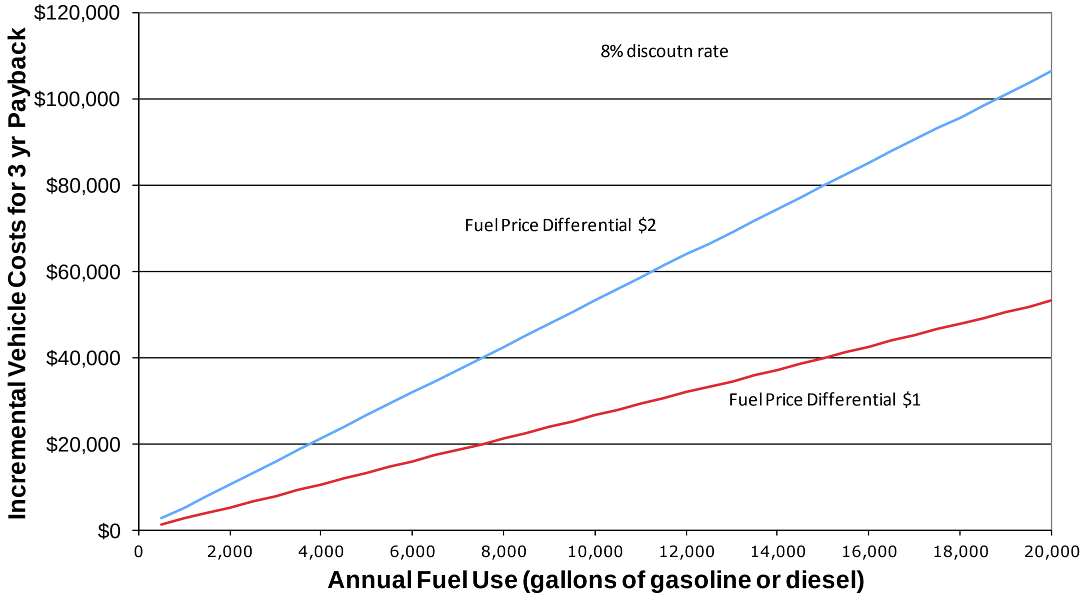

Figure 7. Annual fuel use required to amortize incremental vehicle costs over 3 years

The heavy-duty sector has been relatively successful for NGVs provided the application's duty cycle uses enough fuel and a reasonable business case can be made for building fueling infrastructure. If the fleet is large enough or if the demand from several fleets can be aggregated, then a good business case is possible for both the end user and fuel supplier.

The situation is not so clear for high duty vehicles especially for the retail customer where annual gasoline use is 500 gallons or less.[11] It is very difficult to offset the higher NGV costs with low annual use. Figure 8 compares payback periods for several advanced light-duty vehicles including both natural gas and gasoline hybrids. The advanced technologies are compared to equivalent gasoline models and the assumptions on vehicle price (MSRP) and fuel economy are shown in the figure. At a gasoline price of $3/gal only the Toyota Prius has a payback less than 5 yrs. Only at near gasoline price highs (near $4/gal) does the Honda GX dedicated NGV start to have reasonable payback.

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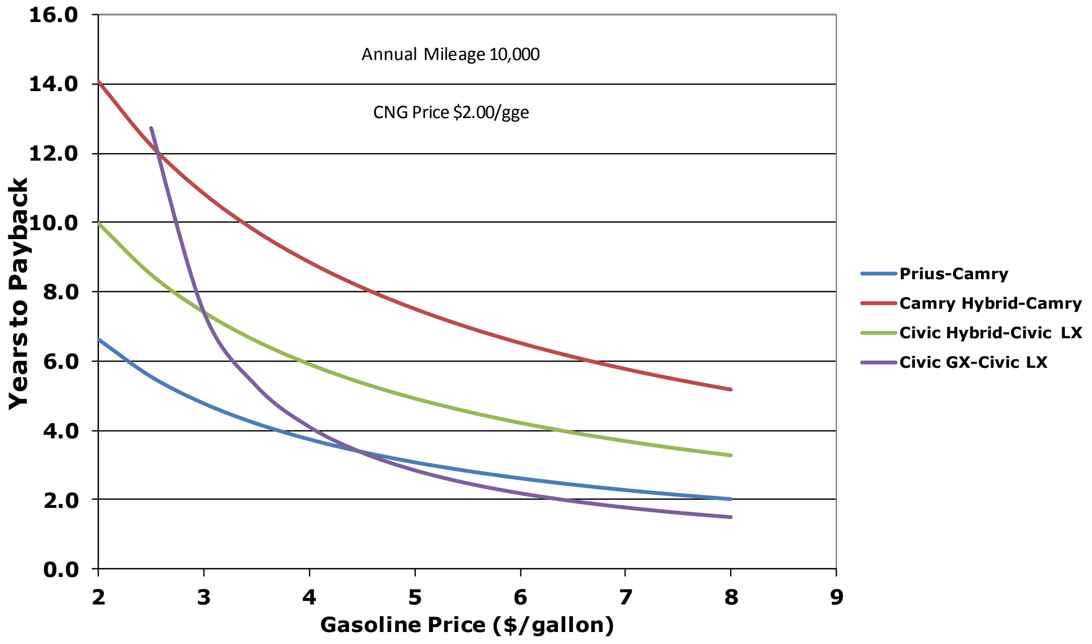
[11] Much of the following discussion was taken from work performed by theCarLab as a subcontractor to TIAX.



Assumptions:		
Vehicle Make and Model	MSRP	MPG
Honda Civic GX	$25,280	28
Honda Civic Hybrid	$23,800	42
Honda Civic LX	$18,360	29
Toyota Camry	$19,720	26
Toyota Camry Hybrid	$26,150	34
Toyota Prius	$22,800	50
(8% discount rate is included in this payback analysis)		

Source: theCarLab

Figure 8. Years to payback higher initial costs of natural gas and gasoline hybrid technologies.

The Honda GX is a dedicate NGV and therefore dependents on a convenient fueling infrastructure. Honda did for a period market a home CNG appliance called Phill through Fuelmaker. The appliance is now being market by an Italian Company BRC Gas Equipment. Phill costs were about $4,500 and depending on the customer's residential gas rate, installation costs, operating and maintenance costs, the resulting cost of CNG could be in the $3 to $5 per gasoline gallon equivalent.[12] Anecdotal comments on Honda's experience of selling both the GX and Phill in Southern California indicated that once the customer understood the existing fueling infrastructure this was deemed acceptable and not worth the additional investment for home refueling. Of course, not all regions of California let alone the U.S. have as much CNG infrastructure as Southern California. Other regions are therefore dependent on the need to aggregate demand as

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[12] Whyatt, GA, "Issues Affecting Adoption of Natural Gas Fuel in Light- and Heavy-Duty Vehicles," Pacific Northwest National Laboratories, PNNL-19745, September 2010.

fast as possible in order to not strand CNG station investments. A bi-fuel vehicle could help in this regard provided station investments are made.

The relative success of hybrid electric vehicles (HEVs) for personal consumer use strongly illustrates the advantage of leveraging gasoline's extensive and familiar distribution system to lower consumer objections to alternative powertrains. The recent sales volume of "FlexFuel" gasoline/ethanol vehicles (FFVs) also illustrates this point, even if few buyers actually use the intended ethanol capability. Both vehicle types have outsold other alternative fuels/powertrains precisely because consumers are not asked to change their behavior. In such cases, only economic resistance is then left to overcome. In the case of FFVs, the case to adopt these vehicles is strengthened by the fact that incremental vehicle costs to the buyer are essentially zero. Fundamentally, FFVs, hybrids, and bi-fuel NGVs are essentially equivalent, differing only in the form of alternative energy storage—ethanol, battery, and natural gas, respectively (Figure 9).

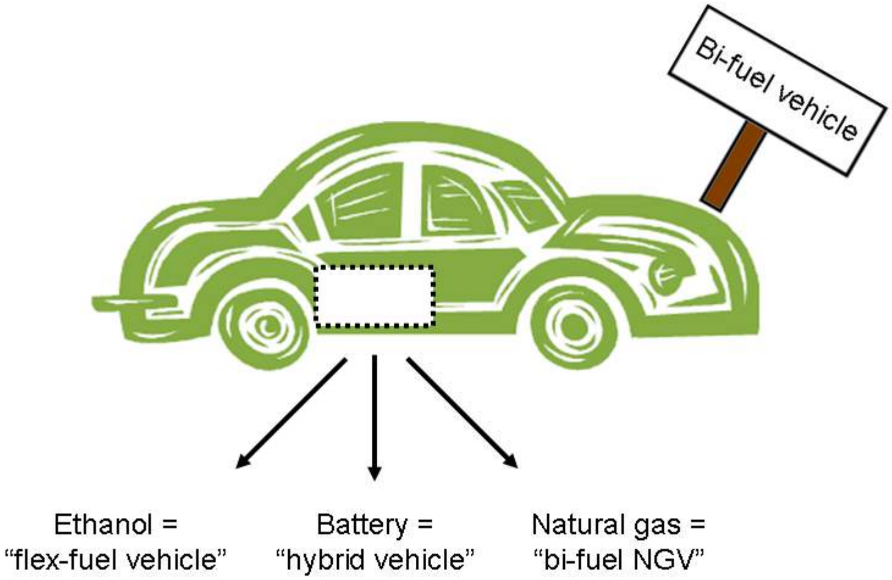

Figure 9. Fundamentally, FFVs, hybrids, and bi-fuel NGVs are essentially equivalent, differing only in the form of alternative energy storage—ethanol, battery, and natural gas, respectively.

Ethanol flex-fuel capability was essentially provided without incremental cost to consumers because the costs to OEMs were minor to allow the vehicles to run on alcohol. Millions of such vehicles are and were sold, as consumers effectively faced no real trade-off relative to the gasoline-only version. HEVs, however, have significant cost (for batteries, controllers, motors, and other components) that ultimately must be recovered by OEMs from consumers. In comparison to dedicated EVs, though, HEVs have a cost advantage principally because the volume of battery they must contain is far lower than required for dedicated EVs, and these batteries are by far the highest cost item in the vehicles' build. Hybrids are therefore much less expensive to build and buy than full EVs, which, when combined with their easy use of existing fueling infrastructure, make them much more rational options for consumers than dedicated EVs. Therefore, while HEVs have outsold pure battery electric vehicles (BEVs), their cost premium continues to be a constraint on their success over gasoline vehicles.

In contrast, the cost of a bi-fuel NGV is nearly the same as that for a dedicated NGV, which means actual cost or purchase price does not affect a comparison of the two. Instead, the relative advantages of each must be compared from the perspective of the end user. Here again, bi-fuel has the clear advantage precisely because the buyer is not forced to change behavior, especially in cases where range or resultant drive routes might be impacted. Instead, drivers of such vehicles can selectively take advantage of the lower operating cost and greener footprint of natural gas, knowing that there is no "walk home" factor that threatens their convenience or safety should travel take them beyond natural gas pumps. Drivers of such vehicles simply have more choice when the fuel range and availability issues that plague EVs, hydrogen vehicles, and dedicated NGVs are removed. As HEVs (the equivalent of bi-fuel EVs) are to dedicated EVs, bi-fuel NGVs are potential fatal competitors to dedicated NGVs at least in the light-duty retail market. As it is with HEVs, the cost premium of bi-fuel NGVs is a natural constraint on their success over gasoline vehicles.

The lower natural gas energy density compared to gasoline means that sufficient tank volumes cannot be achieved for almost any dedicated NGV light car or truck without degrading the effective "size" of the remaining vehicle as shown in Figure 10 for two vehicle examples. Compromises, for any reason, to occupant package (logically limited to second or third row seating volume) have historically been detrimental in terms of buyer appeal and subsequent market share. This has led many OEMs and small volume manufacturers (SVMs) to move natural gas tanks into cargo areas, a fact aptly demonstrated by NGV conversions of cars such as the Ford Crown Victoria for taxi use. While regulated livery fleets are often forced to accept such impositions on usability – even despite still extant luggage capacity demands – private consumers are so far not inclined to do so.

Vehicle performance is more challenging for NGVs, as private users will accept little compromises in the long term. Natural gas offers slightly lower performance relative to gasoline in unmodified gasoline engines, and this presents both a planning and engineering challenge. Here, NGV creators must resist the temptation to apply natural gas to the lowest specification gasoline engines offered in particular models in an effort maximize fuel economy. Rather, conversions and bi-fuel NGV installations are better applied to mid and upper trim level powertrains to meet or exceed customer expectations, especially as natural gas is in the nascent stages of broad market exposure. Looking much farther forward, it is obvious that dedicated NGVs designed from the ground up should have engines optimized for natural gas, especially in terms of usable compression ratio.

Figure 10. Recently introduced 2012 Dodge Ram 2500 Pickup Truck and Ford Crown Vic taxi cab application. Both pictures show how CNG storage tanks were integrated in vehicle.

As a variety of Battery Electric Vehicles (BEVs) and HEVs enter the North American market, consumers are becoming conditioned to calculate payback period when considering any AFV. Volume hybrids, for instance, owe much of their success to relatively favorable payback scenarios, with the Prius having the best payback of all contemporary hybrids (as was shown in Figure 8). Current annualized fuel costs for light vehicles are relatively insignificant when compared to the cost premiums for acquisition of most AFVs. This issue is critical if NGVs are going to be accepted by the retail customer.

Bi-Fuel Vehicles for the U.S. Retail Market

The U.S. retail market for light-duty vehicles is highly competitive with automakers providing a variety of gasoline and alternative fueled vehicles. Hybrid electric vehicles have been quite successful at least compared to other alternatives due to favorable user economics. Since U.S. energy pricing for petroleum based fuels and natural gas is less favorable than other regions, a different vehicle approach maybe needed for NGVs to compete against gasoline. Unlike European NGV designs, the fuel price differential is insufficient to support the higher costs of their bi-fuel vehicles. Instead, U.S. bi-fuel vehicles will require lower costs than the European market.

The dominant costs of bi-fuel NGVs are the CNG storage tanks. If bi-fuel NGVs are going to be successful in the U.S. market, storage costs need to be reduced. Currently, just the opposite approaches seem to be happening both in Europe and the U.S. The prevailing experience seems to be to maximum CNG storage and therefore range achievable on natural gas. In other words, design a bi-fuel vehicle that maximizes CNG range but also can operate on gasoline in order to extend range beyond that of the volume and costs constraints of CNG. Another way to approach the design of bi-fuel NGVs is to design the CNG storage system to meet only the demands of most every day drivers and to have a gasoline capacity that would match the range requirements of consumers. This approach is similar to the philosophy of HEVs and to the plug-in HEVs (PHEVs). Like batteries natural gas storage is both expensive and takes up lots of space. Minimizing CNG storage would reduce costs and make it easier to package on vehicles.

The PHEV analogy is interesting from two perspectives. First, PHEV battery energy storage is been designed to meet the average daily mileage of most retail users of 40 miles or less per day. As shown in Figure 11, 2/3 of all drivers in the U.S. drive fewer than 40 miles per day and over five days per week 52 weeks per year this results in 10,400 miles per year close to the nominal 12,000 miles annually driven in the U.S.[13] This being the case, then natural gas storage should be reduced to provide this range. Depending on the vehicle and model year this is equivalent to 1 or 2 gge or 14 to 28 liters (water volume at 250 bar). This is almost a 10 times reduction from current CNG vehicles. The Honda GX has a 8.3 gge (113 liter) storage tank and the Opel Zafira Tourer has a 9.8 gge (173 liter at 200 bar) storage tank.

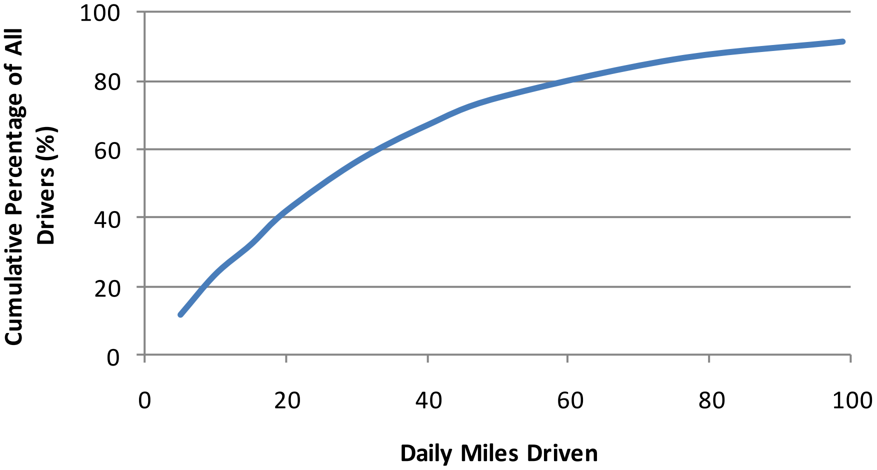

Figure 11. 67 percent of all drivers in the U.S. drive fewer than 40 miles daily, a consideration when designing alternative fuel tank capacities.[14]

Secondly, the PHEV analogy requires home refueling. Most consumers would be unwilling to refuel their vehicle every day unless it was convenient. Cars and light trucks today are designed with a refueling range of around 350 miles. At average annual mileage, this works out to 40 fueling events per year or nominally once per week. Asking consumers to fuel once per day is unacceptable. The savings from reducing the storage costs could offset the costs of a home refueler. However, this home appliance would not have to be designed to the same characteristics as the Phill unit. Phill was designed to provide 0.42 gge/hr at 3600 psi. For a 2 gge storage tank, this rate could be halved and with some storage this rate could be further reduced.

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[13] There is distribution of daily mileages that will limit the penetration of vehicles designed for a daily range of 40 miles.

[14] XPrize Foundation. "National Household Travel Survey Data Summary for XPrize." http://www.progressiveautoxprize.org/files/downloads/auto/AXP_FHWA_driving_stats.pdf. March 2007.

Figure 12 shows how the economics of this concept might play out for a bi-fuel Honda Civic GX. Here it was assumed that the incremental vehicle costs could be reduced from $6,920 to $4,080 by reducing CNG storage from 8.3 gge to 1.5 gge or enough for 40 + miles on CNG. Secondly, it was assumed that a simpler home CNG appliance could be manufactured and installed for $3,000. A discount rate of 8 percent was also assumed. As shown, with gasoline prices at $4/gal and CNG prices at $1.8/gge it would take over 7 years to payback both the vehicle and fuel appliance costs. This is probably too high but some of these costs would be offset by not having as frequent visits to gasoline stations (assuming this is a benefit consumers are willing to value).

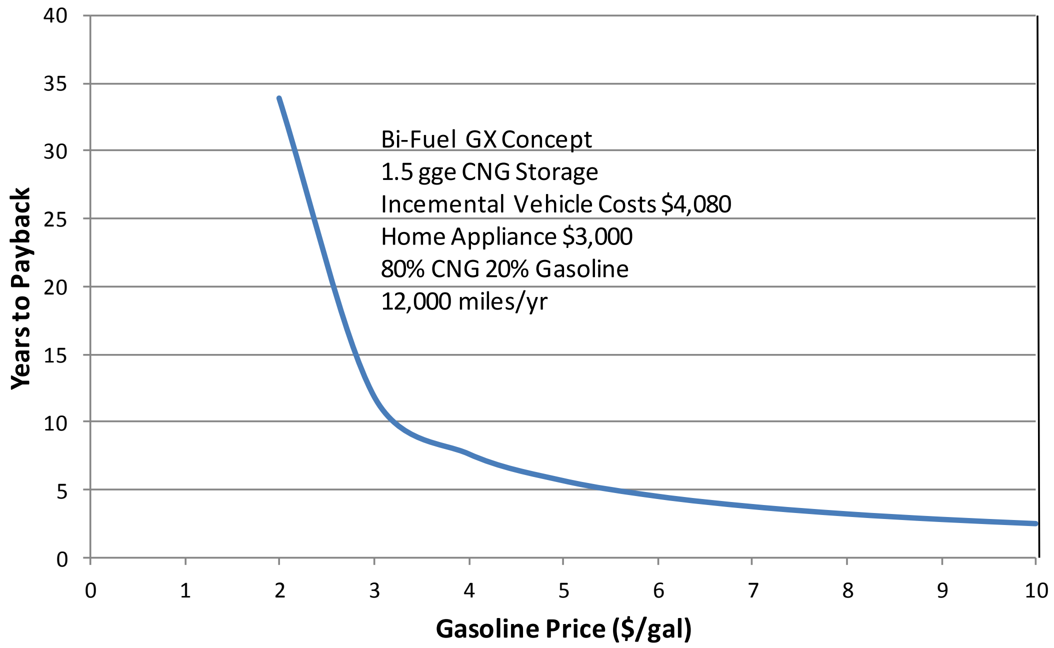

Figure 12. Estimated payback for 40 mile CNG range bi-fuel vehicle

It is possible the vehicle costs could be further reduced in volume production especially since the tank volumes and presumably costs have been substantially reduced. A more sophisticated analysis would be needed to investigate this. Similarly, a simplified design and cost analysis of a home fueling appliance is also needed.

Another interesting option with reduced storage is to reduce storage pressure. Much of the costs of the tanks and compression are related to the system's operating pressure. If vehicles only need several gge of natural gas, it may be possible to simplify storage by reducing the pressure. Pressure and volume are related so decreasing the pressure would increase the volume, but perhaps more conformable shapes could be used to help vehicle packaging. Reduced pressure would also reduce stages of compression possibly simplifying compressor design and function. It is possible that at low pressures total vehicle and home appliance costs could be further reduced.

An obvious drawback of reducing storage pressure is that the existing CNG fueling stations would not be usable unless the pressure was regulated down. Even in this situation the potential safety issues may out weigh the advantages of lower natural gas storage pressures. Other disadvantages of bi-fuel compared to dedicated operation are compromises in:

- vehicle performance (power and torque)
- fuel consumption
- emissions

Some of these disadvantages can be overcome with today's technologies and some will require more advanced engine and powertrain technologies. For example, the emission performance of today's vehicles is extremely low whether for a gasoline or natural gas vehicle. Integrating gasoline and natural gas together and meeting the most stringent emissions will require effort, but this should not be insurmountable.

Policies at the federal and state levels may also need to be changed so that bi-fuel NGVs have the same incentives as other alternative fuels. In recent TIAX work, NGVs both dedicated and bi-fuel were compared on a full fuel cycle analysis to electric vehicles (for different generation mixes), and ethanol vehicles (with different feedstocks). Societal costs were estimated for criteria (or local) pollutants, greenhouse gases, and petroleum dependency. Surprisingly, the societal benefits were about the same for each alterative averaging about $3,000 over the vehicle's lifetime.

Acknowledgement

Sources and references for this work were taken from recent TIAX work on light- and heavy-duty natural gas vehicles; TIAX staff that contributed to this work included Karen Law, Jeffrey Rosenfeld, Michael Chan, and Jon Leonard. TIAX's efforts were also supported by efforts from Jeffrey Seisler, Clean Fuels Consulting, and theCarLab. The concept of lower CNG storage volumes was advanced by theCarLab.

Evolution of alcohol fuel blends towards a sustainable transport energy economy

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ABSTRACT

Work undertaken by Lotus Engineering and partners has shown that the miscibility of the low-carbon-number alcohols with gasoline provides a powerful tool to enable the introduction of methanol as a transport fuel in a wholly evolutionary manner. This is primarily facilitated by the fact that the CAFÉ regulations in the US (together with other incentives in other countries, such as Sweden) have created a situation in which there are 7-8 million E85/gasoline flex-fuel vehicles on the roads there, for which insufficient E85 can be provided at an affordable price. This paper will show that the introduction of methanol (which can be made extremely simply and cheaply from natural gas) into gasoline-ethanol mixtures, can be used to create drop-in fuels equivalent to E85 and can bring the price of an alcohol-based fuel for spark-ignition engines down to less than that of gasoline (on a per-unit-energy basis, before tax is applied). It can thus more than compete with that fuel. This opens up the possibility of using the US's reserves of naturally gas (be it conventional or unconventional types such as shale) immediately to manufacture methanol to displace gasoline, as a bridge to a broader energy economy based on higher concentrations of methanol made from renewable sources.

The vehicle work conducted has shown the possibility of realizing this state of affairs, and related laboratory tests on some of the potential fuel blends have similarly demonstrated that they possess some of the necessary characteristics to be truly 'drop-in' alternatives to E85. These necessary characteristics are considered to be equal volumetric energy content (to enable compliance with on-board diagnostics requirements), equal octane numbers and latent heat (to provide invisibility to the combustion and air handling systems), and inherent miscibility with gasoline (to avoid the requirement to change the fundamental nature of the vehicle fuel system). A further requirement in practice is that the vehicles still be of adequate performance with regard to tailpipe emissions standards using the existing exhaust after treatment systems fitted to them. In the present work this is demonstrated by reporting data for oxides of nitrogen emissions (NOx) taken from a standard production Saab 9^3

certified to the EU5 emissions standard using ternary blends (such NOx emissions being especially important from a human health point of view in built-up areas), which shows that generally such emissions are significantly lower for all of the alcohol blends than for gasoline. All results are found to be well within the EU5 limits, with the gasoline results showing that the after treatment system was indeed functioning correctly.

INTRODUCTION

Around the world, concerns with climate change and energy security have prompted the investigation and introduction of renewable fuels in order to reduce usage of fossil oil. In the US, the Energy Independence and Security Act of 2007 (and related Renewable Fuel Standard 2) has mandated that a total of 36 billion US gallons of ethanol be used in the fuel pool by 2022 [1], and in the European Union (EU) the Renewable Energy Directive (RED) seeks to establish a minimum proportion of renewable energy in the fuel pool of 10% by 2020 [2].

The conversion of fossil hydrocarbons to carbon dioxide (CO_2) causes atmospheric levels of greenhouse gas to increase, which, due to the fact that much of the world's oil supply comes from areas outside of those of the main consumer regions, gives rise to a further concern with respect to security of energy supply.

The European situation is complicated by the facts that diesel penetration in the vehicle pool is high (at approximately 50% in the light-duty sector) and the volume of bio components in diesel which it is practical to include in the fuel is limited to approximately 7% by volume if future emissions standards are to be met. Together these imply that the proportion of ethanol blended into gasoline in Europe will have to be approximately 13% *by energy*, which equates to ~20% by volume as a result of the lower volumetric lower heating value (LHV) of ethanol versus gasoline. Although most current vehicles fitted with spark-ignition (SI) engines can accept 10% by volume ethanol as standard (a situation essentially initiated by the presence of 10% ethanol in gasoline in wide areas of the US), 20% is beyond their capability. Realization of this fact, coupled to the impending fines on the fuel suppliers if they do not meet their legal obligations under the RED, has prompted calls by one oil major to give vehicle OEMs credits in terms of tailpipe CO_2 for any E85[1]/gasoline flex-fuel vehicles that they manufacture, in order to produce a larger market for high-blend-concentration ethanol fuels [3].

This situation is desirable since selling large volumes of ethanol is probably the most pragmatic way for the fuel suppliers to comply with the requirements of the RED and the related Fuel Quality Directive (FQD) (which defines minimum standards before a fuel can be considered a biofuel). In actual fact, the EU vehicle tailpipe CO_2 fines system does presently allow a 5% reduction in tailpipe CO_2 to be claimed for any flex-fuel vehicle that an OEM sells, provided one-third of the fuel forecourts in the country in which it is sold has at least one E85 pump [4]. It could be said, therefore, that the potential remedy to the RED impasse for the fuel suppliers is in fact in their own hands. Furthermore, for a theoretical vehicle at the 2011 EU average of 145.1

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[1] Throughout this paper, the use of E followed by a number refers to the proportion *by volume* of ethanol in a blend. The same applies for M (methanol) and G (gasoline). Thus E85 is nominally 85% ethanol in bulk gasoline (a high blend rate), and E10 is 10% ethanol in bulk gasoline (a low blend rate).

gCO_2/km, and at the highest proposed fine rate in 2015 of €95/gCO_2, this represents a saving to the OEM of €689 per car, which the authors contend is significantly greater than the costs of modifying a standard gasoline-fuelled vehicle to be flex-fuel with E85 in the first place. Thus all of the notional prerequisites are in place for ethanol to become a major transport fuel, which begs the question as to why this should not already be so.

Ethanol as a minor blend component in gasoline has two main benefits: firstly, there is the renewability and energy security factor, and secondly it is an excellent octane enhancer, in part because of its high heat of vaporization [5]. This latter fact means that even at low blend rates of 5-10% it can provide a significant uplift in octane number, which concomitantly means that a fuel supplier can reduce the volume of other octane enhancers in the bulk gasoline [6], reducing its net price and increasing profits. Unfortunately this low blend effect means that the price of ethanol is kept high and is closely tied to the price of gasoline. Thus, when it is used at high blend rates to make E85, there is little decontenting possible in the gasoline comprising the remaining 15% of the fuel; in fact, in commercial E85, the bulk gasoline often has to have its composition altered to facilitate cold starting, ethanol being a difficult fuel in this respect[2].

Hence, any mechanism to offset the high price of ethanol while still permitting its use in large volumes across the fuel pool will be of benefit to the fuel suppliers and, if they are encouraged to put pumps with the necessary capability on sufficient fuel station forecourts it would also be of benefit to OEMs selling in the EU, providing fuel renewability factors as mandated by the RED and FQD are adhered to. If the resulting fuel was cheaper than gasoline to use in terms of operating cost the consumer would readily move to its use. Approached in terms of taxation per unit energy, migration to this situation could be achieved without a reduction in tax take for governments, together with no requirement for direct subsidies, which are necessary in the case of electrification of the vehicle fleet. Hence all stakeholders could benefit if a suitable introduction mechanism could be found.

At the same time, the biomass limit for ethanol production has been used by some as a reason not to pursue alcohol fuels for transport, since only about 27% of the energy required can be gathered within it (this figure varies country by country)[3]. The biomass limit only applies to fuels made using biological processes (such as bioethanol and biodiesel). In fact, using thermochemical processes, it is possible to manufacture liquid fuels from anything containing carbon and hydrogen via Fischer-Tropsch chemistry or a syngas-to-methanol-to-gasoline (or similar) process. Thermochemical routes therefore open up the possibility of using more waste as a carbon feed stock, meaning that the amount of renewable fuel which could be manufactured moves beyond the biomass limit and prevents more conventional biofuels from being regarded as a strategic dead end. As an end game, in order to cover the full amounts of energy necessary for transport, atmospheric CO_2 and

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[2] Note that commercial E85 is often not configured with 85% ethanol; US limits are 51-83% by volume. Generally, in winter months ethanol concentration is often reduced to 70% to aid cold starting, and even in summer months the ethanol component may only comprise 77%.

[3] It is interesting to contrast this with the fact that even in optimistic scenarios electric vehicles are not expected to penetrate to more than 10% in the short term, yet that is *not* seen as a reason not to pursue them vigorously.

molecular hydrogen could be used as the physical ingredients to carry renewable energy either in liquid or gaseous form [7-9].

Thus there exist various possibilities to increase renewable fuel supply as a result of the miscibility between gasoline and the alcohols, the fact that a liquid fuel infrastructure already exists, that the necessary vehicles also exist and are cheap to manufacture, and that the feed stocks required are not limited if the necessary technologies can be developed. The only thing missing is to construct a route to enable this scenario to play out, with the necessary fuel and vehicle specification changes linked to it. A first step along this road to energy security and sustaianability would be to employ ternary (three-component) blends of gasoline, ethanol and methanol.

TERNARY BLENDS OF GASOLINE, ETHANOL AND METHANOL

Gasoline, ethanol and methanol are all miscible together and ternary (i.e. three-component) blends can be configured to have the same target stoichiometric air-fuel ratios (AFRs) as any binary gasoline-ethanol blend. In the present paper we concentrate on such 'GEM' ternary blends with a target stoichiometric AFR of 9.7, i.e. that of E85, but equally ternary blends targeted at E10, E22, etc. could be arranged. For a fixed stoichiometric AFR the relationship between them is defined by linear volumetric relationships and this has been discussed in detail in earlier publications [10,11]. Furthermore, when configured in an iso-stoichiometric manner, all such blends have near-identical volumetric lower heating value (LHV) and practically the same octane numbers when configured to constant stoichiometric AFRs; they also have extremely close enthalpies of vaporization (to +/- 2%). For the case of a stoichiometric AFR of 9.7:1 the volume relationship between the components is shown in Figure 1, as determined using the Lotus Fuel Mixture Database [12]. In this figure one can see that as the volume percentage of ethanol is reduced, so the rate of increase of the methanol proportion is faster than that of the gasoline proportion. This is because as one volume unit of ethanol is removed, a volume unit of the binary gasoline-methanol mixture with the same stoichiometric AFR as ethanol (i.e. 9:1) has to be used to replace it, and the necessary volume ratio of gasoline:methanol is 32.7:67.3, as discussed in detail in [10].

Several points of interest arise from Figure 1: firstly (and most obviously) is that E85 contains no methanol; secondly, that the binary equivalent of E85 for a gasoline and methanol mixture occurs at volume percentages of 44 and 56, respectively (i.e. the left hand limit, where no ethanol is present); and thirdly, the ratio where the proportion of gasoline and methanol are equal occurs at approximately 42.5 volume percent ethanol. Aspects related to this will be returned to later.

Initial experimental results using four such GEM blends in a production vehicle showed that, provided a certain minimum level of cosolvent was present, the blends were invisible to the vehicle's on-board diagnostics (OBD) system [10]. Ethanol performs the cosolvency function in gasoline-methanol mixtures, and the minimum level of ethanol concentration in a GEM blend was further investigated in a car certified to a higher emissions standard and using a different alcohol concentration sensor technology (actually a physical sensor as opposed to the virtual sensor the first vehicle used). Here, no such minimum requirement for ethanol was identified, despite repeated cold soaks to -20°C and cold start tests [11]. From these pieces of work it is presumed that a minimum ethanol concentration is needed to ensure satisfactory operation of all of the vehicles in the fleet, since they do not all use the same alcohol sensing technology.

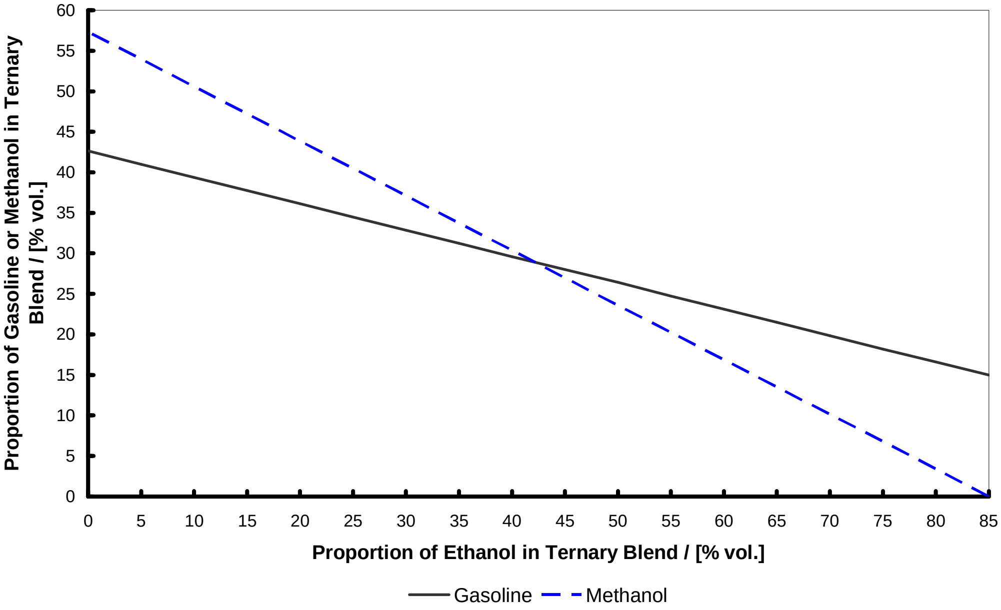

Fig. 1: Relationship between blend proportions of gasoline, ethanol and methanol in iso-stoichiometric ternary blends configured with a stoichiometric AFR of 9.7. Blend ratios determined using the Lotus Fuel Mixture Database [12]

Note that it is possible to produce ternary blends of other alcohols with gasoline, should their use be beneficial with regard to the utilization of all available feed stocks, or even quaternary (or higher number) blends; examples of these may be mixtures of gasoline, methanol and butanol with or without ethanol respectively. It is intended to investigate blend ratios of these in a later publication [13].

TEST FUELS, VEHICLE AND EXPERIMENTAL RESULTS

Test Fuels

The fuel blends used were as described in Table 1. Note that the terminology used to describe the blends from this point hence in this paper is as follows: G, E and M refer to gasoline, ethanol and methanol, and the percentage proportion by volume is given after each letter (i.e., GEM component ratios). Hence E85 would be G15 E85 M0 and from Figure 1 the binary equivalent using gasoline and methanol only would be G44 E0 M56. The blends were given the names shown in the table.

Several points of interest arise from the choice of these fuel blends. Blend C takes the same amount of ethanol as was used to make one volume unit of Blend A (the commercial E85 surrogate) and spreads it across four times the volume of fuel. Similarly, Blend D4 takes the same volume of ethanol and spreads it across 8.5 times the volume of fuel. Thus, if the amount of ethanol that can be supplied is constrained for any reason – by feed stock supply, a desire to avoid interference with the food chain, or concern over indirect land use change (ILUC), for example – one can extend how far the limited amount of ethanol can reach into the fuel pool by introducing methanol in a ternary blend with it. The situation is improved if the methanol used is better, from an energy security or carbon intensity perspective, than gasoline. It should be pointed out that this is effectively the situation in the US, if one considers that the Energy Independence and Security Act mandates the production of a specified amount of ethanol. This can be coupled to the recent shale gas finds and the ease with which methane can be turned into methanol, and is synergistic with the fact that there exist many more vehicles which can take high-alcohol blend fuels than currently use them. The subjects of gasoline displacement and cost will be returned to in the Discussion.

Table 1: GEM ternary blend fuels used in the vehicle tests described. Properties calculated using Lotus Fuel Mixture Database [12] or measured to the relevant ASTM standards where applicable

Original Blends				
Fuel	**Blend A**	**Blend C**	**Blend D4**	**Blend D**
GEM Component Ratios	G15 E85 M0	G37 E21 M42	G40 E10 M50	G44 E0 M56
Stoichiometric AFR	9.69	9.71	9.65	9.69
Density (kg/l)	0.781	0.769	0.767	0.765
Gravimetric LHV (MJ/kg)	29.09	29.56	29.46	29.66
Volumetric LHV (MJ/l)	22.71	22.71	22.60	22.69
Carbon Intensity (gCO_2/l)	1627.9	1623.9	1613.9	1620.2
Carbon Intensity (gCO_2/MJ)	71.69	71.49	71.42	71.41
RON (to ASTM D2699)	107.4	106.4	105.6	106.1
MON (to ASTM D2700)	89.7	89.3	89.0	89.0
Sensitivity	17.7	17.1	16.6	16.2

Test Vehicle and Facility

A production flex-fuel Saab 9^3 BioPower station wagon was used for these tests. This vehicle was fitted with an automatic gearbox and was certified to Euro 5 emissions standards. It was tested on the rolling road dynamometer at Lotus Engineering and was operating with the standard production flex-fuel calibration and OBD system. The drive cycle used was the New European Drive Cycle (NEDC). Two gasoline baseline results were taken before and after the tests, and the order in which the fuels were tested was gasoline, Blends A, C, D, D4 and then the repeat of the gasoline tests.

The same procedure was followed for each test fuel, in line with the requirements for testing vehicles on the NEDC. Each fuel was tested twice on sequential days, and on each day a hot NEDC test was conducted after the cold test. Only the cold test results will be reported here, since this is what is used to determine the emissions compliance of a vehicle. The Euro 5 oxides of nitrogen (NOx) emissions limit is 0.06 g/km [14][4].

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[4] Note that the NOx limit for Euro 5 regulations stated also applies at Euro 6; the major difference for spark-ignition engines at Euro 6 level is that there are additional particulate number limits. Euro 5 came into effect in September 2009 and Euro 6 will come into effect in September 2014.

Experimental Results

Figures 2 and 3 show the fuel consumption (in miles per US gallon[5]) and tailpipe CO_2 emissions (in terms of gCO_2/km, which is the parameter used to establish a manufacturer's total tailpipe CO_2 emissions for the purposes of establishing any fiscal penalties in Europe, weighted by sales volume [4]), respectively. Figure 4 shows the energy utilization of the vehicle, calculated using the data in Table 1.

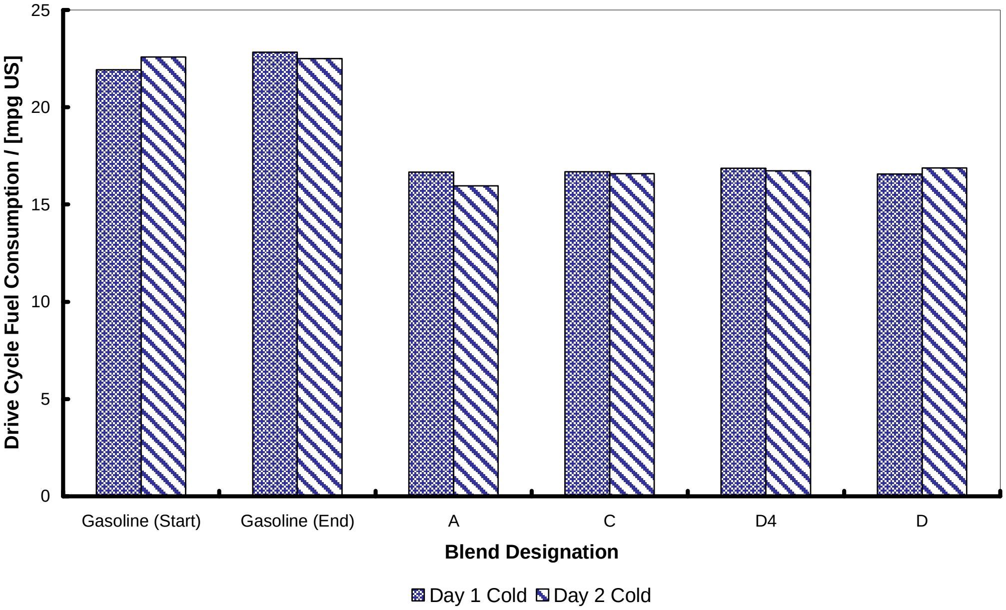

Fig. 2: Production flex-fuel vehicle fuel consumption (in terms of miles per US gallon) when operated on four GEM blends and gasoline on the New European Drive Cycle. Vehicle certified to Euro 5 emissions level

From the data in Figure 4 one can see that the vehicle was energetically more efficient when operated on the alcohol blends than it was when operated on gasoline. The result for the second cold test on Blend A (G15 E85 M0) is considered a slight outlier, but nevertheless (and disregarding the Blend A result from the second day) the improvement in energy utilization across all of the alcohols was 2.8-4.9% for the first day and 2.0-3.4% for the second day [15]. This improvement in energy utilization was echoed in a higher result when the vehicle was hot in earlier work with a car with a different alcohol sensing system and certified to an earlier emissions level (Euro 4), where 3-5% improvement was seen when the vehicle was warm [10]. The implications are that there would be a reduction in energy consumption from a fleet of vehicles using such alcohol blends versus gasoline, with obvious advantages if those fuels were to have to be synthesized in the future from another feed stock, e.g. from shale gas.

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[5] In order to convert miles per US gallon to miles per Imperial gallon, divide the data in Figure 2 by 0.833.

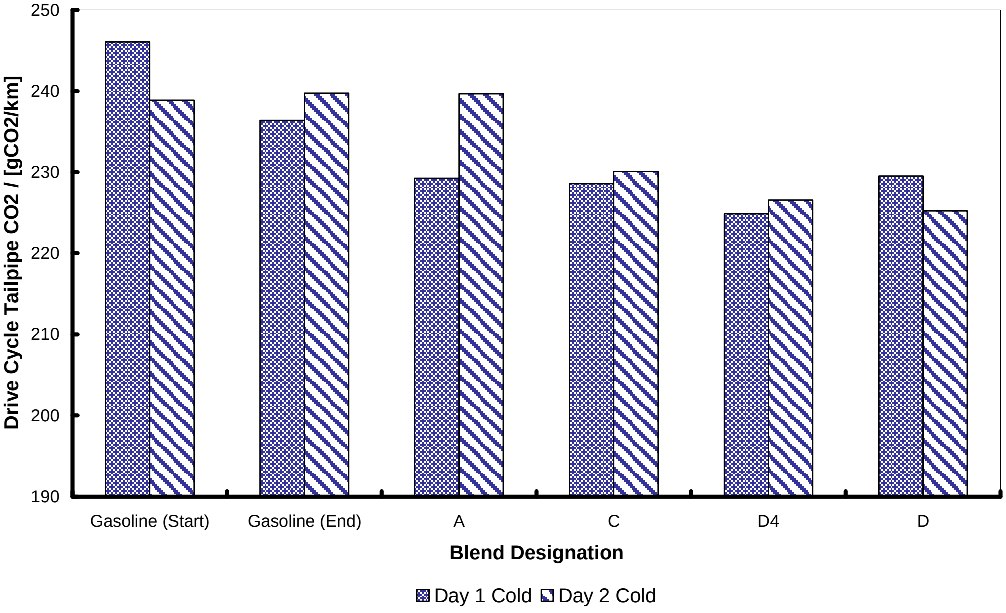

Fig. 3: Production flex-fuel vehicle tailpipe CO_2 emissions (in terms of gCO_2/km) when operated on four GEM blends and gasoline on the New European Drive Cycle. Vehicle certified to Euro 5 emissions level

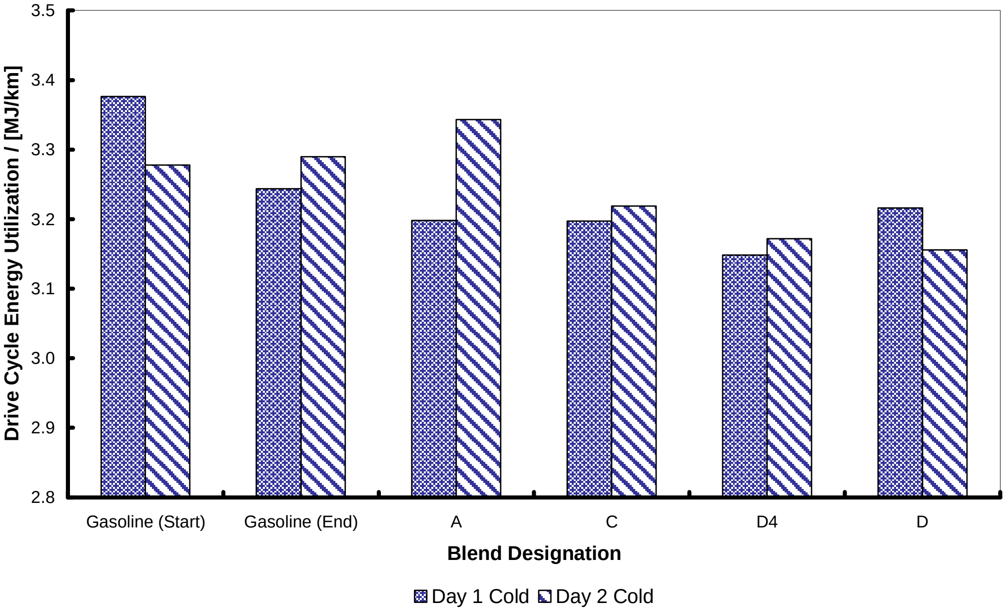

Fig. 4: Production flex-fuel vehicle drive cycle energy utilization (in terms of MJ/km) when operated on four GEM blends and gasoline on the New European Drive Cycle. Vehicle certified to Euro 5 emissions level. Data calculated from tailpipe CO_2 emissions shown in Figure 3 using the Lotus Fuels Mixture Database [12]

Results for NOx emissions are shown in Figures 5(a) and 5(b), in absolute terms and as an average percentage of the regulated maximum of 0.06 g/km, respectively.

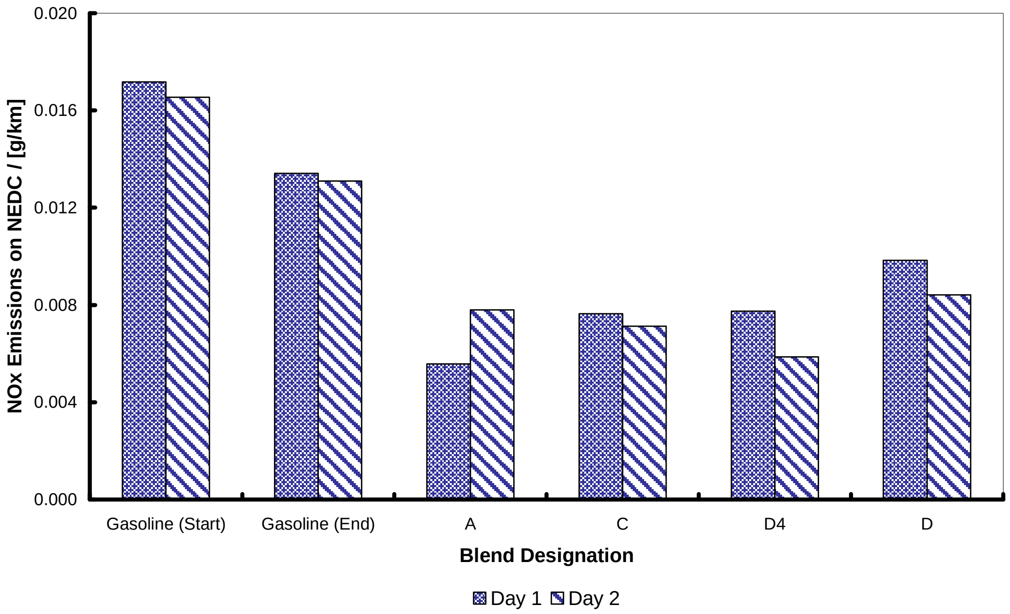

Fig. 5(a): Production flex-fuel vehicle tailpipe NOx emissions in g/km when operated on four GEM blends and gasoline on the New European Drive Cycle. Vehicle certified to Euro 5 emissions level

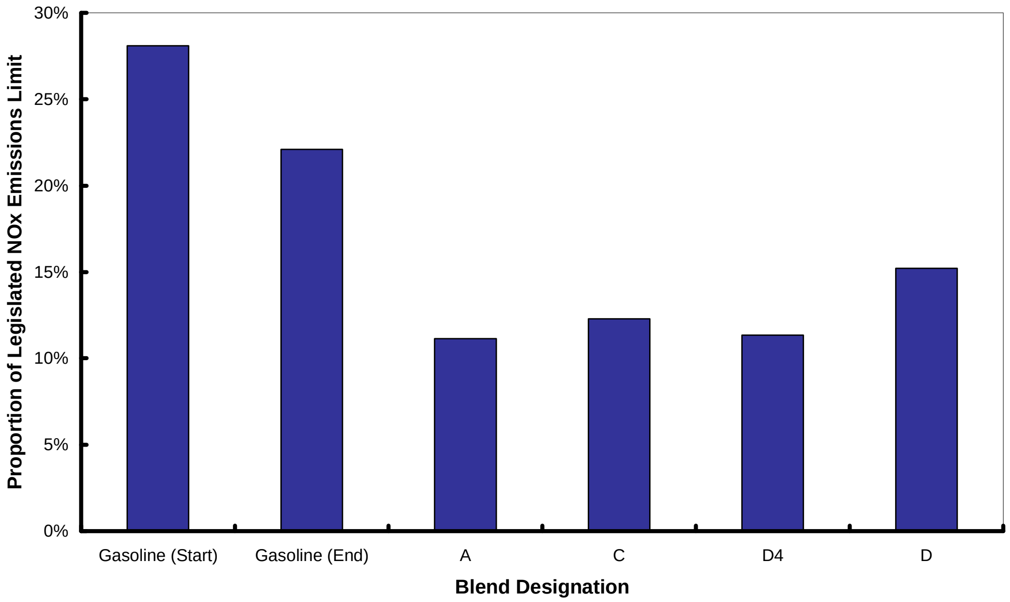

Fig. 5(b): Production flex-fuel vehicle averaged tailpipe NOx emissions as a proportion of the maximum permitted value when operated on four GEM blends and gasoline on the New European Drive Cycle. Vehicle certified to Euro 5 emissions level

From the results of Figure 5 it can be seen that the vehicle has no problem delivering legal NOx emissions when operated on the four ternary GEM fuels. The average of the four alcohol blend fuels is 0.0075 g/km, and is over 50% less than the average of the two gasoline tests (0.0151 g/km). Additionally, the results of all the fuels are less than 30% of the legislated maximum for NOx of 0.06 g/km, which is significantly lower than the normal engineering target of 50% to ensure compliance of the whole fleet over the lifetime of the vehicles. (Note that after catalyst light-off there will be virtually zero emissions anyway due to the conversion efficiency of three-way-catalysts.) Therefore, from these results there is likely to be little concern with regard to NOx emissions when existing flex-fuel vehicles are operated on any of the GEM ternary blends. Results for hydrocarbon and carbon monoxide emissions will be reported in a later publication.

Finally, the vehicle exhibited no driveability problems when using any of the ternary blends, and the on-board diagnostics were not upset, as shown by the fact that there was no malfunction indicator lamp (MIL) activity on the dashboard, regardless of fuel blend used. Approximately 1500 km were covered on a wide range of the GEM fuels (both as specific blends and as general tankfuls of one blend following another) and it always started well and has done so ever since as far as the authors are aware. For more details of this, plus the cold-temperature operation testing that was carried out, see [11].

DISCUSSION

The results presented here suggest that ternary blends can be true drop-in alternatives to E85, and that the NOx exhaust emissions important to human health will be lower than those for gasoline. This is important when considering how they can help with energy security in countries where they can be manufactured from indigenous feed stocks, such as is the case with the recent shale gas finds in the US [16], which create an opportunity for it to become more energy independent. The scale of the opportunity was illustrated by Moniz *et al.* [16], who estimated that with recent finds the total US reserves of natural gas equal 92 times the current annual consumption, and thus these resources can provide a bridge to a low-carbon future. From this work, the issue of how to apply this opportunity to increase energy independence to transport (which is especially reliant on imported oil) is one that can be addressed by two routes in terms of making liquid energy carriers: full Fischer-Tropsch (FT) synthesis of liquid hydrocarbon fuels, or conventional methanol synthesis from natural (shale) gas.

While full FT synthesis produces drop-in fuels for all vehicles (including ships and aircraft), direct methanol synthesis is a more efficient means of converting methane to a liquid fuel, and furthermore, requires less investment in plant and is economical on a smaller scale. An extension of this could see small, economical methanol plants feeding the fuel pool with their products directly (via ternary blending) or providing methanol as a feed stock for larger methanol-to-synfuels (MtSynFuels) plants. This might help to open up some more of the stranded shale gas fields because of the relative ease of transporting energy dense liquids over distance.

If the methanol produced in this manner is introduced in the near-term via the ternary blending approach discussed above, one can extend the available ethanol significantly and displace more gasoline. For illustrative purposes, there follows an assessment of how much methanol fuel could be used. Of the 36 billion US gallons of ethanol which the US Energy Independence and Security Act mandates for 2022, some can be blended into gasoline. Currently the permitted level is 10%, although EPA is moving towards 15% in the future for 2001 and newer light-duty motor vehicles (subject to certain conditions) [17]. Assuming that 140 billion US gallons of gasoline are used for light-duty vehicles from 2016 onwards[6], and that ~12% of it by volume is ethanol (most in E10 but some in E15), let us assume that there will be 19 billion US gallons available for flex-fuel vehicles, which, at an E85 blend rate of 85% (disregarding the fact that less ethanol is typically used in commercial E85 in the winter months), implies that 22.4 billion gallons of E85 could be supplied.

These 22.4 billion gallons of E85 are equivalent in energy terms to 16.1 billion gallons of gasoline, although they do contain 3.4 billion gallons of gasoline themselves (the 15% gasoline in E85). Effectively, 19 billion gallons of ethanol is equivalent to 12.7 billion gallons of gasoline (i.e. the ratios of the volumetric LHVs of gasoline and ethanol, 31.6 MJ/l for and 21.2 MJ/l respectively) Thus, 140 billion gallons are reduced to 140-12.7 = 127.3 billion gallons of gasoline, and there is a reduction in gasoline usage of 9.1%.

Consider now that the 19 billion gallons of ethanol instead be used to manufacture a ternary blend such as Blend C (G37 E21 M42). As mentioned earlier, it is possible to show that the methanol displaces gasoline if the total ethanol volume in the fuel pool is held constant. Figure 6 shows this relationship; on the left-hand side of the figure one supplies four units of energy as three units of gasoline and one unit of E85, and on the right-hand side all four units are supplied as Blend C instead. Note that there is effectively the same volume of ethanol on both sides of the figure – which is the case when ethanol supply is constrained. Summing the gasoline volume on both sides one arrives at 231 volume units on the left (i.e. the traditional approach) and 148 on the right, i.e. 35.9% extra gasoline has been displaced *over and above that already supplied by the ethanol.* Put another way, 168 volume units of methanol have displaced 83 units of gasoline.

Because of the blend proportions then for ternary Blend C one would require twice as much methanol – i.e. 38 billion gallons (from a total of 90.5 billion gallons of Blend C that can be made from 19 billion gallons of ethanol). The situation compared to the traditional E85 approach is that the 38 billion gallons of methanol have been used to displace 18.8 billion gallons of gasoline (i.e. 38 x 83/168, which again is the ratio of the volumetric LHVs of gasoline and methanol, 31.6 MJ/l for and 15.7 MJ/l respectively).

Now one can see that in addition to the 12.7 billion gallons of gasoline displaced by the ethanol, there is an additional 18.8 billion gallons displaced by the methanol, and the gearing on the ethanol is considerable. Effectively, instead of the 140 billion gallons of gasoline needed, the new volume required is 140-12.7-18.8 = 108.5 billion gallons, or a reduction of 22.5% by volume of gasoline in the entire fuel pool *with the same volume of ethanol being supplied.*

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[6] Based on the actual 2007 consumption of 134.8 US gallons, with an assumption that vehicle fuel economy improves on the one hand and that there are more vehicles on the road on the other.

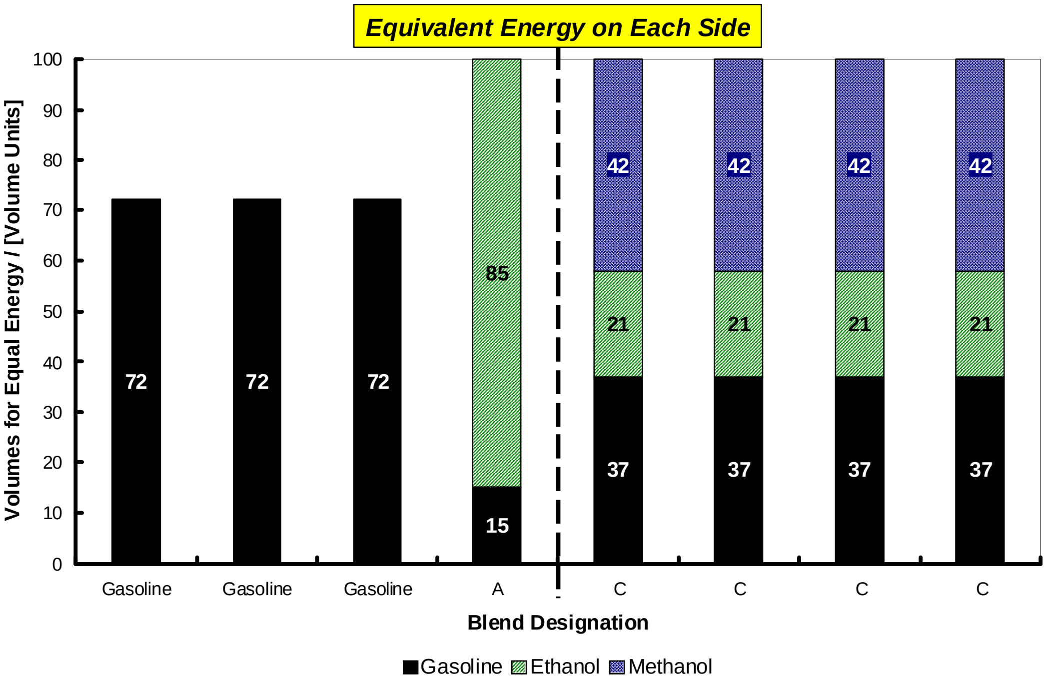

Fig. 6: Example of enhanced gasoline displacement by the introduction of methanol into ternary Blend C equivalent to E85 (for explanation, see text)

Note that the above argument is not extended to the 17 billion gallons of ethanol going into the remaining gasoline. In fact an iterative approach must be taken as the displacement of more gasoline (containing ethanol) implies more of it being available for a ternary blend. Furthermore, a ternary blending approach can be adopted at any blend rate, so assuming that methanol can be introduced via this method into E10 or E15 equivalents, a significant further proportion of gasoline could perhaps be replaced. This mechanism and overall system of displacement is perhaps worthy of further investigation and modelling.

Such an approach is academic if the vehicles do not exist to take the fuel (which can be easily rectified since the cost of making a flex-fuel vehicle is very low, and the CAFÉ regulations in the US are forcing this anyway) or if the blends are too expensive for the vehicle owner to use. Fortunately the low price of methanol means that the cost of ternary blend fuels can be lower than gasoline, on a per-unit-energy basis. As previously mentioned E85 is more expensive than gasoline in energy terms because the twin benefits of ethanol being renewable and a significant octane enhancer at low blend ratios drive its price up. It is interesting to illustrate the potential in cost reduction in ternary blends due to the introduction of the methanol blend component using assumed prices for gasoline, ethanol and methanol. We shall take these to be 3.21, 2.30 and 1.11 dollars per US gallon respectively, which was the case in September 2011 (before tax). Figure 7 shows how the price per unit energy relative to gasoline changes as the proportion of methanol in the ternary blend is increased. Only 24% methanol is required for the blend to be on a par with gasoline; at this point the user would see a reduction in operating costs anyway because of the reported higher efficiency with an alcohol blend fuel. Blends A to D are shown on Figure 7; specifically Blend D4 (G40 E10 M50), considered a practical fuel in terms of low-temperature phase separation, would be approximately 9.3% cheaper than gasoline on an energy basis.

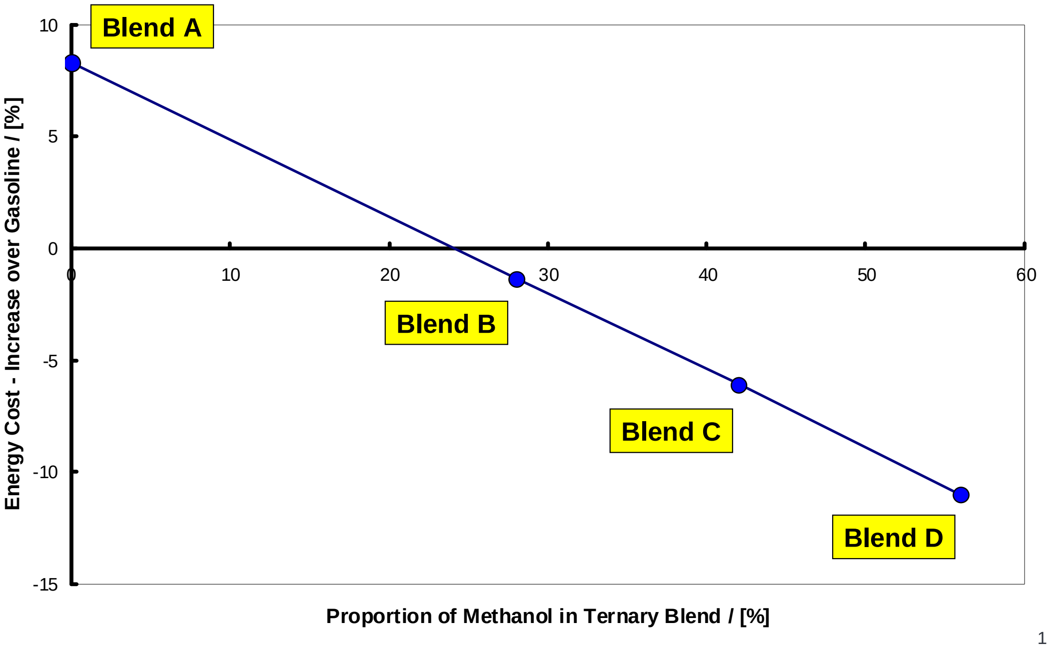

Fig. 7: Variation in energetic cost of GEM ternary blends versus that of gasoline as a function of the methanol concentration. Assumed costs per US gallon: gasoline $3.21, ethanol $2.30 and methanol $1.11. Ternary blends equivalent to E85

It should be remembered that a proportion of the gasoline required can be also made by either the FT or a MtSynFuels process (using methanol synthesis as an intermediate step). This will help with the gradual balancing of the two fuel products against the introduction of the necessary E85/gasoline flex-fuel vehicles. Given that the necessary fuel energy can be supplied in this manner, and that eventually a practical limit will be reached in terms of utilization in the existing vehicle technology (and that heavy-duty vehicles will otherwise continue to need diesel-type fuels, with the attendant energy losses from their onward synthesis from methanol) the remainder of this paper will discuss a pathway from ternary blends to the supply of fuels in full amounts to the light- and heavy-duty markets.

Having shown that the ternary blend approach produces functionally invisible drop-in blends suitable for E85/gasoline flex-fuel vehicles, further work will investigate the effect of such blends on fuel systems materials. The production flex-fuel vehicle used for these tests exhibited no problems in this regard, and has not done so ever since as far as the authors are aware. It is hoped that since many flex-fuel fuel system components are (it is believed) tested with methanol as a default that there will be no danger to existing vehicles through moving to an E85-equivalent blend containing methanol as well; even so, any potential issues can be mitigated by a phased introduction, which will be discussed in the following section.

Potential Rollout of the GEM Fuels and Possiblel Future Scenarios

From the work conducted to date it is entirely possible that methanol can be introduced into the fuel pool for existing flex-fuel vehicles (blended at E85-equivalent stoichiometry of 9.7:1) or for normal vehicles at blends equivalent to E10 or E15 in the near future. It is suggested that initial rollout be for E85/gasoline flex-fuel vehicles, since their smaller number automatically keeps the number of cars using the fuels down. Obviously some form of fleet test and further validation in-vehicle needs to be carried out before any rollout can be fully imagined, and it is hoped to do this with a small number of vehicles. Following successful conclusion of fleet trials, the release of the blends can be carried out in a manner controlled by both geography and blend ratio (obviously a blend containing much less methanol than Blend B can be created – such a blend is discussed later). This will allow the evolutionary change of the fuel and vehicles to gradually-increasing amounts of methanol in a steady and controllable manner. It is imagined that the ramp-up in plants converting shale methane to methanol would effectively mirror this, making the whole process complimentary.

Given that the existing light-duty fleet can start to use methanol by its incorporation as a blend component in a GEM fuel compatible with E85/gasoline vehicles, at some point the number of suitable vehicles able to take the fuel will become a limiting factor. It is suggested that early on in the process of GEM fuel introduction, given its successful implementation, government would enact legislation to encourage the wider production of the number of flex-fuel cars necessary so that the demand side is not a limiting factor. It is suggested that the approach of shale gas to methanol and use in the fuel pool would, at this point, have been considered a success, and that more far-reaching strategies could be created at that point. This section will discuss some such options.

With minimal impact on the vehicle manufacturers, it could be made mandatory that all spark-ignition vehicles should be made E85/gasoline flex-fuel. Some extension of the CAFÉ regulations would help to offset any costs incurred by the vehicle OEMs in doing this. However, considering the longer term, it would perhaps be advantageous to encourage the engineering of vehicles for sale which could take more than the maximum proportion of the methanol blend component in a blend equivalent to E85. This limit is Blend D (G44 E0 M56), although the actual maximum methanol proportion may need to be lower than this due to the need to have a cosolvent; it is suggested that Blend D4 (G40 E10 M50) would represent some upper limit in vehicles with E85/gasoline flex-fuel technology, due to the desire to be sure of avoiding low-temperature phase separation [11].

Since M85 was very successfully used before in the California methanol trial [18], it might be considered to make sense to move to that blend rate of methanol and gasoline as the next step, but it may equally be considered desirable to move straight to M100, while maintaining flex-fuel capability. This has been shown to be straightforward in previous work by the authors [19] and has also been called for in [16], together with more support of the US Open Fuel Standard (OFS). The vehicle engineering costs are likely to be similar to just providing M85 flex-fuel capability, since new technologies to aid starting in the form of direct injection are becoming commonplace now, and the efficacy of such technologies in cold starting pure alcohols having been known for some time [20]. A significant secondary advantage of this larger step is that the ensuing demand for pure methanol would then permit the use and adoption of either direct methanol fuel cells (DMFCs), proton exchange membrane (PEM) fuel cells with a simple reformer or optimized solid oxide fuel cells (SOFCs). In separate work, Bromberg and Cohn have suggested that heavy-duty trucks could move to M100 with the fuel being supplied by the smaller infrastructure necessary for such vehicles, which would limit the expenditure necessary [21]. This infrastructure would also play its part in the gradual evolution towards a full alcohol-based energy economy, since the necessary modifications to the heavy duty infrastructure could lead those in the light-duty infrastructure.

That emissions compliance is possible to achieve with current technology even at very high methanol concentrations was demonstrated at Euro 4 emissions level in [19]. In line with the above comments regarding NOx emissions for the ternary blends tests described above, Figure 8 reproduces the NOx results from [19], with the approximate blend ratios in the tank for each different test shown on the bars. Note that in the work reported in [19], constant stoichiometry was not aimed for in the fuel blends tested; rather the mixtures tested in that work were arbitrary since it was aimed at showing that any blend of gasoline, ethanol and methanol in a single vehicle fuel tank could be automatically compensated for by a modern engine management system. The modified Lotus vehicle used for this work was fitted with the standard-specification gasoline catalyst and was certified to Euro 4 emissions level, for which the NOx limit was 0.08 g/km. Figure 8 shows that the working engineering limit of approximately 50% when operating on gasoline was achieved for NOx. However, from the changes in the alcohol concentrations it is clear to see that in general the higher the proportion of ethanol or methanol (or both) the lower the tailpipe NOx emissions. Test 3 in Figure 8 uses G12 E0 M88 which is close to the notional M85 blend used in [18], and represents a reduction in NOx of nearly 70% versus gasoline; furthermore, the calibration was being refined as the test numbers increased, so the final value for M100 could be expected to be lower (for more details of the other emissions and how these interact, together with potential trade-offs enabled by the extremely low NOx output, see [19]).

In parallel with the above, Cohn and co-workers have proposed using the direct injection (DI) of ethanol or methanol in SI engines employing port-fuel injection (PFI) of gasoline as way of increasing the knock limit due to the chemical octane of the fuel coupled to the physical octane effects due to the high latent heat [22]. This they proposed under the banner of Ethanol Boosting Systems and their work was continued by Stein *et al.* [23]. The gearing on gasoline displacement was found to be significant since the direct injection of low-carbon-number alcohols helps to offset enrichment fuelling and to permit higher boost pressures, and thus greater degrees of downsizing.

Importantly with regard to this approach of PFI gasoline with DI of alcohol, the ternary GEM blends equivalent to E85 discussed earlier in this paper could be used instead of E85. This is because, when calculated on basis the of their mass ratios, the latent heat of all such ternary blends is the same from Blend A to Blend D to within +/- 2% (see Appendix I of [11]). Functionally this would not be expected to adversely impact the EBS concept, and it also acts as another means of introducing methanol into the fuel pool, should any such concept be commercialized. It represents another aspect of the invisibility of the blends to E85-optimized combustion systems.

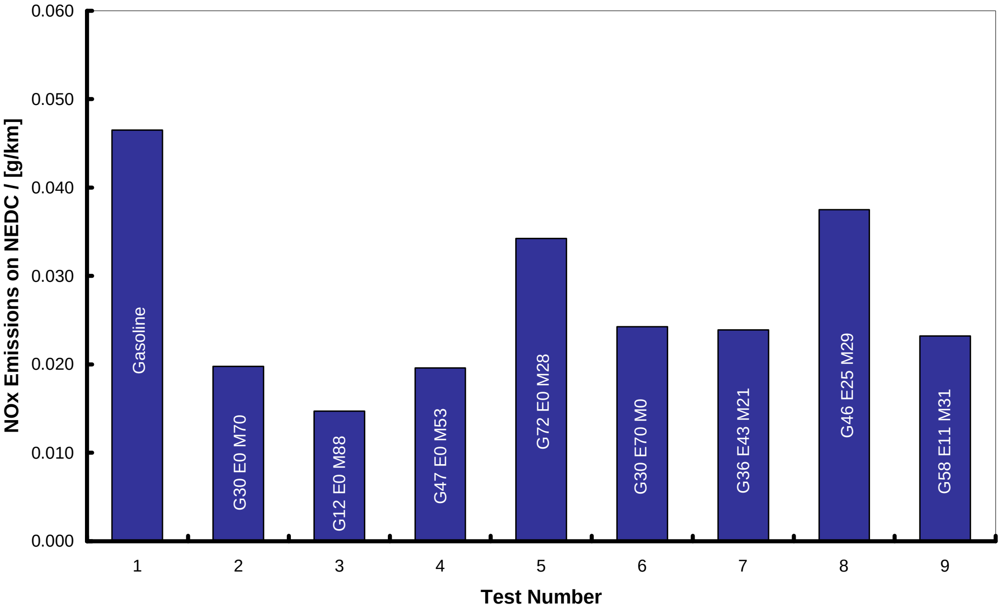

Fig. 8: Prototype gasoline-ethanol-methanol tri-flex-fuel vehicle tailpipe NOx emissions in g/km when operated on various blends of alcohol and gasoline on the New European Drive Cycle. Vehicle certified to Euro 4 emissions level. Calibration being developed from one test to the next; for more information see [19]. Note: fuel blend rates are not configured to a fixed, target stoichiometric AFR value (see text); limit = 0.08 g/km

Bromberg and Cohn discuss the use of DI of methanol in heavy-duty engines in general in [25] and Brusstar and co-workers have investigated alcohol fuels in very-high-compression ratio SI engines, showing that higher peak thermal efficiencies can be achieved with such concepts than the diesel engines on which they are based [26,27].

Thus high-blend alcohol fuels can offer the prospect of a future energy economy with increased energy security due to the high energy conversion efficiencies possible with these energy carriers. Furthermore, because of the miscibility with gasoline, flex-fuel approaches can ensure that the driver will not be left without a fuel to operate the vehicle on (although, as alcohol fuels become more commonplace, the engines may be biased towards operation on alcohols, and their may be a concomitant reduction in performance and range on gasoline; modern engine management systems will still permit safe operation despite the high compression ratios which such engines may adopt due to the superior characteristics of such high-blend alcohol fuels). A suggested time line for this process, showing how the fuels and their manufacturing processes interact with the vehicles, is shown in Figure 9, where it is proposed that the first ternary blend introduced contains only a relatively small percentage of methanol, and that this is ramped up in proportion and/or geographical area over time until all of the fuel is at Blend D4, which would represent saturation point for the vehicles was it not for mandating that all SI vehicles be capable of operating on E85 or similar (in

Figure 9 see the arrow moving from a potential introductory blend which we call Blend B1 (G20 E70 M10) to Blend D4 (G40 E10 M50)).

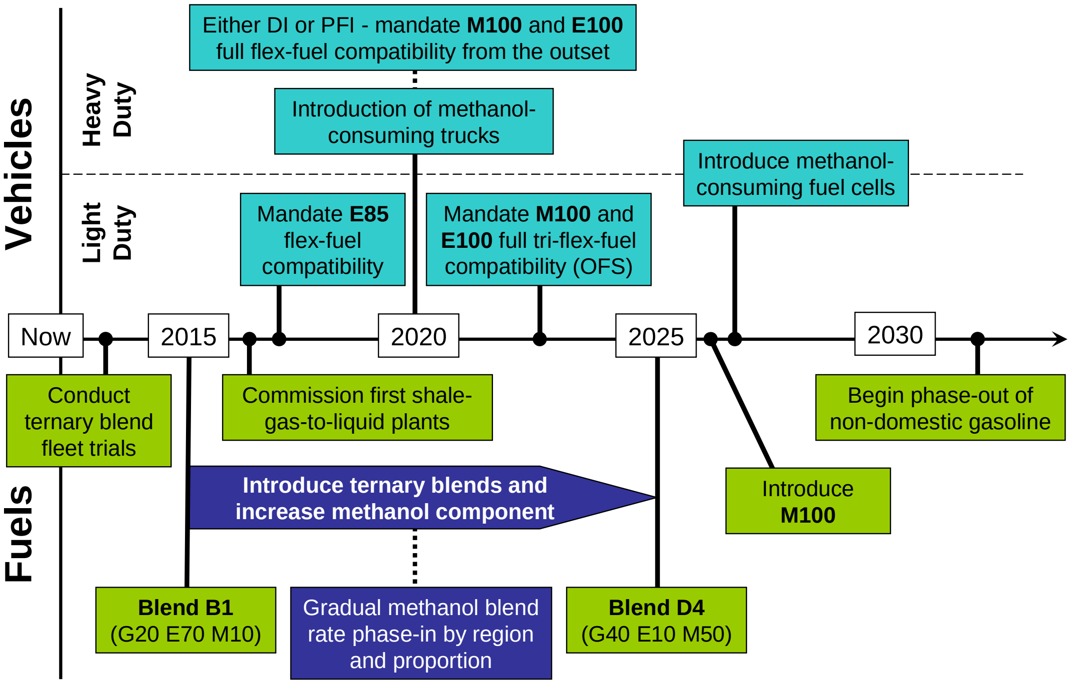

Fig. 9: Roadmap for introduction of increasing amounts of methanol into the US fuel pool via GEM ternary blends, eventually leading to M100.
OFS = Open Fuel Standard

If the gasoline price does not increase further then the energy in Blend B1 (G20 E70 M10) would cost about 4.8% more than gasoline, which would likely be offset by the higher efficiency of the vehicles, so this blend could be expected to be cost neutral. However, it is not unreasonable to assume that the gasoline price will increase, and an increase of 10% would make Blend B1 2.3% cheaper (Blend D4: 12.7% cheaper). Thus Blend B1 would appear to be a practical target introduction blend; furthermore, since there would now only be 70% ethanol and both gasoline and methanol cold start more easily, it may be possible to stay with this blend ratio year-round (see [11] for the effect of the introduction of methanol on the cold startability of ternary blends).

Eventually, there will be supply side limitations even with methanol made from shale gas, and it must also be remembered that this is a finite resource. Many researchers have proposed that methanol (and higher hydrocarbons, albeit at an efficiency penalty) can be made using CO_2 extracted from the atmosphere, electrolytic hydrogen and renewable energy [7,28-32]. This has the potential to provide liquid transport fuels in full amounts, which fuels using biomass as a feedstock cannot do due to the biomass limit. It can be seen how the gradual introduction of such fuels would be facilitated by the vehicles and infrastructure having already moved in that direction. The high value of transport fuel will ensure that the investment necessary can be supported, and the volume used will help to bypass the issues faced by renewable energy in general, i.e. that the ability of the electricity grid to absorb renewable electricity is limited by the base load condition (which cannot be circumvented), and the fact that electricity cannot easily be stored. When the wind blows and the renewable energy output is above what the electricity grid can absorb, conversion to a hydrocarbon energy carrier is an excellent means of buffering such renewable energy [7,9].

Taking all of the foregoing into account, alcohol fuels therefore represent a pragmatic solution to future transport energy requirements for all stakeholders, since a continuous process of gradual evolution to a practical end game can be followed, with no quantum investment necessary at any stage by governments, OEMs, fuel suppliers or customers in either infrastructure or vehicles. This is because the alcohols are miscible with the gasoline that we use now, many flex-fuel vehicles already exist to use it, and it is feasible to make all future vehicles alcohol-compatible at minimal extra cost as the fuels become available in larger amounts.

REFERENCES

1. Energy Independence and Security Act of 2007, Public Law 110-140, 110th Congress, DOCID: f:publ140.110, 2007.
2. "On the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC," Directive 2009/28/EC of the European Parliament and of the Council, 23rd April 2009.
3. Cooper, J., "Future fuels for transport: Regulatory and supply drivers", Internal Combustion Engines: Improving Performance, Fuel Economy, and Emissions, Institution of Mechanical Engineers Conference, London, UK, 29th-20th November, 2011.
4. "Setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO_2 emissions from light-duty vehicles", Regulation (EC) 443/2009 of the European Parliament and of the Council, 23rd April, 2009.
5. Milpied, J., Jeuland, N., Plassat, G., Guichaous, S., Dioc, N., Marchal, A. and Schmerlzle, P., "Impact of Fuel Properties on the Performances and Knock Behaviour of a Downsized Turbocharged DI SI Engine - Focus on Octane Numbers and Latent Heat of Vaporization", SAE paper number 2009-01-0324, SAE 2009 World Congress, Detroit, Michigan, USA, 20th-23rd April, 2009.
6. Anderson, J.E., Kramer, U., Mueller, S.A., and Wallington, T.J., "Octane numbers of ethanol- and methanol-gasoline blends estimated from molar concentrations", Energy Fuels, Vol. 24, pp. 6576-6585, 2010.
7. Pearson, R.J., Eisaman, M.D., Turner, J.W.G., Edwards, P.P., Jiang, Z., Kuznetsov, V.L., Littau, K.A., di Marco, L., and Taylor, S.R.G., "Energy storage via carbon-neutral fuels made from CO_2, water, and renewable energy", Special Issue of Proc. IEEE: Addressing the intermittency challenge: Massive energy storage in a sustainable future. To be published Feb. 2012.
8. Olah, G. A., Goeppert, A. and Prakash, G.K.S., "Beyond Oil and Gas: The Methanol Economy", Second Edition, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, 2009. ISBN 98-3-527-32422-4.
9. Sterner, M., "Bioenergy and renewable power methane in integrated 100% renewable energy systems", Dr.-Ing Thesis, University of Kassel, September 2009, ISBN 978-3-89958-798-2.
10. Turner, J.W.G., Pearson, R.J., Purvis, R., Dekker, E., Johansson, K. and Bergström, K. ac, "GEM Ternary Blends: Removing the Biomass Limit by

using Iso-Stoichiometric mixtures of Gasoline, Ethanol and Methanol", SAE paper number 2011-24-0113, The 10th International Conference on Engines and Vehicles, Capri, Naples, Italy, 11th-16th September, 2011.

11. Turner, J.W.G., Pearson, R.J., McGregor, M.A., Ramsay, J.M., Dekker, E., Iosefa, B., Dolan, G.A., Johansson, K. and Bergström, K. ac, "GEM Ternary Blends: Testing Iso-Stoichiometric mixtures of Gasoline, Ethanol and Methanol in a Production Flex-Fuel Vehicle Fitted with a Physical Alcohol Sensor", SAE paper number 2012-01-0113, SAE 2012 World Congress, Detroit, 24th-26th April, 2012.
12. Lotus Fuels Mixture Database, proprietary software of Lotus Engineering, 2008.
13. Pearson, R.J., Turner, J.W.G., Davy, M. and Stone, R., "Iso-stoichiometric ternary blends: Characterization of some physico-chemical properties of potential future transitional fuels", in preparation for submission to Proc. Instn Mech. Engrs Journal of Automotive Engineering, Part D.
14. "Worldwide Emissions Standards – Passenger Cars and Light Duty Vehicles 2011/2012", Delphi Corporation, Troy, Michigan, USA.; available on line at www.delphi.com/emissions-pc, last accessed 28th March, 2012.
15. Turner, J.W.G., Pearson, R.J., Dekker, E., Iosefa, B., Dolan, G.A., Johansson, K. and Bergström, K. ac, "Extending the role of alcohols as transport fuels using iso-stoichiometric ternary blends of gasoline, ethanol and methanol", submitted to Journal of Applied Energy, 2012.
16. Moniz, E.J., Jacoby, H.D., Meggs, A.J.M., Armstrong, R.C., Cohn, D.R., Connors, S.R., Deutch, J.M., Ejaz, Q.J., Kaufman, G.M., Kenderdine, M.A., O'Sullivan, F., Paltsev, S., Parsons, J.E., Perez-Arriaga, I., Reilly, J.M., Seto, C., Yang, Y., McRae, G.S., Ruppel, C., Fletcher, S., Hagerty, J.M., Kragha, O., Leung, T., Murphy, P., Rachokonda, A., Tapia-Ahumuda, K., Toukan, I., Ucok, D. and Yao, Y., "The Future of Natural Gas - An Interdisciplinary MIT Study", Massachusetts Institute of Technology, available at: http://web.mit.edu/mitei/research/studies/documents/natural-gas-2011/NaturalGas_Report.pdf, 2011, last accessed 28th March, 2012.
17. "E15 (a blend of gasoline and ethanol)", available at: http://www.epa.gov/otaq/regs/fuels/additive/e15/, last accessed 28th March, 2012.
18. Ward, P.F. and Teague, J.M., "Fifteen years of fuel methanol distribution", 11th International Symposium on Alcohol Fuels, Sun City, South Africa, 14th-17th April, 1996.
19. Pearson, R.J., Turner, J.W.G. and Peck, A.J., "Gasoline-ethanol-methanol tri-fuel vehicle development and its role in expediting sustainable organic fuels for transport", 2009 I.Mech.E. Low Carbon Vehicles Conference, London, UK, 20th-21st May, 2009, pp. 89-110.
20. Siewert, R.M. and Groff, E.G., "Unassisted Cold Starts to -29°C and Steady-State Tests of a Direct-Injection Stratified-Charge (DISC) Engine Operated on Neat Alcohols", SAE paper number 872066, 1987, doi:10.4271/872066.
21. Bromberg, L. and Cohn, D., "Alcohol Fueled Heavy Duty Vehicles Using Clean, High Efficiency Engines"
22. Cohn, D.R., Bromberg, L. and Heywood, J.B., "Direct Injection Ethanol Boosted Gasoline Engines: Biofuel Leveraging for Cost Effective Reduction of Oil Dependence and CO_2 Emissions", MIT report PSFC/JA-06-16, MIT Plasma Science and Fusion Centre, 20th April, 2005, available at:

http://www.psfc.mit.edu/library1/catalog/reports/2000/06ja/06ja016/06ja016_full.pdf, last accessed 28th March, 2012.
23. Stein, R.A., House, C.J. and Leone, T.G., "Optimal Use of E85 in a Turbocharged Direct Injection Engine", SAE paper number 2009-01-1490, SAE Int. J. Fuels Lubr. 2(1):670-682, 2009, doi:10.4271/2009-01-1490.
24. Blumberg, P.N., Bromberg, L., Kang, H. and Tai, C., "Simulation of High Efficiency Heavy Duty SI Engines Using Direct Injection of Alcohol for Knock Avoidance", SAE paper number 2008-01-2447 and SAE Int. J. Engines 1(1):1186-1195, 2009, doi:10.4271/2008-01-2447.
25. Bromberg, L. and Cohn, D., "Alcohol Fueled Heavy Duty Vehicles Using Clean, High Efficiency Engines", SAE paper number 2010-01-2199 doi:10.4271/2010-01-2199.
26. Brusstar, M., Stuhldreher, M., Swain, D. and Pidgeon, W., "High Efficiency and Low Emissions from a Port-Injected Engine with Neat Alcohol Fuels", SAE paper number 2002-01-2743, doi:10.4271/2002-01-2743.
27. Brusstar, M.J. and Gray, C.L., "High Efficiency with Future Alcohol Fuels in a Stoichiometric Medium Duty Spark Ignition Engine", SAE paper number 2007-01-3993, doi:10.4271/2007-01-3993.
28. Steinberg, M., "Production of synthetic methanol from air and water using controlled thermonuclear reactor power – I. Technology and energy requirement", Energy Conversion, vol. 17, pp. 97-112, 1977.
29. Bandi, A., Specht, M., Weimer, T. and Schaber K., "CO_2 recycling for hydrogen storage and transportation – electrochemical CO_2 removal and fixation", Energy Conversion and Management, vol. 36(6-9), pp. 899-902, 1995.
30. Stucki, S., Schuler, A. and Constantinescu, M,. "Coupled CO_2 recovery from the atmosphere and water electrolysis: feasibility of a new process for hydrogen storage" , Int. J. Hydrogen Energy, vol. 20, 8, pp. 653-663, 1995.
31. Weimer, T., Schaber, K., Specht, M. and Bandi, A., "Methanol from atmospheric carbon dioxide: a liquid zero emission fuel for the future", Energy Conversion and Management, vol. 37(6-8), pp. 1351-6, 1996.
32. Specht, M., Staiss., F., Bandi, A. and Weimer, T., "Comparison of the renewable transport fuels, liquid hydrogen and methanol, with gasoline – energetic and economic aspects", Int. J. Hydrogen Energy, vol. 23, 5., pp. 387-396, 1998.

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ABBREVIATIONS

AFR	Air-fuel ratio
CAFÉ	Corporate Average Fuel Economy
CO_2	Carbon dioxide
DI	Direct injection
DMFC	Direct methanol fuel cell
EBS	Ethanol Boosting Systems
EPA	Environmental Protection Agency
EU	European Union
FQD	Fuel Quality Directive
GEM	Gasoline, ethanol and methanol
ILUC	Indirect land use change
LHV	Lower heating value
MIL	Malfunction indicator lamp
MtSynFuels	Methanol-to-synfuels
OBD	On-board diagnostics
OEM	Original equipment manufacturers (i.e., vehicle manufactuers)
OFS	Open Fuel Standard
PEM	Proton exchange membrane
PFI	Port-fuel injection
NEDC	New European Drive Cycle
NOx	Oxides of nitrogen
RED	Renewable Energy Directive
SI	Spark-ignition
SOFC	Solid oxide fuel cell

2012 MIT Energy Initiative Symposium

Prospects for Flexible- and Bi-Fuel Light Duty Vehicles: Consumer Choice and Public Attitudes

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ABSTRACT

Based on an analysis of several case studies of alternative fuel introductions [ethanol, biodiesel, liquefied petroleum gas (LPG), compressed natural gas (CNG)], requirements for alternative fuels, vehicles, and the fueling infrastructure are postulated that are necessary for successful market implementation. Affordable vehicle technology and cost-competitive fuel were identified as the most critical factors. Payback periods for additional vehicle costs associated with different alternative fuels are discussed. Fuel costs need to be consistently competitive in both the near-term and the long-term as demand for the fuel rises.

For the vehicles, other considerations include backwards-compatibility or capability for two fuels, retrofit kits controlled by original equipment manufacturers (OEMs), and emissions compliance. For the fuel distribution infrastructure, affordable development and initially sufficient filling station numbers are required. For the fuel, important factors include energy density and adequate fill time, as well as the need for incentives and sufficient natural resource availability for sustainable fuels.

For the long-term sustainability of an alternative future fuel, there should be a future source that is non-fossil (low CO_2 emissions), renewable, and cost-competitive even when required in large volumes. Also considered are two possible future sustainable fuel scenarios involving ethanol and renewable methane. Ethanol in E85 can be used in today's flex-fuel vehicles (FFVs) to overcome backwards compatibility limits of the existing fleet, allowing time for a compatible fleet to be deployed. Renewable methane (bio-methane, e-methane) could be used at any blend level in today's compressed natural gas vehicles (CNGVs). Near-term fuel flexibility from FFVs and bi-fuel or mono-fuel CNGVs is a key enabler for both scenarios.

1. INTRODUCTION

Rising energy costs (particularly oil price), energy security, and greenhouse gas (GHG) emissions are the main drivers of the active, ongoing discussion of alternative fuels in the transportation sector. Several alternative fuels have been proposed and brought into different markets in recent years, including natural gas, liquefied propane and butane gas, biodiesel and ethanol as both neat fuels and blend components in diesel and gasoline, respectively, and electricity. Many introductions have failed or have only led to niche applications, whereas others have been truly successful in local markets. Since only a few alternative fuels are compatible with conventional vehicle technology, several fuels require additional vehicle actions to ensure compatibility. Depending on the technology used, different types of alternative fuel vehicles have been developed or proposed. Given the variety of possible configurations, consistent terminology and definitions would be desirable for the various industries and regulatory bodies involved. The definitions presented in *Table 1* were developed [1] based on a review of various national regulations and industry standards.

Table 1 – Types of Alternative Fuel Vehicles [1]

Dedicated-fuel vehicle	Any vehicle engineered and designed to be operated using a single fuel.
Mono-fuel vehicle	Any vehicle engineered and designed to be operated using a single fuel, but with a petrol system for emergency purposes or starting only, with petrol tank capacity of no more than 15 liters.
Bi-fuel vehicle	Any vehicle engineered and designed to be operated on two or more different fuels using two independent fuel systems, but not on a mixture of the fuels.
Flex-fuel vehicle (FFV)	Any vehicle engineered and designed to be operated on the original fuel(s), alternative fuel(s), or a mixture of two or more fuels that are combusted together.
Dual-fuel vehicle	Vehicle with two independent fuel systems that can run on both fuels simultaneously. It also may run on one fuel alone.

In this paper several case studies of alternative fuel introduction are considered and reasons leading to success or failure in each case are identified. A general set of "lessons learned" for successful market introduction is outlined. In addition, basic requirements of the alternative fuel, vehicles, and fueling infrastructure are postulated that are necessary for successful market implementation.

2. ALTERNATIVE FUEL MARKET EXAMPLES

A wide variety of alternative fuels are in use in markets globally. Ethanol has been used as an alternative to gasoline as both a neat fuel and as blend component in various concentrations. Other important alternative fuels currently in use include biodiesel (fatty acid methyl esters, FAME) and hydrogenated vegetable oil in diesel blended at various concentrations and in a neat form, as well as liquefied petroleum gas (LPG, a mixture of propane and butane) and compressed natural gas (CNG) in gaseous fuel applications.

Electricity as a vehicle energy source is seeing increasing development, in both dedicated-fuel vehicles (battery electric vehicles, BEVs) and dual-fuel vehicles (plug-in hybrid vehicles, PHEVs), but is not discussed here as BEV and PHEV market development has only recently started. Likewise, hydrogen is not discussed here as there is no example yet of a large-scale market introduction, as is also the case for PHEVs and BEVs.

Examination of examples of actual market introduction of these fuels allows some conclusions to be drawn that can be generalized for future fuel introduction scenarios.

2.1 ETHANOL – BRAZIL

Brazil has the most fully developed market for ethanol used in light duty vehicles (LDVs). Today there is no gasoline-type fuel available in Brazil that does not contain ethanol. Gasoline in Brazil contains 18–25% ethanol by volume and is sold as a fuel called “gasohol”. In addition, hydrous ethanol (E100) is sold, consisting of at least 94.5% v/v ethanol, with the balance being water and allowed minor components such as hydrocarbons and other alcohols [2].

Ethanol was introduced in scale in Brazil in the 1970s when oil prices rose rapidly and the Brazilian government initiated the “Pro-Álcool” program to develop a renewable fuel for vehicle purposes from sugar cane [3,4,5]. A timeline of the development of Brazil’s ethanol market is provided in *Table 2.*

In 1979 the first E100-vehicle was built, a Fiat model 147, which was a dedicated-fuel application. As can be seen in *Figure 1,* the E100 dedicated-fuel vehicle market first grew significantly and successfully. By 1985, E100 dedicated-fuel vehicles comprised more than 80% of LDV production. Subsequently, the ethanol market struggled and production of E100 dedicated-fuel vehicles declined [3]. High sugar prices led to an ethanol shortage and higher ethanol prices. Meanwhile, petroleum prices dropped and ethanol became more expensive than gasoline. As a result, demand for E100 dedicated-fuel vehicles rapidly declined. As seen in *Figure 2,* while gasoline and diesel fuel demand increased from 1986 to 2006, ethanol consumption was unchanged.

Table 2 – E100 History in Brazil [3,4]

1974	Brazilian government issued national alcohol program to develop a renewable fuel for vehicle purposes from sugar cane.
1979	First E100 dedicated-fuel vehicle built: Fiat model 147
1985	Dedicated-fuel E100 vehicles comprise more than 80% of LDV production.
1990s	Challenges for dedicated-fuel E100 vehicle market: low oil prices and high sugar prices => Ethanol shortage in internal market => Consumers stop purchasing dedicated-fuel E100 vehicles.
2002	First flexible-fuel vehicle (FFV) demonstrated: Ford Fiesta
2003	OEMs begin offering FFVs in the market
2008	FFVs comprise 87% of new LDV registrations.

In 2003-2004, Volkswagen, Fiat, GM, and Ford brought their first Flexible-Fuel Vehicles (FFVs) to the Brazilian market. Unlike their dedicated-fuel predecessors, FFVs could be operated with gasohol or E100 (or any mixture of the two), and thus allowed a choice between the two fuels at each fill. By 2008, FFVs made up 87% of registrations of new passenger cars and light commercial vehicles. With this flexibility, consumers began purchasing E100 in increasing amounts after 2006 as oil prices increased once again. Based on the chronology, it appears that FFVs and high oil prices have been key factors in the revival of the Brazilian E100 fuel and vehicle market [5].

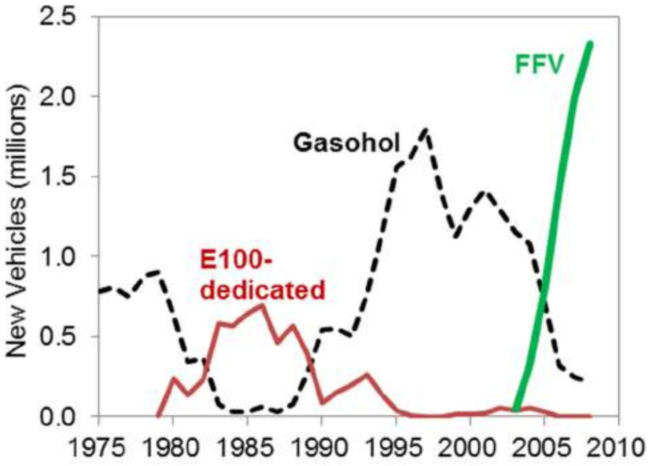

Figure 1 – Registrations of new light-duty vehicles in Brazil by vehicle type, 1975 to 2009 [6].

Another reason for the market success of E100 and FFVs appears to be the fuel price benefit of E100 versus gasohol, in part due to higher taxes on gasoline. For the period 2003 to 2010, de Freitas [5] showed that the price differential between the national-average prices for E100 and gasohol (after correcting for energy content differences) were within 15% (in either direction). Price differentials are likely to vary more by region than the national average. In general, the availability of both gasohol and E100 in the fuel marketplace, and the availability of FFVs to allow free consumer choice of either fuel based on price, provides a mechanism to dampen the effects of price fluctuations in the oil, gasoline, sugar, and ethanol markets.

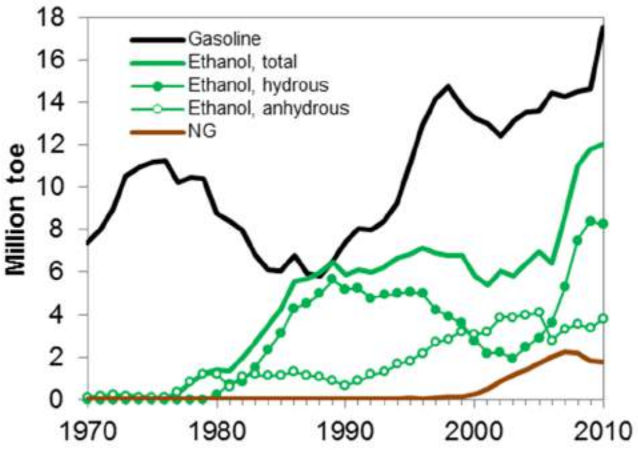

Figure 2 – Automotive fuel consumption in Brazil, 1970 to 2010 [7]

A third reason for the success of FFVs is the relatively simple and cost-effective vehicle technology that is required to upgrade a conventional vehicle to a FFV. The flex-fuel technology for Brazil mainly consists of hardened valve seats and valves, a dedicated flex-fuel controls system with two data maps, and a separate cold start system with a separate small fuel tank containing gasohol for cold engine starts. The next generation of cold start system being introduced uses a heated fuel system to replace the secondary fuels. Given the high percentage of FFVs in new vehicle sales, any changes in vehicle costs (net of additional vehicle cost ["on-cost"] and lower vehicle taxes for FFVs) have obviously been acceptable to consumers, with the benefit that it allows them to participate in the fuel price benefits of E100 while being insulated from E100 shortages or price spikes relative to gasohol.

The following conclusions can be drawn from the Brazilian market case.

Lessons learned:

- Flex-fuel capability significantly supports the successful introduction and market penetration of a new alternative fuel.
- Low vehicle on-cost for flex-fuel capability supports the alternative fuel market development.
- Market fuel prices need to remain competitive even if fuel demand rises (no steep fuel price increase when fuel demand exceeds feedstock or production capacity).
  - ⇨ Sufficient feedstock supply and production capacity is required.
  - ⇨ Flexible fuel demand (enabled by cost-efficient FFVs) should help stabilize the alternative fuel price relative to the competing fuel.
- Long-term, consistent governmental policies that can be relied upon by industry and consumers contribute greatly to successful implementation.

2.2 ETHANOL – UNITED STATES

The oil crisis of the 1970s was a key motivation for development of alternatives fuels and FFVs in the US, as was the case in Brazil. Methanol was initially identified as the preferred alternative fuel due to low production costs and abundant feedstock (coal, natural gas) and the air quality benefits relative to gasoline. As such, FFVs were first designed to operate on 85% methanol (M85) or gasoline [8].

The first FFVs were sold in the US retail market in the early 1990s and were designed for M85 capability. A few years later, in part due to greater emphasis on addressing global climate change, FFVs were instead being designed for ethanol (E85). Ethanol production in the US, primarily from starch obtained from corn, received considerable support from the agricultural industry. It also was understood to address the initial objective of reducing petroleum consumption and the new objective of reducing GHG emissions.

Policy mechanisms stimulating production of FFVs by automakers began with the Alternative Motor Fuel Act of 1988, which contained incentives in the form of credits that could be applied to corporate fuel economy targets within the Corporate Average Fuel Economy (CAFE) program. The next year, the federal governmental committed to major purchases of alternative fuel vehicles for federal fleets [8]. The Energy Policy Act of 1992 mandated the purchase of alternative fuel vehicles by certain federal and state government fleets. The Energy Policy Act of 2005 provided additional mechanisms to further promote alternative fuel vehicle acquisition (including FFVs), develop alternative fuel supply infrastructure (including E85), and mandate alternative fuel usage [9].

The FFVs and fuels in the US are different from those in Brazil. In Brazil, FFVs use either anhydrous gasohol (E18–E25) or hydrous E100. In the US and Europe, FFVs are designed to be fueled with anhydrous E0 (or E5 or E10), anhydrous E85 (85% v/v ethanol), or any mixture of these. The vehicle technologies are very similar, except for a different cold start system [10,11]. Due to the lack of a volatile gasoline fraction in hydrous E100, Brazilian FFVs use E22 fuel from a secondary tank (or a heated fuel system) for cold starts below approximately 15°C. FFVs in the US have no secondary fuel tank and can usually start on E85 down to approximately -15°C (5°F) without any auxiliaries. For cold start at lower temperatures, an engine block heater can be included (e.g., in Europe and the northern US). In these cold climates, the E85 itself is sold with lower ethanol content (as low as 70% v/v in Sweden [12] and Germany [13] and now as low as 51% v/v in the US [14]). Cold starting below -15°C (5°F) is possible with these lower ethanol content forms of E85 without utilizing auxiliary devices. The technology used in typical US and European FFVs is shown in *Figure 3*.

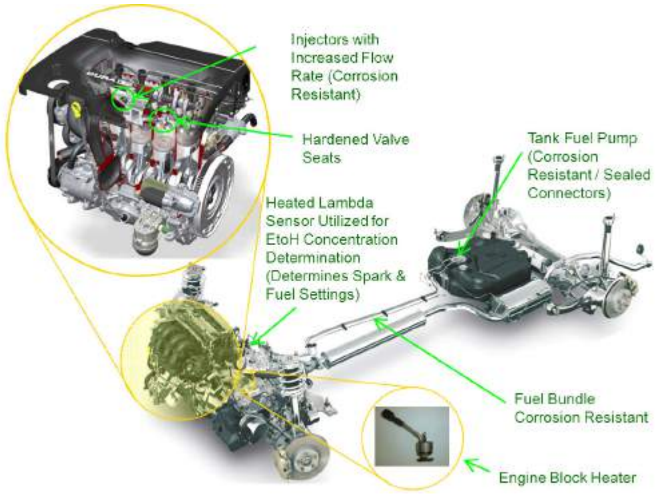

Figure 3 – US and European FFV Technology [10,11]

From the outset, FFVs in the US were generally sold without a price premium relative to comparable gasoline versions [8], despite higher production costs (engineering, tooling, materials, and controls).

FFV production began with a few thousand produced each year from 1993 to 1997, and then increased to several hundred thousand per year (*Figure 4*). In 2006, the three major US-based automakers (GM, Ford, Chrysler) announced their intention to double production of FFVs by 2010 and that FFVs would comprise half of new LDV offerings by 2012 if the appropriate supporting fuel infrastructure existed. As of late 2011, over 9 million FFVs were registered in the US (approximately 4% of all LDVs) [15], with their numbers steadily increasing at over 1 million FFVs per year.

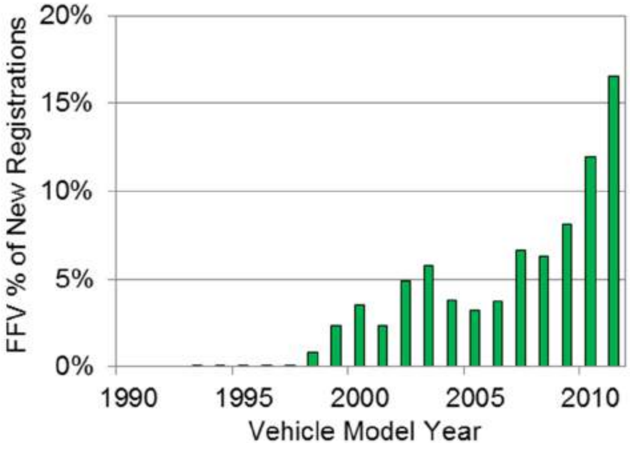

Figure 4 – FFV percentage of new vehicle registrations in the US, 1993 to 2011, *estimated from FFV and total vehicle registrations by vehicle model year as of March 2012 [16].*

Despite the increasing numbers of FFVs on the road, E85 use has not been as significant. Although the use of fuel ethanol in the US grew steadily through the year 2000 as shown in *Figure 5*, nearly all of it was used in low level blends in gasoline (up to E10) rather than in E85 [17]. At that time, ethanol and methyl tertiary butyl ether (MTBE) were being used as oxygenates for tailpipe emissions reductions and octane rating value in the fuel [15]. Ethanol use accelerated after 2000 as the use of MTBE was phased out due to groundwater contamination issues.

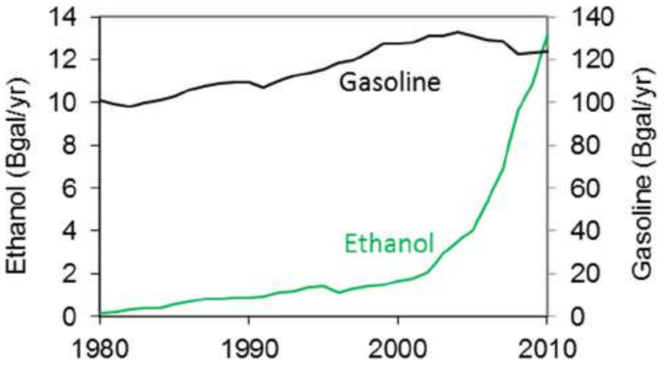

Figure 5 – Ethanol and gasoline consumption in US road transportation, 1980 to 2010 [15].

The first Renewable Fuel Standard (RFS1) was created from the Energy Policy Act of 2005 and mandated alternative fuel use of 4 billion US gallons (15 billion liters) in 2006 increasing to 7.5 million gallons (28 billion liters) in 2012 (*Figure 6*). Most of the mandate was expected to be fulfilled by ethanol, but it did not differentiate between ethanol used in low-level blends and E85. Starting in 2003, several states began mandating minimum concentrations of ethanol in gasoline, generally E10.

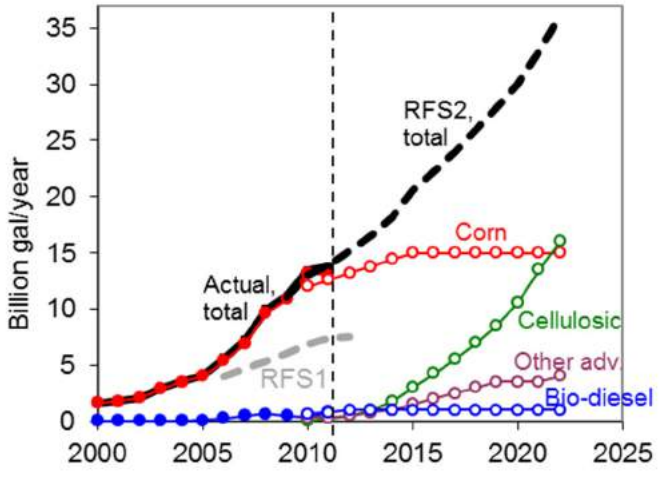

Figure 6 – Renewable fuel targets for the US mandated by RFS1 (2006 to 2011) and RFS2 (2010 to 2022). *RFS2 includes specific requirements for conventional (corn) biofuel and advanced biofuels, the latter including specific requirements for cellulosic biofuel, biomass-based diesel, and other advanced biofuel. Actual historical ethanol and biodiesel use is also shown (2000 to 2011) [15,18].*

In 2007, shortly after the RFS1 schedule was finalized, the Energy Independence and Security Act became law. This act called for a new Renewable Fuels Standard (RFS2) that accelerated and extended the mandated volumes of renewable fuel, starting at 11.1 billion gallons (42 billion liters) in 2009 increasing to 36 billion gallons (136 billion liters) in 2022 (*Figure 6*). Within these total mandated volumes, there are mandates for specific types of fuels, including "advanced" biofuels (defined as having at least 50% GHG reduction relative to gasoline), cellulosic ethanol, and biomass-based diesel. At the time, most of this renewable fuel was expected to be supplied as ethanol.

Although fuel ethanol consumption in the US has grown rapidly in the last decade (*Figure 5*), only 1.0-1.5% of this was used in E85 [17] while the balance was blended into gasoline at levels up to E10. Use of E85 in FFVs has grown steadily, but the volumes have been limited. In 2009, E85 use was approximately 0.05% that of total highway gasoline use on an energy-equivalent basis [17]. Reasons for the low E85 use include the limited availability of E85 at service stations, higher E85 prices than gasoline on an energy-equivalent basis, perceived lower fuel economy (volumetric basis) and lower travel range compared to gasoline, and ethanol's greater value for fuel suppliers in low-level blends [15].

As shown in *Figure 7*, the number of filling stations supplying E85 in the US has continuously grown since 2004, aided by various government incentives. As of early 2012, approximately 2500 stations sold E85, with nearly half located in six states (MN, IL, IA, IN, WI, and MI) [19] that have a significant agricultural base and are major corn producers. The current number of E85 stations represents less than 2% of the total number of filling stations in the US, and is only half the corresponding percentage of FFVs in the LDV fleet (4%). Thus, at present, the E85 fueling infrastructure can be seen as lagging the E85 vehicle fleet.

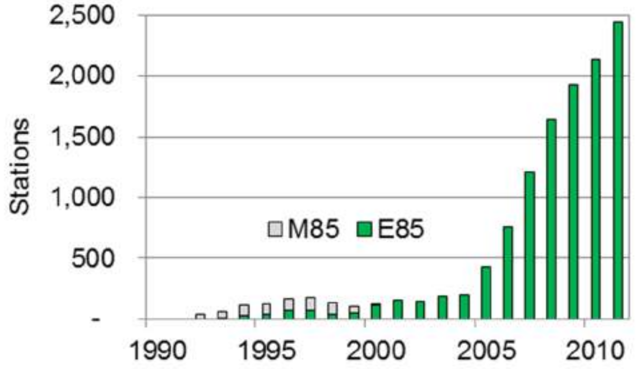

Figure 7 – Filling stations offering M85 and E85 in the US, 1992 to 2011 [20].

As discussed earlier, due to the energy content difference, E85 prices need to be lower than gasoline on a volumetric basis ($/gallon) to be competitive on an energy basis. Until 2011, the US industry specification for "E85" has required between 68% and 83% v/v ethanol, depending on climate [21], and has contained approximately 74% v/v ethanol on an average basis [22]. Gasoline contained 1 to 10% v/v ethanol over the last decade based on *Figure 5*. As such, for energy equivalent pricing, "E85" should have been priced (on a per-gallon basis) at a discount of 23–28% relative to E0 gasoline or 21–26% relative to E10.

Average retail prices of E85 and gasoline in the US (both adjusted to E0 energy-equivalent price) are shown in *Figure 8*, as well as the infrequent cost benefit for E85. With the exception of a brief period in early 2009 after a rapid drop in fuel prices, the pricing of E85 has generally provided less consumer value than gasoline on an energy-equivalent basis. Thus, the insufficient price discount for E85 has probably contributed to the low E85 use observed to date in the US.

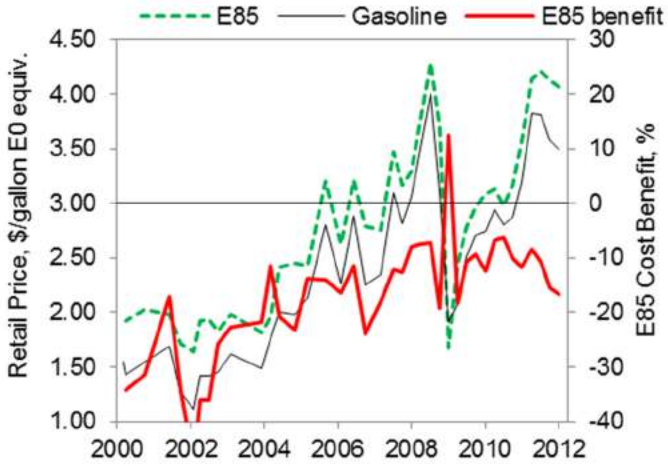

Figure 8 –E85 and gasoline prices (energy equivalent) in US and calculated E85 cost benefit, 2000 to 2011. *Retail fuel prices from [23], and assuming average of 74% v/v ethanol in E85 and gasoline ethanol content implied from Figure 5.*

Going forward, RFS2 requires continuing increases in the amount of renewable fuel in road transportation. In the near term, most of this is expected to be supplied as ethanol. In 2012, the gasoline pool will become effectively saturated with E10 and other ethanol outlets will be needed. This "E10 blend wall" issue is amplified by the fact that total LDV energy demand is expected to decrease in the future as a result of more stringent fuel economy requirements [15,22].

Although there have been regulatory efforts to increase the ethanol content in regular gasoline, exemplified by the recent US EPA waiver allowing E15 for MY2001+ vehicles, there are several administrative, technical, and marketing hurdles for E15, and it is not yet present in the marketplace. Alternatively, the use of high-level ethanol fuel blends (up to E85) in FFVs is an immediately available outlet. High-level ethanol fuel blends have been commercially identified as E85 (containing 70–85% v/v denatured ethanol), but a recent change now allows for a wider range (51–83% v/v) of ethanol content [14]. For E85 to see greater use, it will need to be priced more attractively for consumers.

More cost-competitive pricing for E85 could be facilitated in the near future by the Renewable Identification Number (RIN) system within RFS1 and RFS2. As part of the Energy Policy Act of 2005, the RIN system was initiated to allow more efficient compliance by the fuel supply industry. The RINs are generated when renewable fuel is produced or imported and are transferred as it is blended into motor vehicle fuel for the marketplace. Fuel blenders must acquire a certain number of RINs for every gallon of fuel prepared, either by selling the biofuel blend or by buying RINs from others who have done so. (The RIN requirement is determined annually by US EPA to ensure that the national RFS2 mandates are met) [24]. If insufficient amounts of biofuel are being blended into fuel, then insufficient numbers of RINs are being generated and RINs will be in greater demand and command a higher price. This mechanism should provide an incentive to sell E85 at lower cost relative to gasoline based on the value of the additional RINs that would be generated. (This mechanism has recently come into play in the US biodiesel market [24].)

Now that the US gasoline market is nearly saturated with E10, the RIN mechanism should encourage fuel suppliers to price the higher ethanol content fuels (E85 and possibly E15) more competitively as their renewable fuel obligation continues to increase. If the RFS2 total renewable fuel mandates are retained (and not downgraded as has recently been the case for the cellulosic ethanol mandate [24]), then E85 (and by extension FFVs) should become more attractive to consumers. This situation should also provide additional motivation for the installation of E85 pumps at filling stations. Thus, although E85 consumption has been somewhat limited thus far, the growing presence of FFVs in the vehicle fleet may be a critical enabler that allows the RFS2 mandate to be met in the future.

Lessons learned:

- Alternative fuels need to be priced competitively (on at least an energy equivalent basis) for consumers to choose to purchase them in meaningful quantities.
- Vehicles designed and built with compatibility for an alternative fuel need to enter the marketplace and accumulate in the on-road fleet before the alternative fuel is made available; otherwise there is no viable outlet for the fuel.
- Without a consumer pull for the alternative fuel (attractive energy equivalent price), incentives are needed to induce automakers to produce vehicles compatible with that fuel.
- Without charging the vehicle on-cost for an FFV to the consumer, the FFV fleet size can grow significantly. However, competitive fuel pricing is needed to ensure that the alternative fuel (here E85) will be used to a similar extent.
- Incentives to install alternative fuel tanks and pumps at filling stations are helpful, but not sufficient to ensure consumption of that fuel, particularly if the fuel cannot be (or is not) priced competitively.

2.3 ETHANOL – EUROPE

In Europe, Sweden was the first country to introduce FFVs and has developed a strong market. FFVs have also been introduced in other European countries, but with far less success. The FFVs in Europe use the same technology as those in the US (*Figure 3).*

2.3.1 ETHANOL – SWEDEN

In the late 1990s, the cities of Stockholm and Gothenburg started a purchasing consortium of communities and private companies committed to buy several thousand ethanol cars for municipal fleets and public transport if a company could supply them [25]. Ford accepted the challenge and developed a FFV specifically for the Swedish market. The vehicle, the Ford Focus Flex-Fuel, was launched in 2001. Saab followed in 2003, Volvo in 2006, and other original equipment manufacturers (OEMs) followed later. As shown in *Figure 9*, FFV sales in Sweden started to increase rapidly in 2004 and continued through 2008 when 22% of all new cars sold were FFVs.

This early success was enabled by several measures taken by the Swedish government, including a lower sales tax rate for E85 than gasoline, incentives for FFV purchases, as well as local incentives for FFVs (e.g. exemption from congestion charges, free city parking) [26,27]. Similar incentives were provided for other alternative fuels. Some of these incentives were linked to the inclusion of FFVs and other alternative-fuel vehicles in the federal and local "clean vehicle" programs.

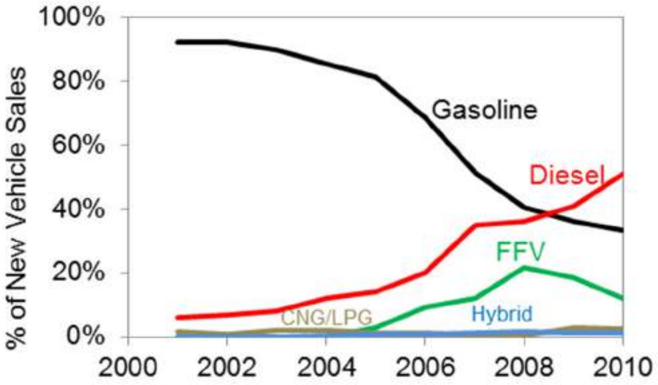

Figure 9 – Fraction of new vehicle sales in Sweden by type, 2001 to 2010 [28]

The "clean vehicle" standard, introduced in 2005 defines a "clean vehicle" as one that is driven primarily with renewable fuels or electricity or one that is conventionally-fuelled with less than 120 g/km CO_2 emissions. Government fleets are required to purchase "clean vehicles". The vast majority of vehicles meeting the "clean vehicle" standard have been FFVs [27].

However, as shown in *Figure 9*, sales of FFVs declined after 2008. At the same time, diesel car sales rose significantly. The reasons for this change likely included the rapid drop in oil and diesel prices after the economic crisis in 2008 and the greater availability of diesel cars with CO_2 emissions below 120 g/km that meet the "clean vehicle" standard (including meeting EU4+ emissions limits). Such vehicles are attractive due to vehicle purchase incentives and annual vehicle taxes that are linked to CO_2 emissions [29].

In terms of fuel infrastructure, a law was passed in 2006 that required all fuel stations above a certain size to offer at least one alternative fuel. Stations selling E85 numbered less than 100 in 2003 (2% of all stations) but steadily increased to nearly 1700 in 2011 (59% of all stations) [30]. Stations chose to install E85 pumps (SEK 350,000–400,000; € 40,000–45,000; US $50,000–$55,000) rather than biogas pumps due to a ten-fold lower installation cost [27].

Retail fuel pricing has provided an inconsistent benefit for E85 relative to the prevailing E5 gasoline [30]. As shown in *Figure 10*, after adjusting for energy content differences in the two fuels, the E85 price benefit has generally varied between +10% and -10% that of gasoline, with mostly positive pricing prior to late 2008. However, in late 2008 a drop in oil and gasoline prices and an increase in E85 price resulted in E85 having up to a 30% cost penalty relative to gasoline. Since that time, oil prices have steadily risen again, gasoline has become more expensive, and E85 retail pricing has been more competitive.

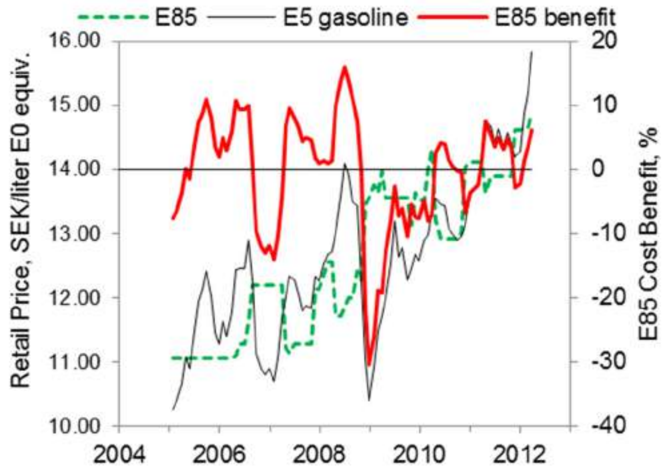

Figure 10 – E85 and E5 gasoline prices (energy equivalent) in Sweden and E85 cost benefit, 2005 to 2012. *Retail fuel prices from [30] and assuming 85% v/v ethanol in E85.*

Despite the decline in FFV sales after 2008, E85 has been sold in steadily increasing volumes through 2011, as shown in *Figure 11*. The exception was 2009 when there was a 19% year-over-year decline, likely due to uncompetitive E85 prices (*Figure 10*). In 2011, sales of E85 were approximately 4% that of E5 gasoline [30] after adjusting for energy content. Furthermore, the volume of ethanol blended into E85 was approximately equal to that blended into E5 gasoline in 2011.

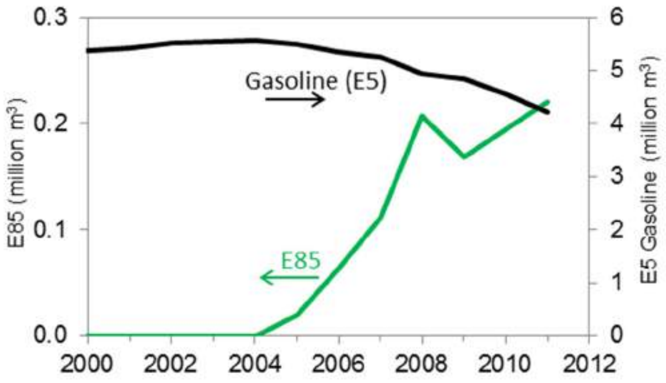

Figure 11 – E85 and E5 gasoline consumption in Sweden, 2005 to 2011 [30]

The Swedish example demonstrates that the actual fuel price benefit (based on energy content) of an alternative fuel is an extremely important factor for its success in the market. This is particularly true for cases in which the fuels are in direct competition with little to no performance difference. This situation exists with gasoline and E85 in markets with significant penetration of FFVs.

The availability of E85 pumps is another important factor that determines the utilization rate of E85. The Swedish policy of requiring alternative fuels at filling stations has undoubtedly been important. Consistently low E85 prices would also offer an attractive investment climate that would help the development of a comprehensive fuel pump network.

Lessons learned:

- Consumer fuel price benefits (versus gasoline and diesel) are very important. An energy-based price benefit of 5–10% for E85 seems to be sufficiently attractive. The benefit need not be continuous, but should occur with sufficient frequency that consumers see a benefit for considering the alternative fuel and vehicle.
- Sufficient availability of E85 pumps is obviously an important requirement for enabling significant E85 usage.
- Governmental actions are likely to be necessary to accelerate development of the fuel supply network for the alternative fuel, particularly if its price is not consistently attractive relative to competing fuels.

2.3.2 ETHANOL – GERMANY

While E85 and FFVs have seen some success in Sweden, ethanol has not been nearly as successful in the rest of Europe. The following sections describe the German experiences with E85 and E10 as examples.

2.3.2.1 E85 – GERMANY

The first FFVs entered the German market in 2005 with the same technical content as in Sweden and the US. Unlike Sweden, significant incentives have not been provided for FFVs in Germany. In 2010, FFVs represented 0.05% of light duty vehicle sales (1409 out of 2.9 million vehicles) [31].

E85 prices in Germany tend to be more attractive than typical 95-RON gasoline, even after adjusting for energy content. As shown in *Figure 12* for the period from January 2007 to November 2011, the energy-equivalent E85 price was usually 5–10% less than gasoline, but also exceeded it by up to 18% when gasoline prices were low. In general, the E85 price advantage has been small and the benefit inconsistent.

No incentives have been granted for E85, thus it has remained a niche product in Germany thus far. (Only 1% of the ethanol sold in Germany in 2010 was as E85; the rest was blended into gasoline as ethanol or ethyl tertiary butyl ether [ETBE] [32]). Thus, the modest but inconsistent cost benefit of E85 in Germany (-18% to +10% in 2006 to 2011) seems to be insufficient to attract many consumers to FFV technology, at least under the given competitive conditions with other alternative fuels (CNG and LPG) and a strong diesel market, as well as a poorly developed E85 infrastructure.

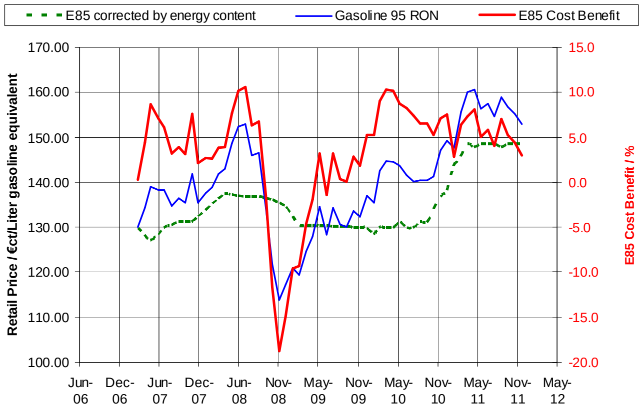

Figure 12 – Unstable E85 Cost Benefit vs. Gasoline in Germany, 2007 to 2011 [33,34,35]

As shown in *Table 5* (in Section 2.6 below), E85 FFVs have had the lowest vehicle on-cost, and partly as a result, have the shortest payback period of all reasonably available alternative fuels in Germany, shorter than diesel, LPG and CNG. But, as discussed in Sections 2.5 and 2.6, LPG is the clearly preferred alternative fuel in Germany, even though it has a longer payback period than E85. Consumers probably prefer LPG because the long-term cost savings are much greater than with E85. Furthermore, E85 fuel stations are very limited in number as compared to LPG. As of March 2012 in Germany, there were approximately 6500 LPG stations and only 311 E85 stations [36]; out of the total 14,700 filling stations [37], this represents 44% with LPG and 2% with E85. One reason is that the installation of E85 stations has not been supported by incentives. Furthermore, legal hurdles for installing an E85 station have been very high and in some parts of Germany it has been generally forbidden to build E85 stations. In most parts of Germany, E85 pumps have only received interim exceptions to operate, not permanent legal approval. As a result, long-term planning is not possible and many bureaucratic hurdles have to be overcome. Thus far the sizeable investment to install an E85 tank and pump (approximately € 20,000 [38]) has been a questionable investment and has been avoided.

Lessons learned:

- Consumer fuel price benefits (versus gasoline and diesel) need to be positive and stable over time. Although an (energy-based) consumer fuel price benefit of 5–15% may be sufficient, market development may be hindered if that benefit is inconsistent.
- Without governmental actions to accelerate infrastructure development for an alternative fuel, and with a modest but inconsistent fuel price benefit, the fuel distribution system may grow slowly.
- As with cost-efficient vehicle technology, a new fuel introduction is likely to fail if the reduction in cost of ownership is small and inconsistent.

2.3.2.2 E10 – GERMANY

The recent attempt to increase the ethanol content of gasoline in Germany from 5% v/v to 10% v/v (E10) has not gone smoothly. Concerns had been identified for materials capability with E10, particularly for the high pressure fuel systems of the first-generation direct injection engines (not sold in the US). After extensive discussions and capability reviews by the OEMs, E10 fuel was introduced in 2011 [39]. Because 7% of the German vehicle stock was identified as not being E10-capable [40], vehicle compatibility lists were issued (a very challenging process in itself) and a protection grade fuel (E5) had to be kept in the market. This approach caused considerable consumer confusion. Consumers have expressed uncertainty about the correct fuel for their vehicle and have mostly chosen to avoid E10, resulting in much less E10 consumption than expected [40].

Lessons learned:

- Widespread blending of the standard market fuel with a new fuel is ideally accomplished with complete backwards-compatibility with the existing vehicle stock. If the fleet is only partially compatible, then vehicle compatibility lists must be issued, detracting from consumer confidence in the new fuel.
- Depending on the fuel, the maximum blend rates can be very limited without introducing compatibility issues.

2.4 BIODIESEL – GERMANY

In the 1990s, biodiesel in a neat form (B100) was introduced in Germany. Rapeseed for biodiesel production was cultivated on fallow land in the 1990s. Because the German government did not impose any taxes on biodiesel during the introduction phase, B100 could be sold with a consumer price benefit relative to fossil diesel [41]. For example, from 2004 to 2006, the production cost of B100 (approx. 0.76 €/liter [41]) was much greater than the pre-tax cost of diesel (0.35–0.53 €/liter [33]). However, due to taxes on the diesel fuel the retail price for B100 was approximately 5–15% lower than fossil diesel on an energy-equivalent basis.

In addition, some OEMs announced that their light duty vehicles in the existing market fleet were compatible with B100. This very important step led to B100 becoming rapidly accepted and purchased by consumers within a short time.

As can be seen in *Figure 13,* biodiesel sales rose from 1990 to 2006, mostly as B100. By 2006 there were approximately 1900 biodiesel stations in Germany [41]. Then, deficits in fuel tax income, caused by the increasing B100 sales, were recognized by the German government. As a consequence, B100 as neat fuel was taxed as of 2008. Compensatory regulations were enacted that supported greater blending of biodiesel into fossil diesel, such that the maximum allowed biodiesel blend limit was extended from 5% v/v (B5) to 7% v/v (B7).

At the same time vehicle incapability issues increased because many modern diesel vehicles – equipped with common-rail fuel injection systems, particulate filters and post-injection strategies for purging these filters – were not B100-capable. In 2008, B100 sales declined by 0.74 Mt or 41% from the prior year. Despite the regulations supporting greater biodiesel blending in fossil diesel, the increase of the blended biodiesel was only 0.19 Mt such that total biodiesel sales declined by 17% [41].

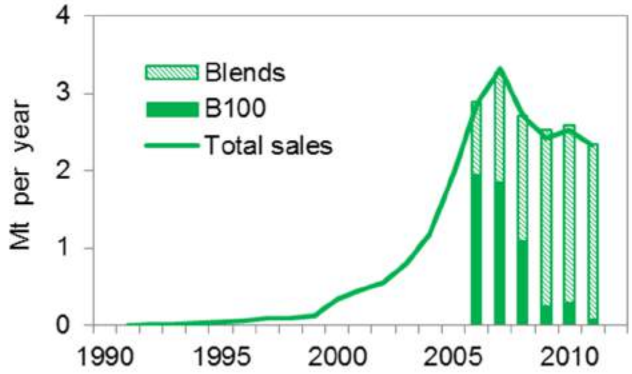

Figure 13 – Biodiesel Sales in Germany, 1990 to 2011 [42,43]

At present, biodiesel is primarily used in Germany as a blend component in fossil diesel in concentrations up to B7, because of backwards compatibility limits of the existing vehicle fleet and the existing European diesel fuel standard that limits the maximum blend rate to B7 [44]. The original German government proposal in 2008 was to increase the biodiesel blend limit to 10% v/v (B10). But because of OEM concerns about incompatibility with B10, with risks such as oil dilution, oil degradation, deposit formation, and materials compatibility, the limit was set to the current B7 and the <u>complete</u> vehicle stock was declared to be capable. This approach largely created widespread consumer acceptance, unlike the recent transition from E5 to E10 in which the entire fleet was not declared to be compatible.

<u>Lessons learned:</u>

- Backwards vehicle fleet capability is critical to the success of an alternative fuel introduction.
- When a sufficient number of capable vehicles are available in the market, a fuel cost benefit of 5–15% versus the established fuel (in this case diesel) seems to be sufficient to generate consumer demand.
- Incentives (here sales tax reduction) can spur the growth of an alternative fuel market and can make an alternative fuel successful if a sufficient fraction of the existing vehicle fleet is declared compatible with the fuel.
- Governments will be motivated to withdraw incentives if they become too costly (paradoxically due to successful growth of the alternative fuel market), which can rapidly reverse the market success.
- The greater the cost-competitiveness of the alternative fuel in the long-term (without subsidies), the more likely the fuel will be able to avoid a market collapse as incentives are reduced. However, the long-term cost-competitiveness of an alternative fuel may be influenced by differing policy treatment to account for differences in perceived external costs.

2.5 LPG – EUROPE

LPG consists primarily of a mixture of propane and butane. Under typical storage pressure (8–12 bar under normal ambient conditions [49]), the fuel is in a liquid form. Even though LPG is not renewable, it can deliver an approximately 10% tank-to-wheel (TTW) CO_2 emissions reduction versus gasoline, due to its greater hydrogen-to-carbon ratio [45].

LPG is currently the most used alternative fuel in Europe and has a 3% European market share [46]. For comparison, biofuels represented approximately 2% of road transport energy used in the EU in 2007 [47]. European LPG vehicle (LPGV) registrations have increased greatly in the last decade.

Most LPGVs are retrofit systems. More than 450,000 LPGVs were registered in Germany in late 2011 (at the same time about 75,000 natural gas vehicles were registered) [48]. The total number of new OEM bi-fuel LPGVs registered from

2006 to 2010 was only 43,000 [31,48]. Prior to this, there were essentially no OEM LPGV registrations. Assuming that all of these OEM LPGVs are still on the German market (average age of German cars is 8.5 years [48]), their share of the total LPGV fleet was 9.4% in late 2011. This implies that approximately 90% of German LPGVs are retrofits. The share of retrofitted LPGVs in other European countries is even greater [46].

The majority of retrofitted LPG systems use a gaseous LPG port fuel injection system [49,50]. The additional LPG tank, with typical capacity of about 40 liters (10 US gallons) enabling a 400–500 km (250–300 mile) range, is usually mounted in the spare wheel well. The additional system weight, including tank, is about 60 kg (130 lb). Usually LPG is conveyed by the vapor pressure of the fuel in the fuel tank. The LPG first flows to the evaporator where it is vaporized. The gaseous fuel is injected through separate fuel injectors into the intake manifold. To start the engine at low temperatures, these retrofitted LPGVs need the additional gasoline capability (bi-fuel) from the existing fuel tank, since the evaporator and fuel supply do not work properly at low temperatures. At very low temperatures the LPG has a very low vapor pressure and fuel does not flow to the injectors. In that case the system is automatically switched to gasoline operation (bi-fuel capability required). Retrofitters also offer systems with liquid LPG injection into the manifold, which require an additional fuel pump but eliminate the need for an evaporator. There are also systems offered (typically not approved by OEMs) where LPG is directly injected into a modified gasoline high-pressure direct injection system.

Typical retrofit kits utilize a “slave” control unit to operate the LPG injectors, which is placed between the injection signal output of the engine control unit (ECU) and the LPG injectors. When the driver selects LPG operation, the gasoline injectors are switched off. Most OEM bi-fuel vehicles also utilize this kind of control system.

The LPG infrastructure has been growing in response to vehicle registrations and consumer demand. As shown in *Figure 14*, LPG stations in Germany have seen significant growth since 2005 and are now widely available, considerably more than CNG stations [51]. In early 2012, LPG and CNG were available at approximately 44% and 6%, respectively, of German filling stations. Meanwhile, there is a very sufficient LPG infrastructure in many parts of Europe, with Turkey, Poland, and Italy being the most developed. The main reasons for the success of LPG are incentives and tax reductions in many European countries.

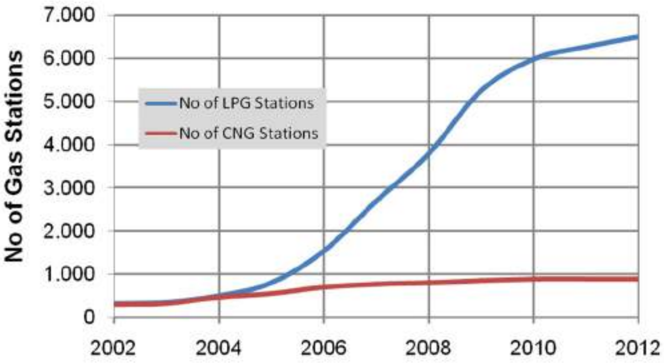

Figure 14 – LPG and CNG filling stations in Germany, 2002 to 2012 [51].

Another important reason for LPG success is the availability of aftermarket retrofit conversion kits for used gasoline vehicles (bi-fuel vehicles). The conversion of used cars is particularly attractive in cost-sensitive markets, as the strongest LPG markets tend to be, because the main reason for consumers to change from a well-established fuel (gasoline) to an alternative fuel such as LPG is the lower operational cost. LPG aftermarket conversion kits are available for only moderate on-costs (German OEM consumer on-cost approximately € 2000–2500 [$ 2600–3300)] per vehicle [52,53]; Eastern Europe retrofit, non-OEM on-cost starting at approx. € 700 per vehicle). The less expensive, usually “OEM uncontrolled” retrofit kits are typically of lower quality and durability. For example, OEMs typically upgrade the valves and valve seat inserts of their LPG engines, whereas retrofit conversions usually do not use these relatively expensive replacement parts. Therefore the engines of many aftermarket converted vehicles will have considerably reduced durability, since the poor lubricity of LPG fuel leads to increased valve seat wear [54,55].

Lessons learned:

- Consistently low consumer fuel prices with readily available vehicle bi-fuel capability are strong driving forces for the market penetration of an alternative fuel.
- Cost-efficient retrofit conversion possibilities for existing vehicles can significantly help to develop the fuel market.
- However, typically “OEM uncontrolled” retrofit kits reduce engine durability. Therefore, reliance on aftermarket vehicle conversion through retrofit kits should be considered very carefully in any introduction strategy for an alternative fuel.

2.6 CNG – ASIA AND EUROPE

Natural gas (NG) is mostly methane (CH_4) with a wide range of other components (e.g. N_2, CO_2, C_3H_8, H_2, etc.) depending on the source and how it is processed. Liquid fuels are generally preferred to gaseous fuels in vehicle applications because of their ease of handling and storage. However, NG is an attractive automotive fuel because it is available worldwide, found in abundant supply, and much of it can be developed at relatively low cost [56]. The current mean projection of the recoverable NG resource is 16,200 trillion cubic feet (460 trillion m^3), or 150 times current annual global NG consumption [57]. Furthermore, because of its greater hydrogen-to-carbon ratio, it provides a 20-25% TTW CO_2 emissions reduction versus gasoline [45].

In the mid-1990s, compressed natural gas (CNG) became a significant automotive fuel for mass-production passenger vehicles in the European market when several auto manufacturers introduced CNG-capable vehicles [58]. For automotive application, NG is compressed up to 250 bar pressure and the CNG remains gaseous under all typical temperature conditions [59].

Practically all CNG vehicles (CNGVs) use a retrofitted port fuel injection system [49,60]. Because CNG remains a gas at typical storage temperature and pressure, the additional CNG containers require much more storage volume than LPG tanks and as such cannot be mounted in the spare wheel well. CNG containers are typically placed on the trunk floor (decreasing trunk capacity) or as an under-floor system when the vehicle platform is supporting this (OEM solution only). OEMs also typically upgrade the valves and valve seat inserts due to the poor lubricity of CNG [55].

CNG flows using the pressure within the CNG storage container. A pressure regulator reduces the CNG pressure to approximately 2–10 bar (system-dependent) before it is injected through separate CNG injectors into the intake manifold. Typical retrofit kits and many OEM bi-fuel vehicles utilize a slave control unit to operate the CNG injectors, placed between the injection signal output of the ECU and the CNG injectors. When the driver selects CNG operation, the gasoline injectors are switched off.

The typical amount of CNG stored on the vehicle is about 12–20 kg (26–44 lb) depending on vehicle size, which usually enables a cruising range of 250–450 km (160–280 miles). The additional weight of the complete CNG system is approximately 150 kg (330 lb), while the package space occupied by the fuel tanks is approximately 100 liters (3.5 ft^3) [49].

Worldwide in 2010, CNGVs totalled 12.7 million and their numbers grew by 12% from the prior year. More than 18,000 CNG filling stations were available worldwide in 2010, with year-over-year growth of 10% [61]. In *Table 3*, the 20 largest CNGV markets are listed in rank order of CNGVs.

Asia is the largest CNG vehicle market and also accounts for the world's largest growth in CNGVs (42% since 2001) [61]. Pakistan is the worldwide leader with 2.7 million CNGVs or 61% of all passenger vehicles. India has 1.1 million CNGVs but these comprise only 1% of passenger vehicles. China and Thailand are also among the top ten CNGV markets.

Table 3 – Worldwide CNGV Markets [61]

	Country	**No. of CNGVs**	**No. of CNG Stations**	**Year**
1	Pakistan	2,740,000	3,285	2010
2	Iran	1,954,925	1,574	2010
3	Argentina	1,901,116	1,878	2010
4	Brazil	1,664,847	1,725	2010
5	India	1,080,000	571	2010
6	Italy	730,000	790	2010
7	China	450,000	1,350	2009
8	Colombia	340,000	614	2010
9	Thailand	218,459	426	2010
10	Ukraine	200,000	285	2006
11	Bangladesh	193,521	546	2010
12	Bolivia	140,400	156	2010
13	Egypt	122,271	119	2009
14	United States	112,000	1,000	2010
15	Peru	103,712	137	2010
16	Armenia	101,352	297	2010
17	Russia	100,000	244	2009
18	Germany	91,500	900	2010
19	Bulgaria	60,270	81	2009
20	Uzbekistan	47,000	133	2010

CNG development in Pakistan started in the 1980s in an effort to reduce dependency on petroleum. The national Oil and Gas Regulatory Authority has regulated all CNG activities since 1992. The use of incentives enabled Pakistan to become the largest user of CNG in the world by 2008. In addition to the duty-free import of CNG kits and other CNG equipment, policy incentives have included a consumer price advantage versus gasoline of approximately 60% ensured by national fuel price controls. Almost 70% of the CNGVs are after-market conversions. Approximately 3,300 CNG stations are operational and more than 10,000 CNG conversion facilities are supporting the installation and maintenance of CNG kits and vehicles [62].

In India, several government mandates led to the development of the CNGV market. In many areas, public transportation vehicles (buses, taxis, and three-wheelers) are obligated to use CNG. The price of CNG in India is approximately 40% less than diesel fuel and more than 50% less than gasoline. (Because NG is a gas, its price is often provided in terms of a gasoline gallon equivalent.) Lower sales tax on CNG contributes to the favorable pricing (an average of 11% compared to 12% to 33% for gasoline and diesel). Concessions on import taxes for CNG kit components are also provided [62].

Most other regions of the world have also seen a significant growth in CNGV markets. After Asia, the region with the second largest CNGV market growth (2001–2010) is Latin America with 18%, followed by Africa (15%) and Europe (14%). The only region without growth was North America

(-0.1%) [61]. The more cost-sensitive markets in developing countries appear to have preferentially adopted CNG relative to more developed countries.

Besides the two successful CNG markets in Asia already discussed, it is worthwhile to consider Europe with its relatively fragmented market situation. Italy is the largest CNGV market in Europe (No. 6 worldwide) and was the first European country that attempted to develop a CNGV market (in the 1970s). All Italian CNGVs were retrofits until the mid-1990s when OEM CNGVs became available [63]. Various incentives for CNG fuel stations, retrofit conversions, and favorable CNG tax treatment have aided the market [64].

The number of CNGVs has reached this high level with the help of a very active retrofit conversion industry. There has also been a strong economic reason behind this growth. Fuel costs with CNG have been about 60% less than gasoline and 33% less than diesel. The availability of more new car models with OEM CNG options is pushing the growth of the CNGV market further [58].

In Germany, the second largest European market, CNGVs have been significantly less successful than in Italy. The market development started in the mid-1990s with the introduction of OEM CNGVs. In a few years, more than 90,000 CNGVs were present, appearing to be a good start.

This development has been pushed by two main strategic initiatives and policies from the German NG industry and government. The NG industry committed to a rapid development of the public CNG filling station network, now more than 900 locations (the most of any European country). In 1994, the German government committed to a reduced tax rate for NG as a vehicle fuel until 2009. In 2002 the German government acknowledged CNG's potential and extended the tax benefits until 2020, but did not extend the tax benefit of LPG (a competing alternative fuel) past 2009 [65].

However, in 2006 a new German government revised the expiry dates for the tax reduction to 2018 for both CNG and LPG [65]. As can be seen in *Figure 15,* this policy change directly impacted new CNGV registrations after 2006. New CNGV registrations (bi-fuel and mono-fuel) peaked in 2006–2008 at approximately 11,000 vehicles per year. In the next two years, annual CNGV sales decreased by more than 60% to 4500 vehicles. In the same time (2006–2010), registrations of LPGVs doubled from 4000 to 8000 vehicles per year, despite the fact that LPG has been more expensive than CNG on an energy basis [66]. In 2011, there were approximately 96,000 CNGVs in Germany, accounting for only 0.2 % of the German vehicle stock [66].

In December 2011, the average cost of CNG in Germany was 0.74 €/m³, or 1.03 €/kg, while gasoline cost 1.60 €/liter, diesel 1.49 €/liter, and LPG 0.73 €/liter [66]. Fuels are priced based on different units of measure and have different energy content, thus *Table 4* summarizes these fuel prices corrected to an equal energy basis of 1 liter of gasoline. On this basis, CNG was 58% lower cost than gasoline and 50% lower than diesel, but only 29% less than LPG, while LPG itself had a cost benefit of 40% versus gasoline and 30% versus diesel.

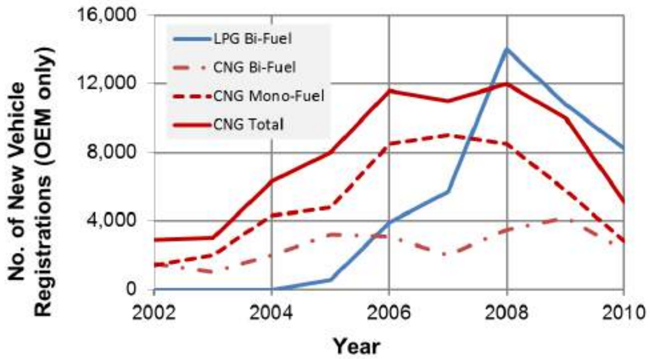

Figure 15 – New vehicle registrations of alternative fuel vehicles in Germany (excluding retrofits), 2002 to 2010 [31]

Thus LPG replaced CNG in Germany as the most-used alternative fuel despite a CNG price advantage of nearly 30% versus LPG. There are several likely reasons for this. First, CNGVs are more expensive than LPGVs due to a more expensive fuel system. For vehicles purchased from OEMs, the consumer on-cost for a CNGV is approximately € 3400 ($ 4500) relative to a gasoline version [67], whereas the on-cost for a LPGV is approximately € 2000–2500 ($ 2600–3300) per vehicle [52]. While retrofitting for CNG is difficult and is in the same cost range as OEM solutions [68], lower-quality retrofit kits for LPG can be bought and installed starting at € 700.

Table 4 – German Fuel Prices and Taxes per Energy Content of 1 Liter of Gasoline Equivalent, December 2011, *adapted from [66].*

Fuel	**Fuel quantity with energy content of liter of gasoline**	**Fuel Price, € per liter gasoline equivalent**	**Fuel Tax, € per liter gasoline equivalent**
Gasoline	1 liter	1.60	0.665
Diesel	0.92 liter	1.37	0.432
CNG	0.66 kg	0.68	0.120
LPG	1.31 liter	0.96	0.120

As shown in *Table 5* (a scenario comparing the 2008-MY Ford Focus with CNG, LPG, diesel and gasoline powertrains [69], assuming German fuel prices as of December 2010), the payback time for the CNGV is significantly higher than that of the LPG or diesel version. This calculation neglects the increased service and system inspection requirements (enforced by law) for the gaseous fuel systems, and differences in insurance and automobile taxes.

Table 5 – Payback time for CNGV, LPG, E85 and diesel vehicle on-cost in Germany based on fuel prices in Dec. 2010 *(excluding costs for maintenance, inspections, insurance, and automobile taxes).*

	Ford Focus CNG 2.0l NA 126 hp	Ford Focus LPG 2.0l NA 141 hp	Ford Focus FFV (E85) Hyphotetical* 2.0l NA 145 hp	Ford Focus Gasoline 2.0l NA 145 hp	Ford Focus Diesel 2.0l TC 136 hp
Fuel Price € / liter or kg (CNG)	1.03	0.73	1.06	1.60	1.49
Fuel Consumption (NEDC) / l/100km or kg / 100km (CNG)	5.7	9.5	9.8	7.2	5.8
Vehicle On-Cost vs. Gasoline / €	3,400	2,500	250	0	2,000
Yearly Mileage / km	**Yearly fuel costs / €**				
15,000	880.65	1,040.25	1,558.20	1,728.00	1,296.30
30,000	1,761.30	2,080.50	3,116.40	3,456.00	2,592.60
45,000	2,641.95	3,120.75	4,674.60	5,184.00	3,888.90
Yearly Mileage / km	**Yearly fuel cost benefit versus gasoline / €**				
15,000	847.35	687.75	169.80	basis	431.70
30,000	1,694.70	1,375.50	339.60	basis	863.40
45,000	2,542.05	2,063.25	509.40	basis	1,295.10
Yearly Mileage / km	**Pay Back Period / years**				
15,000	4.0	3.6	1.5	basis	4.6
30,000	2.0	1.8	0.7	basis	2.3
45,000	1.3	1.2	0.5	basis	1.5

* European E85 FFV only existing as 1.8l version (fuel consumption calculated)

For the assumptions shown, and considering the German average mileage per vehicle of less than 15,000 km/year (13,200 km/year in 2002 [70]), the payback period is estimated to be 4.0 years for the CNGV, 3.6 years for the LPGV, and 1.5 years for the E85 FFV. Diesel vehicles have a longer (4.6-year) payback, but are attractive to German drivers due to their superior drivability vs. conventional natural aspirated spark-ignited powertrains, a fully-developed fueling infrastructure and decent long-term fuel cost savings. For those drivers who focus primarily on cost, LPG is preferred to CNG, diesel, and E85 (despite the shorter payback period for E85). Consumers probably prefer LPG because few E85 stations are available and the long-term cost savings are much higher than with E85. (E85 pays back early because of the low vehicle on-cost, but is inferior in the long-term because of lesser fuel cost savings.) With aftermarket retrofit kits, used cars can be converted to LPGVs at even lower cost and would have an even shorter payback period.

In order for CNGVs to gain the same payback time as an OEM-built LPGV in the cost scenario above, the CNG price would need to decrease from 1.03 €/liter to 0.92 €/liter, which would result in an energy-corrected CNG cost of 0.61 €/liter gasoline-equivalent, or a fuel cost benefit of 62% versus gasoline. A second possibility would be to reduce the CNGV on-cost (€ 3400) by approximately 10% (to € 3000) to compete with OEM-built LPGVs, or by approximately 60% (to € 1300) to compete with aftermarket retrofit LPG conversions, which is unlikely to be feasible.

Another important factor for the relatively low CNGV penetration in Germany is the greater initial cost for filling stations to provide CNG versus LPG and the resulting effect on infrastructure development. The equipment costs for CNG stations are reported to be 10–15 times greater than for LPG stations (approx. € 200,000–350,000 for CNG [71] versus € 20,000–25,000 for LPG). The lower investment cost for LPG stations together with the shorter consumer payback period for LPGVs has led to a considerable increase in the number of LPG stations since 2005, while the number of CNG stations has only increased slightly *(Figure 14*). While in 2004 there were approximately the same number of CNG stations and LPG stations in Germany (about 500 each), by March 2012 there were approximately seven times as many LPG stations (6500) as CNG stations (900). Of the total number of German filling stations in March 2012, 44% sold LPG whereas only 6% sold CNG.

Finally, given the greater costs associated with vehicle and filling station conversions relative to LPG, CNG can only become a significant automotive fuel if it is priced more favorably with respect to LPG. As the German market has demonstrated, it is difficult to develop multiple alternative fuel markets at the same time.

<u>Lessons learned:</u>

- Due to the high conversion costs of CNGVs and the slowly growing fuel station infrastructure (due to high infrastructure investment costs), CNG as a fuel appears to require an energy-based cost benefit versus gasoline on the order of 50–70 % to develop a significantly growing CNG market (examples: Pakistan, India, Germany).
- Cost-efficient retrofit conversion possibilities for existing vehicles as well as cost-efficient OEM-built CNGVs may help to develop the market (examples: Pakistan, India, Italy) but cannot guarantee it.
- The LDV fuel market is very cost sensitive. Consumers will choose the fuel that offers the lowest total cost over the first few years of vehicle ownership.
- Fuel cost benefits and operational cost benefits must be reliable in the long term; otherwise, consumers are likely to avoid the alternative fuel (e.g., Germany).
- Simultaneous development of multiple alternative fuel markets can be difficult. An effective future fuel strategy needs to consider the impact of competition between alternative fuels (e.g., Germany) as well as with the existing conventional fuels.

2.7 SUMMARY OF LESSONS LEARNED–ALTERNATIVE FUELS AND INTRODUCTION STRATEGY

From the observations in the preceding sections, some basic requirements can be derived for future alternative fuels that allow for development of a significant market:

1. **Affordability and cost competitiveness** is the most important factor to attract potential consumers to an alternative fuel and vehicle technology. The vehicle and

fuel costs need to be competitive with alternatives. The consumer must have a reasonable chance to recover the vehicle on-cost and to considerably save on operational costs over the first few years.

For FFVs, with low consumer on-cost and moderate E85 infrastructure costs, an energy-based fuel cost benefit of at least 5 % seems to be required.

For OEM-built LPGVs, with a greater consumer on-cost (approx. € 2000–2500 [US $ 2600–3300]) and moderate LPG infrastructure costs, a reliable fuel cost benefit of at least 40 % versus gasoline has been sufficient.

For CNGVs, with a greater consumer on-cost (approx. € 3500 [US $ 4500]) and high CNG infrastructure costs, a reliable fuel cost benefit of 50–70 % has been sufficient to develop its market (e.g., Pakistan, India).

For any alternative fuel, it is important that the cost benefit be reliable and stable in the long-term (e.g., FFVs in Germany and Brazil). Fuel prices need to remain competitive even if fuel demand rises with the successful development of that market (e.g., FFVs in Brazil). Sufficient feedstock and fuel production capacity is required.

Governmental actions are typically necessary to facilitate development of the alternative fuel market, particularly if its price is not consistently attractive relative to competing fuels. When an artificially-stimulated and tax-incentived fuel market grows too much, the lost tax revenue may spur the government to reduce the incentives, which can lead to reversal of the market success (e.g., B100 in Germany). Thus, ideally for a large-scale introduction of an alternative fuel, the fuel should be cost-efficient in the long-term and its price resilient to relaxation of subsidies.

2. **Backwards-compatibility of vehicles** is very beneficial for the successful development of an alternative fuel market (e.g., B100 in Germany). If the vehicle fleet is backwards-compatible, a fuel cost benefit in the range of 5–15 % versus the established fuel seems to be sufficient (e.g., B100 Germany).

   Alternative fuel can also be blended into existing fossil fuels if the existing vehicle fleet is compatible. Even if only a small percentage of the existing vehicle stock is not compatible with the alternative fuel blend, then vehicle compatibility lists must be issued and protection grade fuels must be retained for incompatible vehicles, which can be a politically very complicated process (e.g., E10 in Germany).

3. **Affordable distribution infrastructure** is another important factor for the development of an alternative fuel market (e.g., CNGV and LPG in Europe). High infrastructure investment costs will lead to slow growth in fuel station numbers. A sufficient supply network is required for consumer acceptance and significant use of that fuel (e.g., E85 in Sweden). If the supply network is insufficient, then cost-effective bi-fuel or flex-fuel capability in vehicles can compensate.

4. **Vehicle capability for two fuels (bi-fuel vehicle, mono-fuel vehicle, or FFV)** overcomes issues associated with an alternative fuel that is not backwards-compatible to the vehicle fleet and/or supported by a sufficient supply infrastructure (e.g., B100 in Germany, LPG/CNG in Europe). Capability for two fuels provides consumers with confidence in the ability to refuel even if the alternative fuel is unavailable and with certainty for avoiding uncompetitive fuel pricing if the fuel cost benefits are inconsistent. For example, in the Brazilian E100 introduction, dedicated-fuel vehicles eventually failed while FFVs have become successful. Lower vehicle on-cost for the second-fuel capability provides earlier payback for the additional fuel system installation and improves market success. Capability for two fuels does not necessarily mean that the powertrains are still optimized for gasoline and do not exploit the potential of some alternative fuels (e.g. high octane of ethanol or methane). A bi-fuel vehicle can be optimized to the alternative fuel and in certain situations would provide degraded functionality in the gasoline operation mode. Some mono-fuel applications on the market are already optimized for the alternative fuel [72].

5. **Retrofit kits can** significantly help to develop an alternative fuel market (e.g., LPG in Europe; CNG in Italy, Pakistan, India), because they allow the conversion of used vehicles already in the fleet. The conversion of used vehicles is particularly attractive in cost-sensitive markets, as most alternative fuels markets are, since operational cost is the main reason for these conversions. Retrofit kits are often available at much lower cost than OEM solutions (e.g., LPG in Europe), but these are usually “OEM uncontrolled” and of lower quality and with fewer upgraded components than the OEM systems. For example, OEMs typically upgrade the valves and valve seat inserts of their engines for CNGV, LPGV, and FFV applications, whereas retrofit kits usually do not contain these relatively expensive upgrades. Therefore, engines with these retrofit conversions can have reduced durability, since the poorer lubricity of gaseous and alcohol fuels can lead to increased valve seat wear. Therefore the supporting effect of aftermarket vehicle conversion with retrofit kits should be carefully considered by OEMs in any introduction strategy for an alternative fuel.

6. **Sufficient fuel energy density** is important, since the fuel storage capacity in passenger cars is limited. Long travel range of a vehicle is a consumer demand and is not readily compromised. Also, many consumers are aware of their volumetric fuel economy and are dissatisfied when it is reduced by the fuel, especially when the fuel price has not been discounted appropriately. Most alternative fuels reduce the vehicle range (or reduce the available interior

space with greater fuel storage) in comparison to gasoline and diesel. This is particularly an issue for gaseous fuels, but even more for battery electric vehicles (BEVs).

7. **Acceptable fuel fill time** is also important, as consumers have become accustomed to filling their vehicles with gasoline or diesel within a few minutes. Increasing the filling time to hours (as for BEVs) is a strong source of dissatisfaction. Therefore a compromise in filling time needs to be adequately balanced by other positive attributes.

8. **Sustainability** attributes of the fuel and vehicle should be maximized from a WTW perspective, considering the production and use phases and end-of-life disposition. In addition to GHG emissions, all other tailpipe emissions should be minimized and need to meet applicable regulatory limits. Fuels that enable reduced tailpipe emissions are more likely to be supported. Other factors that should be considered include land use, energy use, water use, strategic materials, and social issues. Future fuel strategies should ideally have an endpoint that includes a sustainable, non-fossil, renewable fuel.

9. **Incentives for sustainable alternative fuels** are initially required if they have higher production and/or distribution costs than gasoline/diesel (after tax) in order to be affordable and cost-competitive. Although continuation of increasing oil prices in the future would make alternative fuels more attractive, some stimulus is usually required for development of the distribution infrastructure. Truly sustainable (non-fossil, renewable, and GHG-reducing) fuels are typically more expensive than gasoline/diesel fuels [71]. Therefore incentives will most likely be required to bring these fuels into the market. Governments may also support their long-term cost-competitiveness through differing policy treatment that accounts for differences in perceived external costs (e.g., climate impact). Governments pursuing climate-friendly policies are unlikely to support unsustainable fuels in the long term.

10. **Scale:** For any fuel, there must be enough feedstock available (at a cost allowing a competitive fuel price) to develop and sustain the market in the long term. If not, the eventual feedstock scarcity will result in demand exceeding supply, and will cause fuel price increases. If the market relies on dedicated-fuel vehicles, this can lead to collapse of the market for that vehicle (e.g., E100 vehicles in Brazil). If there is fuel flexibility, then the sales of the fuel will drop until demand is in balance with supply (e.g., B100 in Germany). The future fuel supply needs to be scalable with future demand when the market develops successfully.

3. POSSIBLE FUTURE SCENARIOS

Considering the above requirements for alternative future fuels, two requirements are essential for long-term sustainability. There should be a future source of the fuel that is non-fossil and renewable and that is eventually cost-competitive even in large volumes without compromising basic societal resource needs (food, water, etc.).

Future fuel prices are difficult to project, however some trends are evident. In 2011, the International Energy Agency (IEA) Renewable Energy Division provided scenarios of future prices of fossil and renewable fuel under different fuel price assumptions [73]. In the long term (2050), two fuels were projected to be less expensive (pre-tax) than gasoline in both scenarios: methane and ethanol. Methane can be used as automotive fuel in CNGVs in any blend up to 100%. Ethanol can be used as a blend component with gasoline in fairly limited concentrations in conventional vehicles, but at higher concentrations in FFVs. Possible development scenarios for these two alternative fuels are discussed in the following section.

3.1 ETHANOL SCENARIO

In the future, higher ethanol volumes are expected in the US fuel pool, driven in the short term by RFS2 [15,22]. In the EU, the Renewable Energy Directive and policies by some member states are expected to result in greater ethanol use than at present. In the long term, greater ethanol volumes may be available due to advances and cost reductions in cellulosic ethanol production, gains in feedstock yields and overall production, policy mechanisms, and/or high oil prices.

An attractive opportunity provided by increasing ethanol availability is to increase the octane rating of regular-grade gasoline [15]. The octane rating of the fuel that will be used in an engine determines the limits to which the engine can be designed and operated to extract useful work out of the fuel, without leading to engine knock. The major automakers design around the most heavily used fuel, typically the regular grade (i.e., lowest octane rating). If minimum octane ratings for regular gasoline were increased, engines in future vehicles would be designed for greater efficiency through higher compression ratios and/or turbocharging and downsizing. Vehicles already on the road would benefit through a reduced need for spark retard and enrichment [15].

Ethanol could enable such a change. Ethanol has higher octane ratings than typical petroleum refinery streams used to make gasoline. Despite this, the E10 on the US market today just meets the minimum octane ratings for regular gasoline because the refining and blending industry adds the ethanol to a gasoline blendstock for oxygenate blending (BOB) that has considerably lower octane ratings [15], thereby reducing production costs. An alternative scenario, as shown in *Figure 16*, would be to increase octane ratings in concert with ethanol addition, particularly for ethanol above the current E10 level. The anti-knock quality of such blends is also effectively increased due to the greater heat of vaporization of ethanol, particularly when used in direct injection engines. Both of these properties would enable the engine design modifications and engine operation adjustments described above, leading to greater efficiency across the entire vehicle fleet.

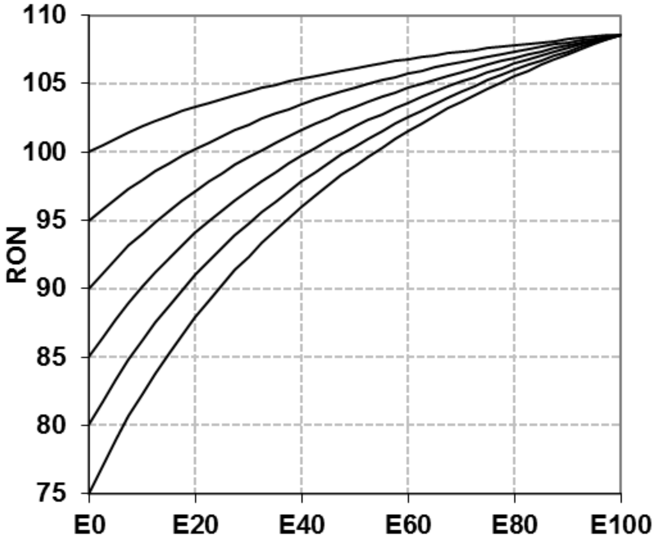

Figure 16 – Estimated Research Octane Number (RON) values for ethanol-gasoline blends with contour lines of constant blendstock RON. *Based on approach in [74].*

Such a change would of course involve challenges [15], including how to accomplish the transition of the gasoline supply from E10 as the primary blend level to one with higher ethanol content. Today's US filling stations and vehicles (designed around E10 as the maximum ethanol content) would need to be gradually replaced with a significant number that were compatible with the higher blend. Likewise, time would be required for the ethanol supply chain to grow to where it has proven that it could reliably produce the ethanol volumes needed to supply the higher blend level. Meanwhile, specifications for the new fuel (most critically the ethanol content range and minimum octane rating) would need to be agreed upon to ensure that fuel suppliers and vehicle manufacturers are working around a common set of fuel properties. Once those first transition requirements were met, then roll-out of the new fuel could begin. After sufficient amounts of the new fuel were available in the marketplace, automakers could start to provide advanced vehicles that were optimized (dedicated) for the new fuel.

FFVs could play an important role in this scenario by providing a means to bridge the fuel supply transition (i.e., while the ethanol industry was ramping up production, but before the ethanol blend level could be increased in the general gasoline pool.) The additional ethanol could be consumed as high-level blends (e.g., E85) by the many FFVs already present in the US and new FFVs that will be produced in the future. FFVs would also be compatible with possible future intermediate ethanol-content blends. FFVs could become particularly desirable to consumers if higher ethanol blend fuels are attractively priced.

As a long-term strategy, use of E85 in FFVs would provide a lesser benefit than blending ethanol across the fuel pool and increasing its minimum octane rating. There are a few reasons for this. First, as shown in *Figure 16*, ethanol provides a greater incremental octane enhancement when blended at low concentrations (in all gasoline) than at high concentrations (in a proportionally smaller E85 volume). Second, although E85 has a high octane rating, FFVs as designed today would not greatly benefit from it. If new FFVs were optimized for E85, they would not provide competitive performance when using lower-octane E0-E10 gasoline (e.g., considerable decreases in power and torque) and thus would be inferior to non-optimized vehicles when driven with the more widely-available E10 fuel. Therefore such vehicles would not be purchased by sufficient numbers of consumers, particularly if E85 is not reliably cost-competitive and widely available.

3.2 METHANE SCENARIO

Although NG is very abundant and attractively priced at present, it originates from fossil sources and is thus not renewable or sustainable in the long-term. However, NG could be replaced in the future by sustainable sources of methane with minimal, if any, changes to the existing NG distribution system or users. Bio-methane or biogas is produced from the anaerobic microbial digestion of biomass, including municipal waste, sewage, animal manure, plant residues, and also crops (e.g., corn). Methane can also be produced directly from CO_2 and H_2 by methanation, using CO_2 (e.g., extracted from flue gas) and H_2 obtained from water via electrolysis using renewable electricity such as solar or wind power. Methane from this potential production pathway is sometimes called “Wind-Methane” or “E-Gas” [75,76,77]. Here, the term “e-methane” will be used to describe methane derived using renewable electricity sources.

CNG vehicles and the NG distribution system are fully compatible with e-methane and post-processed bio-methane (dried and cleaned) to meet appropriate requirements (e.g., German DIN 51624 standard [78]). Unlike ethanol blending in gasoline, properly treated bio-methane and e-methane can be blended at any concentration into NG. Therefore, “CNG vehicles” could instead be considered “compressed methane vehicles” and all methane production pathways can be considered.

NG itself is considered an attractive alternative transportation fuel capable of providing long-term energy security, as it is available worldwide [56] with reserves that are 150 times current annual global consumption [57] and is available at low cost. Bio-methane and e-methane can be considered long-term alternatives that could provide both energy security and sustainability. For example, in the UK the main feedstocks for bio-methane are agricultural manure and food wastes. The UK generates 30 million dry tonnes of these waste materials annually, capable of producing 6.3 million tonnes of oil equivalent as methane gas, or equivalent to 16% of UK transport fuel demand [79].

Sustainability includes many other factors, including cost, GHG emissions, land use, water use, competition with food supply, etc. Bio-methane is particularly attractive because much of it today is produced from a low- or zero-value feedstock that requires disposal (sewage, manure, plant waste). Scaling up bio-methane production is possible but will be more challenging because it would require more valuable feedstocks (energy crops) that have other potential uses, including other biofuel options. E-methane is an intriguing possible source of renewable methane, though its production at scale and economic viability are yet to be demonstrated. If successful, there would also be demand for renewable methane in other sectors that currently use NG including electricity generation, industrial uses, and heating.

NG presently offers a 20–30% TTW CO_2 reduction potential due to its favorable hydrogen-to-carbon ratio and efficiency potential because of its high knock resistance [45,80]. According to a joint CONCAWE-EUCAR-JRC study [81], fossil CNG used in CNGVs today offer a 24% well-to-wheel (WTW) CO_2 emissions reduction versus gasoline. With bio-methane or e-methane close to 100% fossil CO_2 reduction would be possible.

As already discussed, NG is consistently less expensive than gasoline and diesel (on an energy basis) in many countries. NG is likely able to pay back vehicle on-costs in a reasonable time. With an expanding infrastructure and rising vehicle numbers, the positive effects of scale will drive costs down. NG could therefore support the development of a methane infrastructure and CNGV fleet. According to recent IEA fuel price scenarios [73], bio-methane is assumed to become cost competitive with oil in the next few decades however the potential scale of future production and the fraction that would be used in the transportation sector are unclear.

Renewable wind and solar power are likely to grow significantly in some countries (e.g., in Germany where nuclear power generation has come into disfavor). The intermittency of wind and solar power has been cited as a limitation, and suggests the need for large-scale energy storage to fully utilize their potential. One proposal is to convert excess solar and wind power to e-methane with storage in vast, already existing, underground cavities [75]. With growing renewable power sources, e-methane could become available in scale in the long-term.

As of 2010, there were 12.7 million CNGVs in the world and more than 18,000 CNG filling stations, both growing at a rate of 10% or more annually. Dedicated-fuel CNGVs with better efficiency (NG-optimized engines and less vehicle weight), reduced package restrictions (elimination of gasoline fuel system), and lower on-cost would be enabled with the availability of a mature infrastructure. The factors above suggest that methane may become a more important automotive fuel in the future.

A successful introduction strategy would initially require a stable, reliable, predictable and sufficient fuel cost benefit for NG harmonized ideally over continents. In the long-term more sustainable methane (bio-methane, e-methane, or other) may become available and could be blended with fossil methane.

4. SUMMARY/CONCLUSIONS

Based on the analysis of several case studies of alternative fuel introductions, the basic requirements for alternative fuels, vehicles, and the fueling infrastructure are postulated that are necessary for successful market implementation.

To successfully introduce a new fuel into the market it is critical that both the fuel and vehicle technology are **affordable and cost-competitive**. The consumer must have a very good chance of recovering the vehicle on-cost and to realize considerable operational cost savings over the first few years. The fuel cost benefit must be reliable and stable in the long term, even if fuel demand rises with the successful development of that market. Thus sufficient feedstock and fuel production capacity must be available for large-scale introduction.

A precondition for a successful new fuel introduction is the existence of **backwards-compatible vehicles** in the market, which can use a cost-efficient fuel without any vehicle changes. If backwards compatibility is not possible, alternative fuels can also be blended into existing fossil fuels at a blend content that is compatible with the existing vehicle fleet which, depending on the fuel, can be very limited. If even a small fraction of the existing vehicle stock is not compatible with the alternative fuel blend, then vehicle compatibility lists must be issued and protection grade fuels must be retained for incompatible vehicles, which can be a politically very challenging process.

An **affordable distribution infrastructure** is another important factor for the development of an alternative fuel market. High infrastructure investment costs will lead to slow growth in fuel station numbers. A sufficient supply network is required for consumer acceptance of the fuel; otherwise the use will be limited to captive vehicle fleets at best. If the supply network is insufficient, then vehicle bi-fuel or flex-fuel capability can compensate. In that case, the vehicle on-cost needs to be relatively low because of the limited refuelling opportunities that provide the offsetting lower operational (fuel) costs.

The **vehicle capability for two fuels (bi-fuel vehicle, mono-fuel vehicle, or FFV)** is critical to the success of any alternative fuel that is not backwards-compatible to the vehicle fleet and/or supported by a sufficient supply infrastructure. This capability also provides consumers with confidence in buying the alternative fuel vehicle if the fuel cost benefits are inconsistent. To bring bi-fuel capable vehicles into the market, **OEM-controlled retrofit kits** could be of significantly help, because they allow the conversion of used vehicles already in the fleet (particularly attractive in cost-sensitive markets). However, the use of retrofit kits should be carefully considered in terms of their impact on vehicle durability and vehicle quality.

Incentives for sustainable alternative fuels are initially required for fuels with higher production and distribution costs than gasoline/diesel to develop the market. Long-term alternative fuel strategies should have an endpoint that includes a non-fossil, sustainable, and cost-effective renewable fuel, recognizing that the cost competitiveness of the alternative fuel could be influenced by differing policy treatment to account for differences in perceived external costs.

In the long term (2050), two sustainable gasoline substitutes have been suggested as becoming less expensive (pre-tax) than gasoline: renewable methane and ethanol. While ethanol can be used as a blend component with gasoline in nearly any concentration in FFVs, any kind of methane (NG, bio-methane, e-methane) can be used in CNGVs.

For the development of future ethanol markets, the availability of FFVs in the vehicle fleet (already significant in the US) is important. To achieve the maximum benefit from greater future ethanol availability, the ethanol could eventually be blended across the entire gasoline pool and would enable increases in minimum octane ratings. If not, considerable efficiency and fuel savings potential may be lost. The existence of a large FFV fleet provides time to transition the rest of the fleet to compatibility with those future blends.

For the development of future “compressed methane vehicles,” inexpensive CNG can be used to stimulate infrastructure development and market penetration with bi-fuel and mono-fuel CNGVs. Once the infrastructure is built up and a sufficient number of CNGVs are in the fleet, future availability of cost-competitive bio-methane and e-methane could be readily transitioned into the fuel market.

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6. ABBREVIATIONS

BEV	Battery Electric Vehicle
CNG	Compressed Natural Gas
CNGV	CNG Vehicle
ECU	Engine Control Unit
ETBE	Ethyl Tertiary Butyl Ether
FAME	Fatty Acid Methyl Esters (Biodiesel)
FFV	Flexible Fuel Vehicle
GHG	Greenhouse Gas
LPG	Liquefied Petroleum Gas
LPGV	LPG Vehicle
MTBE	Methyl Tertiary Butyl Ether
NG	Natural Gas
OEM	Original Equipment Manufacturer
TTW	Tank to Wheel
WTT	Well to Tank
WTW	Well to Wheel

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8. REFERENCES

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[1] Kauling, D.C. “US Light Vehicle Development Gaps – Current and Future Technology”, Natural Gas Vehicle Technology Forum, San Francisco, California, October 25-26, 2011.

[2] Agência Nacional do Petróleo**,** Gás Natural e Biocombustíveis (ANP, Brazil National Agency of Petroleum). Resolução ANP No. 7, 2011.

[3] Nass, L.L., Pereira, P.A.A. Ellis, D. (2007) “Biofuels in Brazil: An Overview”, *Crop Science* **47**: 2228-2237.

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[4] Soccol, C.R., Vandenberghe, L.P.S., Costa, B., Woiciechowski, A.L., de Carvalho, J.C., Medeiros, A.B.P., Francisco, A.M., Bonomi, L.J. (2005) “Brazilian biofuel program: An overview”, *Journal of Scientific & Industrial Research* **64**: 897-904.

[5] de Freitas, L.C., Kaneko, S. (2011) “Ethanol demand in Brazil: Regional approach”, *Energy Policy* **39**(5): 2289-2298.

[6] Assoiação Nacional dos Fabricantes de Veiculos Automotores (ANFAVEA) (2010) “Brazilian Automotive Industry Yearbook 2010”.

[7] Empresa de Pesquisa Energética (EPE) (2011) “Capítulo 3 (Consumo de Energia por Setor) 1970-2010“, Ministério de Minas e Energia, https://ben.epe.gov.br/BENSeriesCompletas.aspx, accessed April 4, 2012.

[8] Nichols, R.J. (2003) “The Methanol Story: A Sustainable Fuel for the Future”, *Journal of Scientific & Industrial Research* **62**: 97-105.

[9] Alternative Fuels and Advanced Vehicles Data Center. “Key Federal Legislation”, US Department of Energy (DOE), http://www.afdc.energy.gov/afdc/laws/key_legislation#top, accessed March 16, 2012.

[10] Kramer, U., Ford Werke GmbH, “Ford Flexifuel-Fahrzeuge”, CTI-Conference Bio Fuels, Munich, Germany, June 26–27, 2007.

[11] Kramer, U., Ford Werke GmbH, “Ford Flexi-Fuel-Fahrzeug – ökonomische CO2-Reduzierung”, VDI-GVC- Specialist Committee Meeting “High Temperature Technology” and “Bio Fuels”, Würzburg, Germany, March 2006.

[12] Standardiserings-Kommissionen i Sverige (SS), “Automotive fuels – Ethanol E85 – Requirements and Test Methods”, SS 155480, July 2006.

[13] Deutsches Institut für Normung e.V. (DIN), “Automotive fuels – Ethanol Fuel – Requirements and Test Methods”, DIN 51625, Aug. 2008.

[14] ASTM International, “Standard Specification for Ethanol Fuel Blends for Flexible-Fuel Automotive Spark-Ignition Engines”, ASTM D 5798-11, Rev. 2011.

[15] Anderson, J.E., DiCicco, D.M., Ginder, J.M., Kramer, U., Leone, T., Raney-Pablo, H.E., Wallington, T.J. (2012) “High Octane Number Ethanol-Gasoline Blends: Quantifying the Potential Benefits in the United States”, *Fuel* in press, doi:10.1016/j.fuel.2012.03.017.

[16] R. L. Polk & Co. database, accessed March 25, 2012.

[17] Davis, S.C., Diegel, S.W., Boundy, R.G. “Transportation Energy Data Book: Edition 30”, Center for Transportation Analysis, Oak Ridge National Laboratory, Report ORNL-6986, June 2011.

[18] Energy Information Agency (EIA). “Monthly Energy Review”, US DOE, DOE/EIA-0035(2012/02), February 2012.

[19] Alternative Fuels and Advanced Vehicles Data Center. “Alternative Fueling Station Total Counts by State and Fuel Type”, US DOE, http://www.afdc.energy.gov/afdc/fuels/stations_counts.html, accessed March 16, 2012.

[20] Alternative Fuels and Advanced Vehicles Data Center. “U.S. Alternative Fueling Station Count”, US DOE, http://www.afdc.energy.gov/afdc/data/docs/alt_fueling_stations_fuel.xls, accessed March 16, 2012.

[21] ASTM International, “Standard Specification for Fuel Ethanol (Ed70-Ed85) for Automotive Spark-Ignition Engines”, ASTM D 5798-10a, Rev. 2010.

[22] Anderson, J.E., Baker, R.E., Wallington, T.J., Ginder, J.M. (2009) “Implications of the 2007 Energy Independence and Security Act for the US Light-Duty Vehicle Fleet”, SAE Technical Paper 2009-01-2770.

[23] Alternative Fuels & Advanced Vehicles Data Center. “Clean Cities Fuel Survey Report”, May 2000–January 2012 reports, US DOE, http://www.afdc.energy.gov/afdc/price_report.html

[24] McPhail, L., Westcott, P., Lutman, H. “The Renewable Identification Number System and U.S. Biofuel Mandates,” Economic Research Service, US Department of Agriculture, Report BIO-03, November 2011.

[25] Birath, K. “Joint Procurement of Clean Vehicles”, Policy Notes, NICHES Consortium, undated, http://www.niches-transport.org/fileadmin/archive/Deliverables/D4.3b_5.8_b_PolicyNotes/14686_pn11_joint_procurement_ok_low.pdf

[26] Kroh, E. (2008) “FFVs flourish in Sweden”, *Ethanol Producer Magazine*, August 2008.

[27] BioEthanol for Sustainable Transport (BEST), “Promoting Clean Cars: Case Study of Stockholm and Sweden”, BEST Deliverable No 5.12, Stockholm, February 2009.

[28] Campestrini, M., Mock, P. “European Vehicle Market Statistics”, 2011 Edition, International Council on Clean Transportation, Washington, DC, 2011.

[29] European Automobile Manufacturers’ Association (ACEA). “Overview of CO2 based motor vehicle taxes in the EU”, April 28, 2009, http://www.acea.be/images/uploads/files/20090428_CO2_taxation_overview.pdf.

[30] Svenska Petroleum och Biodrivmedel Institutet. “Statistik”, http://spbi.se/statistik, accessed April 4, 2012.

[31] Thordsen, F., Buckle, C. “Fachartikel: Emissionen und Kraftstoffe”, Kraftfahrt-Bundesamt, Germany, March 15, 2011. http://www.kbashop.de/wcsstore/KBA/pdf/Fachartikel_Emissionen_Kraftstoffe.pdf

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[32] Fachagentur Nachwachsende Rohstoffe e.V. (FNR). “Bioethanol” Gülzow, Germany, http://www.bio-kraftstoffe.info/kraftstoffe/bioethanol/, accessed 25.March 2012

[33] Mineralölwirtschaftsverband e.V. (Association of the German Petroleum Industry), “Statistiken – Preise”, Berlin, http://www.mwv.de/index.php/daten/statistikenpreise/, accessed March 25, 2012.

[34] Fachagentur Nachwachsende Rohstoffe e.V. (FNR), “Daten und Fakten über Biokraftstoffe”, Gülzow, Germany, http://www.bio-kraftstoffe.info/daten-und-fakten/, accessed March 25, 2012.

[35] Bayerisch Landwirtschaftliches Wochenblatt , April 23, 2009, www.wochenblatt-dlv.de

[36] Ethanol-tanken.com, “Tankstellen”, http://www.ethanol-tanken.com, accessed March 25, 2012.

[37] Aral Aktiengesellschaft, “Grafiken”, http://www.aral.de/aral/browsebytheme.do?categoryId=4001141&contentId=51281, accessed April 9, 2012.

[38] Baumeister, S., Ford Werke GmbH, “Herausforderung beim Aufbau einer Ethanol-Tankstelleninfrastruktur in Deutschland”, VDI Fachausschuss Sitzung Biokraftstoffe, Würzburg, Germany, March 2007.

[39] Deutsches Institut für Normung e.V. (DIN), “Automotive Fuels – Requirements and Test Methods – Part 1: Petrol E10”, E DIN 51626-1, April 2009.

[40] Verband der Automobilindustrie (VDA, Association of German Automobile Manufacturers), personal communication, 2011.

[41] Bockey, D. (2006) “Biodiesel und pflanzliche Öle als Kraftstoffe aus der Nische in den Kraftstoffmarkt; Stand und Entwicklungsperspektiven”, *Technikfolgenabschätzung - Theorie und Praxis*, **15**(1):10-15.

[42] Bockey, D., von Schenk, W. “Status Report Biodiesel: Biodiesel Production and Marketing in Germany 2005”, Union zur Förderung von Oel- und Proteinpflanzen e. V. (UFOP), June 2005.

[43] Verband der Deutsche Biokraftstoffindustrie (VDB), “Informationen: Biokrafstoffe in Deutschland”, January 2012, http://www.energiewende-sta.de/wp-content/uploads/2012/02/Factsheet_Biokraftstoffe_VDB.pdf

[44] Comite Europeen de Normalisation, “Automotive Fuels – Diesel – Requirements and Test Methods”, EN 590, February 2010.

[45] Wiedemann, H. K. “Carbondioxyd emissions of passenger cars powered by gas with national type approval or EC Whole Vehicle Type approval”, TÜV Saarland (Germany), March 2005, http://www.bmu.de/files/na/application/pdf/fluessiggas_kohlenstoffdixydemissionen.pdf

[46] International Fuel Quality Center (IFQC), “Special Report EU: LPG and CNG Developments”, February 7, 2011, www.ifqc.org

[47] Organization of Economic Co-Operation and Development (OECD), “Economic Assessment of Biofuel Support Policies”, Directorate for Trade and Agriculture, 2008.

[48] Kraftfahrt Bundesamt (KBA), “Statistiken; Fahrzeuge”, http://www.kba.de/cln_030/nn_124584/DE/Statistik/Fahrzeuge/fahrzeuge__node.html, accessed April 1, 2012.

[49] Bohn, K., CNG-Technik GmbH (Ford Werke GmbH),

“CNG und/oder LPG?”, Conference Gas Poweres Vehicles, FKFS, Stuttgart, October 13, 2009.

[50] Prins Alternative Fuel Systems, “VSI LPG Vapour Sequential Injection”, product information sheet, Eindhoven, Netherlands, 2010.

[51] LPG & CNG Tankstellenverzeichnis, www.gas-tankstellen.de, accessed March 2012.

[52] Ford Motor Company, “Ford Focus Preisliste A”, Germany, February 21, 2012, http://www.ford.de/Pkw-Modelle/FordFocus/Broschueren_Preise_Daten

[53] Ford Motor Company, “Ford Fiesta Preisliste A”, Germany, February 21, 2012, http://www.ford.de/Pkw-Modelle/AlternativeAntriebe/Autogas_LPG

[54] Mantey, C.A., Mezzarano, A., Kolkemo, A. (2009) “Exhaust Valve & Valve Seat Insert – Development for an Industrial LPG Application”, SAE Technical Paper 2009-01-1602.

[55] Sato, K., Midorikawa, T., Takahashi, T., Oshige, H. (2000) “Development of Valve Seat Material for Gas-Fueled Engines”, SAE Technical Paper 2000-01-0911.

[56] International Energy Agency (IEA), “World Energy Outlook 2011 Special Report: Are We Entering a Golden Age of Gas?”, Paris, France, 2011.

[57] Massachusetts Institute of Technology Energy Initiative, “The Future of Natural Gas: An Interdisciplinary MIT Study, Interim Report”, 2010.

[58] Natural Gas Vehicle Association (NGVA) Europe, “NGV Market Growth in Europe (1995-2010)”, http://www.ngvaeurope.eu/ngv-market-growth-in-europe-1995-2010, accessed March 2012.

[59] Deutsches Institut für Normung e.V. (DIN), “Automotive Fuels – Compressed Natural Gas – Requirements and Test Methods”, DIN 51624, February 2008.

[60] Prins Alternative Fuel Systems, “VSI CNG Vapour Sequential Injection”, product information sheet, Eindhoven, Netherlands, 2010.

---

[61] International Association for Natural Gas Vehicles (NGV Global), “Natural Gas Vehicle Statistics”, http://www.iangv.org/tools-resources/statistics.html, accessed March 2012.

[62] Special Report: “Asia Pacific: Regional Overview of NGVs”; IFQC; www.ifqc.org, January 7, 2012

[63] Natural & bio Gas Vehicle Association (NGVA Europe), “NGV Market Growth in Italy (1973-2008)”, http://www.ngvaeurope.eu/ngv-market-growth-in-italy-1973-2008; accessed March 2012.

[64] Natural & bio Gas Vehicle Association (NGVA Europe), “Italy”, http://www.ngvaeurope.eu/italy, accessed March 2012.

[65] Vest Marketing GmbH, “Besteuerung von Erdgasfahrzeugen”, Osnabrück, Germany, http://www.gas24.de/cms/26-0-steuern-erdgas.html, accessed March 16, 2012.

[66] Natural Gas Vehicle Association (NGVA) Europe, “European NGV Statistics”, http://www.ngvaeurope.eu/european-ngv-statistics, accessed April 4, 2012.

[67] Ford Werke GmbH, Germany, Price List Ford C-MAX CNG, August 4, 2008.

[68] Vest Marketing GmbH, “Kosten einer Nachrüstung”, Osnabrück, Germany, http://www.gas24.de/cms/91-0-kosten-einer-nachruestung.html, accessed March 16, 2012.

[69] Auto Test Magazine, “Mit neuer Energie in die Zukunft”, August 2010.

[70] Hautzinger, H., Stock, W., Mayer, K., Schmidt, J., Heidemann, D. (2005) “Fahrleistungserhebung 2002 - Begleitung und Auswertung, Band 1: Inländerfahrleistung 2002”; BASt Report V 120; Institut für angewandte Verkehrs- und Tourismusforschung (IVT), Heilbronn/Mannheim, Germany.

[71] German Society for Sustainable Biogas and Bioenergy Utilization (GERBIO), “Nationaler Bericht über die Situation des Erdgastankstellennetzes – Deutschland”, Report No. WP3.1, Kirchberg, Germany, undated.

[72] Jauss, A., GM Europe Engineering, “Exkurs CNG & Biomethane - State of the art and outlook”; 2nd CTI-Conference Bio-Fuels for Combustion Engines”, Mannheim, Germany, 2008.

[73] International Energy Agency (IEA), “Technology Roadmap: Biofuels for Transport”, Paris, France, 2011.

[74] Anderson, J.E., Kramer, U., Mueller, S.A., Wallington, T.J. (2010) “Octane Numbers of Ethanol- and Methanol-Gasoline Blends Estimated from Molar Concentrations”, *Energy & Fuels*, **24**:6576-6585.

[75] Rieke, S., SolarFuelGmbH, “The storage of renewable electricity in gas tanks as fuel–a new approach for sustainable use of NGV technology”, 5th Conference on Gas Powered Vehicles, Berlin, October 1, 2010.

[76] Specht, M., Zuberbühler, U., ZSW–Center for Solar Energy and Hydrogen Research, “Storing Renewable Energy in the Natural Gas Grid–Methane via Power-to-Gas (P2G): A Renewable Fuel for Mobility”, 6th Conference on Gas Powered Vehicles, Stuttgart, Germany, October 26-27, 2011.

[77] Otten, R., Audi, “Audi e-gas-Projekt”; 6th Conference on Gas Powered Vehicles, Stuttgart, Germany, October 26-27, 2011.

[78] Deutsches Institut für Normung e.V. (DIN), “Automotive Fuels – Compressed Natural Gas – Requirements and Test Methods”, DIN 51624, February 2008.

[79] National Society for Clean Air and Environmental Protection (NSCA), “Biogas as a road transport fuel – An assessment of the potential role of biogas as a renewable transport fuel”, England, June 2006.

[80] Douailler, B., Ravet, F., Delpech, V., Soleri, D., Reveille, B., Kumar, R. (2011) “Direct Injection of CNG on High Compression Ratio Spark Ignition Engine: Numerical and Experimental Investigation”, SAE Technical Paper 2011-01-0923.

[81] CONCAWE, European Council for Automotive R&D (EUCAR), Joint Research Centre (JRC), “Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context: WELL-to-WHEELS Report”, Version 2c, March 2007.

Regulations and Incentives for Alternative Fuels and Vehicles

Elisheba Spiller

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Elisheba Spiller*

1. Introduction

Transportation accounts for approximately one third of all US CO_2 emissions and raises serious energy security issues. Increased demand for transportation fuels and low penetration of alternative fuel vehicles has exacerbated these policy concerns and their costs.

In addition, transportation and gasoline consumption have externalities -- spillover effects that are not incorporated in fuel and vehicles costs and prices. These include, for example, lost productivity associated with traffic congestion, accidents, and increased smog and pollution levels. The externalities associated with private transportation, while appreciated for decades, have never been successfully incorporated into the costs of petroleum based transportation fuels and vehicles.

The most efficient way to address the externalities associated with driving and gasoline consumption is through economic instruments. Unfortunately, no single policy, tax or incentive offers an individually optimal solution that would simultaneously diminish driving, decrease gasoline consumption, and enhance energy security – generally agreed upon policy goals. For example, a gasoline tax may change driving patterns or it may cause individuals to simply shift to more fuel-efficient vehicles without the alleviation of congestion. On the other hand, a congestion fee could decrease peak-time usage of highways, though it would not necessarily affect overall gasoline consumption or the choice of fuel efficiency. Therefore, grouping taxes or incentives (such as a gasoline tax combined with congestion taxes) could help to alleviate multiple externalities associated with driving and gasoline consumption. Furthermore, to maximize intended outcomes, a tax would need to vary over time and space depending on congestion levels.

Security, equity and administrative concerns tend to impose political constraints on policy makers, limiting their willingness to price externalities through taxes. Congestion taxes would, for example, negatively impact low income drivers, while emissions or driving taxes are infeasible absent dashboard technologies to measure emissions or driving patterns. Economists estimate an optimal gasoline tax (one that addresses the multiple externalities associated with driving) to be approximately $1/gallon, more than double the current average federal and state gasoline tax on gasoline (see Parry and Small [2005][1] Williams [2006][2], and West and Williams [2007][3]). Yet, discussions of any tax sufficient to alter driving behavior are purely academic given the current anti-tax rhetoric and reticence of many policy makers in Washington.

Policymakers have looked to alternative fueled vehicles that run on electricity, biofuels or natural gas as a means of meeting these policy objectives, and as an alternative to taxes. Yet because the costs of these alternatives – including financial, infrastructure, adjustments and performance tradeoffs – remain high, local and federal government agencies have taken a series of steps to reach key policy goals through the

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implementation of a range of regulations and incentives for alternative transportation fuels (ATFs), alternative fueled vehicles (AFVs), and electric vehicles (EVs).

Many of these incentives and regulations focus on research and development (R&D), demonstration and deployment, and infrastructure development, and most (though not all) are designed to reduce the costs of the alternatives. However, recent presidential administrations have implemented policies that target certain technologies over others. For example, the Bush Administration's policies focused on promoting fuel cell and ethanol (E85) vehicles, while the Obama Administration has placed a strong emphasis on electric vehicles. This pattern of promoting specific technologies has been problematic as it does not allow the more commercially and technologically viable alternative vehicles to emerge as a market choice. Critics of "picking winners" argue that policies like a carbon or gasoline tax would be more "technology neutral" and allow for the most efficient technologies to emerge.[4,5]

In spite of the investment of billions of federal dollars over the past 30 years, market penetration of alternative fuel vehicles remains quite low; even with the enormous federal expenditures in the promotion of these vehicles, they accounted for less than 6% of the overall vehicle stock in 2011.[6] As such, it seems appropriate to take a step back and analyze our decision to incentivize the adoption of alternative vehicles and fuels.

- **First**, have the mandates, incentives and regulations focused on alternative fuels and vehicles been successful in diminishing GHGs and other pollutants, decreasing gasoline consumption, or increasing energy security? While it is important to analyze the effectiveness of these policies in mainstreaming AFVs, their ability to do so matters only in so much as the underlying objectives (such as improving environmental outcomes) are achieved. Can we, for example, be energy independent by mandating alternative fuels and vehicles without also encouraging conservation and decreased vehicle miles travelled?
- **Second**, are these regulations cost-effective, and what is the cost to the government of implementing these incentives and regulations? Given that the current government deficit exceeds $15 trillion, implementing costly incentives and regulations may crowd out other policies and cause significant welfare impacts.
- **Third**, do these mandates and incentives for the adoption and utilization of expensive AFVs impose less of a social and economic cost on society than externality taxes?
- **Fourth**, have these policies resulted in substantial technological development?
- **Finally**, are these policies able to be implemented given the current technological constraints we face? Although these policies may have the goal of improving technology, in the short run the objectives detailed in legislation might not be met, thus it may be necessary to adjust our expectations of what government intervention can quickly achieve.

This paper discusses the incentives and regulations for alternative fuels and vehicles in more detail.

2. Alternative Fuels

2.1 Ethanol and Cellulosic Biomass

Ethanol is the most widely adopted alternative fuel in the US. Since 2005, most gasoline is mixed with up to 10% ethanol, as a result of the federal Renewable Fuel Standard (RFS) and gasoline content regulations. Given its relatively low cost of production (compared to other renewable fuels), the most commonly utilized biofuel in the US is corn based ethanol. This and other incentives have boosted national biofuel production. Cellulosic biomass (CB) and sugar-based ethanols, due to technology and other limitations, have not been utilized to the same extent as corn ethanol in spite of concerns over it GHG balance, associated land use and "fuel for food" issues associated with its production. Furthermore, the US government has established strong barriers to the importation of sugar ethanol in spite of its superior environmental performance. CB also has better environmental performance than corn ethanol, yet it is technologically immature and needs additional research to improve its affordability. [7]

2.1.a US Regulatory History of Ethanol

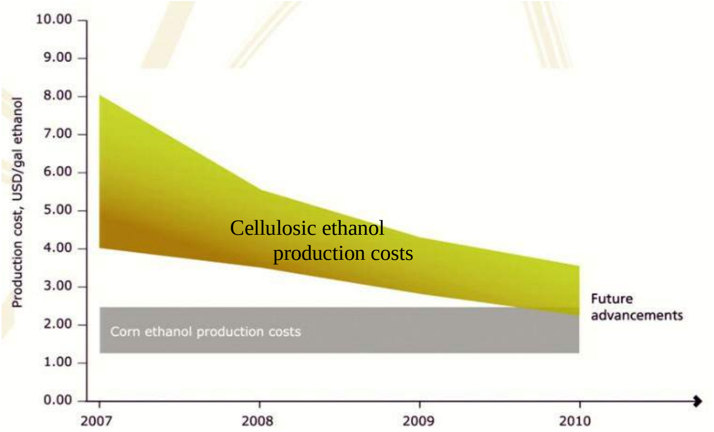
Ethanol has been used as a fuel in the US since before the Civil War. In 1862, however, the US government placed a $2.08/gallon alcohol tax to help fund the war (equivalent to $35/gallon in 2007 dollars) and no exception was made for ethanol. The result of this tax was the replacement of ethanol by kerosene as the fuel of choice. Fifty years later, the tax was lifted, improving market opportunities for ethanol. In fact, the first flexible fuel vehicle (FFV) to run on ethanol, gasoline and kerosene was produced by Ford in 1908.

Over the years, production and utilization of ethanol increased substantially, until the end of WWII, when the increased energy demand for war materials was no longer needed. Ethanol was not viably produced again until the late 1970s, when concerns for energy security and oil dependence after the Arab oil embargos spurred the interest in alternative transportation fuels and the passage of the Energy Tax Act of 1978.[8] This statute helped boost production of ethanol by providing a tax credit for the portion of gasoline that was blended with at least 10% ethanol. At the time, the excise tax for gasoline was 4 cents/gallon, which amounted to a 40 cents/gallon tax credit for every gallon of ethanol blended into gasoline. This subsidy was increased over time: in 1983, the Surface Transportation Assistance Act increased the subsidy to 50 cents/gallon; and in 1984, the Tax Reform Act increased the subsidy to 60 cents/gallon. However, in 1990, the Omnibus Budget Reconciliation Act decreased the subsidy to 54 cents/gallon, and in 1998 the Transportation Equity Act for the 21st Century phased the subsidy down to 51 cents/gallon by 2005. [9,10] The subsidy was further decreased to 45 cents/gallon in 2004, with the American Jobs Creation Act, which also changed the recipient of the credit from the producer to the blender and was due to phase out by December 2011. [11]

By 1980, it was apparent that this incentive was largely going to ethanol importers. In fact, the government surveyed ethanol production in the US and found only 10 producing ethanol facilities.[12] The response was the Energy Security Act of 1980, which imposed an import tariff on ethanol of 40 cents/gallon, effectively offsetting the excise tax credit for those importing ethanol. The Omnibus Reconciliation Act of 1980 also applied a 2.5% ad valorem tariff to ethanol imports from most countries.[13] These import tariffs helped to price Brazilian sugarcane imports out of the US market and helped boost domestic production of ethanol.

Other incentives for the production of ethanol included 10 cents/gallon to small producers (those with production capacities below 60 million gallons per year), established in 1990 and reissued in 2004 through the Volumetric Ethanol Excise Tax Credit (VEETC – part of the American Jobs Creation Act), which also provided a $1.01/gallon credit to producers of cellulosic ethanol.[14] The cost of producing cellulosic ethanol has decreased over the years, but current costs are around $2-$3/gallon, as seen in Figure 1. Though these costs are hard to estimate (and may vary significantly across producers), the trend has been of decreasing costs over the last decade. The VEETC expired at the end of 2011 and cost the government billions of dollars in subsidies over the past 30 years. [15]

Figure 1. Cellulosic Ethanol Production Costs over Time



Source: Novozymes, 2010. Taken from Green Car Congress "New Novozymes Enzymes for Cellulosic Ethanol Enable Production Cost Below US$2 Per Gallon"
http://www.greencarcongress.com/2010/02/cellicctec2-20100216.html

Table 1. Ethanol Tax Policies

Legislation	Tax/Credit
1862 Internal Revenue Act	$2.08/gallon tax
1906 Free Alcohol bill	Repealed 1862 tax
1978 Energy Tax Act	40cents/gallon ethanol excise tax credit
1980 Energy Security Act	Import tariff on ethanol of 40c/g
1980 Omnibus Budget Reconciliation Act	2.5% ad valorem tariff to ethanol imports
1983 Surface Transportation Assistance Act	Increased ethanol excise tax credit to 50c/g
1984 Tax Reform Act	Increased credit to 60cents/gallon
1990 Omnibus Budget Reconciliation Act	Decreased credit to 54c/g, phased down to 51 in 2005; 10c/g credit to small producers
2004 American Jobs Creation Act/ Volumetric Ethanol Excise Tax Credit	Decreased credit to blenders to 45c/g; Added $1.01/gallon credit to producers of cellulosic ethanol -Expired in Dec., 2011.

2.1.b Renewable Fuel Standard (2005 RFS1 and 2007 RFS2)

The Energy Policy Act of 2005 included a Renewable Fuel Standard (RFS1), which mandated a minimum amount of alternate fuels to be blended into gasoline beginning in 2006. The mandate required that refiners purchase a certain amount of renewable fuels (RFs) to be blended into gasoline prior to distribution. The amount of RFs mandated by RFS1 increased yearly from 4 billion gallons in 2006 to 7.5 billion gallons by 2012.[16] However, in 2007 the Energy Independence and Security Act of 2007 (EISA) revised RFS1 and greatly expanded the mandate to 36 billion gallons of RFs by 2022 (now known as RFS2).[17] As seen in Figure 2, total gasoline consumed in the US is approximately 9 million barrels per day,[18] thus the mandate in RFS1 was equivalent to about 5% of total gasoline consumed in 2012, while RFS2 effectively increased that percentage to 11%.

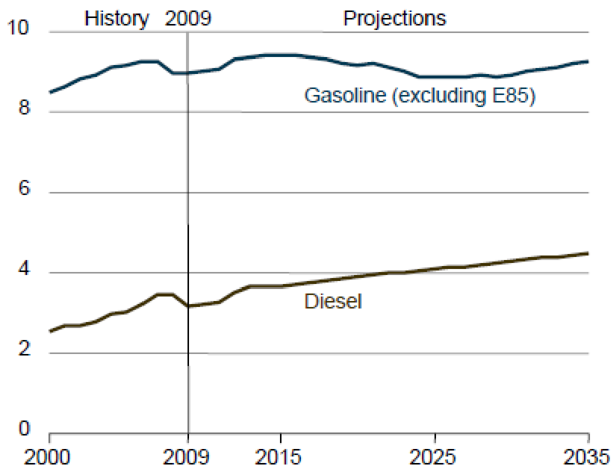
RFS1 also created an incentive for refiners to utilize cellulosic biomass, providing them with 2.5 renewable fuel credits for CB fuel, [19] meaning one gallon of CB fuel would count as 2.5 gallons of renewable fuel. RFS1 also set a floor on the quantity of CB fuel that needed to be included in the overall renewable fuel goal, though the actual minimum volume would depend on the amount of CB that is projected to be available in the coming year and the projected sales of gasoline. The implementation of the law required EPA to estimate the amount of gasoline projected to be sold and CB available, yet the standard could not drop below the floor (as detailed in Table 2).[20] While RFS1 set the floor at 250 million gallons in 2013, RFS2 drastically increased that amount, mandating that by 2022, half of all eligible renewable fuels must be CB.

As Figure 3 demonstrates, RFS1 and RFS2 had significant impacts on total ethanol produced. The USDA indicates that the number of ethanol plants went from 50 in 1998 to 204 in 2010. [21]

Table 2. RFS Standards

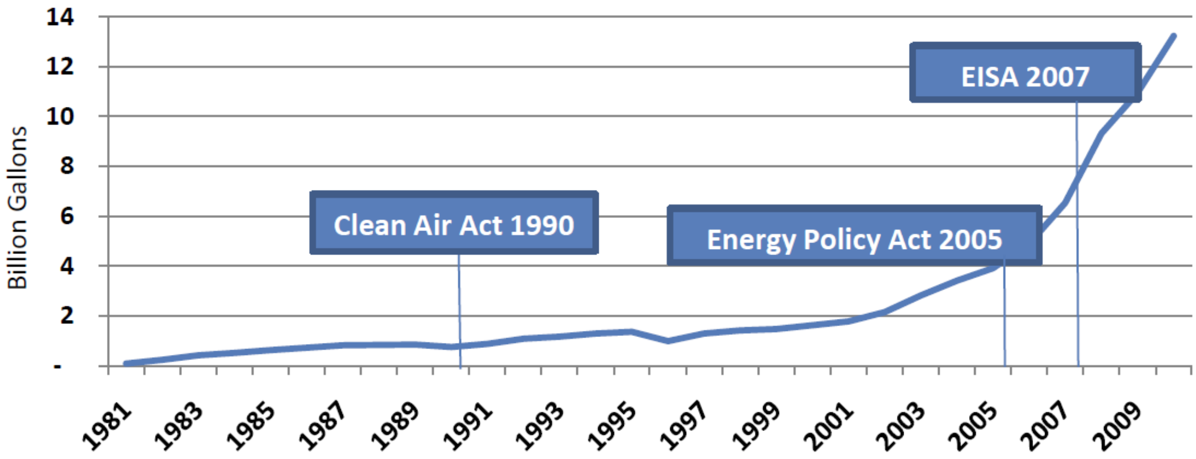
Year	**RFS1 Standard (Billions of Gallons)**		**RFS2 Standard (Billions of Gallons)**	
	Renewable Fuels Minimum	Cellulosic Biomass Min.	Renewable Fuels Minimum	Cellulosic Biomass Min.
2006	4.0	-	4.0	-
2007	4.7	-	4.7	-
2008	5.4	-	9.0	-
2009	6.1	-	11.1	-
2010	6.8	-	12.95	0.1
2011	7.4	-	13.95	0.25
2012	7.5	-	15.2	0.5
2013	-	0.25	16.55	1.0
2015	-	0.25	20.5	3.0
2020	-	0.25	30.0	10.5
2022	-	0.25	36.0	16.0

Figure 2. U.S. motor gasoline and diesel fuel consumption, 2000-2035 (million barrels per day)



Sources: 2010-2035 from EIA, "Annual Energy Outlook 2011," Energy Information Administration, DOE/EIA-0383(2011), U.S. Department of Energy, Washington, DC, 2011.

Figure 3. Historic US Ethanol Production



Graph taken from US Department of Agriculture (2011). "U.S. on Track to become World's Largest Ethanol Exporter in 2011." http://www.fas.usda.gov/info/IATR/072011_Ethanol_IATR.pdf

2.1.c Brazil

Brazil is the world's primary exporter of ethanol, and the second largest producer behind the US. Unlike the US, however, it uses sugar and soy as feedstocks. Sugar ethanol is desirable from a GHG perspective, decreasing GHG emissions by 78% compared to gasoline, though production techniques such as open-field burning of sugarcane leaves can dramatically diminish this benefit.[22] Furthermore, land use associated with sugarcane production in Brazil can be problematic, as it can reduce carbon capture from trees and biodiversity when forest areas are converted to sugarcane. Walter *et.al.* (2011)[23] take into account sugar ethanol's lifecycle and demonstrate that while the GHG benefits relative to gasoline are on average positive, they can be (slightly) negative depending on where the deforestation takes place.

In contrast to the United States, the economy of Brazil is bio-fuels centric. In 1975, Brazil passed the National Alcohol Program (*Pro-Álcool*) with the goal of phasing out all gasoline based transportation fuels.[24] This Program mandated that all Brazilian vehicles run on a blend of gasoline and ethanol, with a minimum of 10% in 1976 and increasing to 22% by 1993. In 2007, the mandate increased the minimum percentage of ethanol to 25%, though it was dropped to 18% in 2011 given ethanol supply shortages.[25] Some vehicles had to make minor adjustments to their engines to comply with the mandate at first, though FFVs soon penetrated the market and by 2003 they comprised 90% of all vehicles purchased in Brazil.[26]

Given the high level of ethanol adoption in Brazil, the question arises of whether the carbon savings from gasoline displacement offsets the emissions due to deforestation or land use change for sugar cane production. Lapola *et.al.* (2010) [27] find that the deforestation due to sugarcane and soybeans from Brazil's increased biofuels mandate would actually create by 2020 a "carbon debt" that would take 250 years to pay off with gasoline. In short, the CO_2 benefits from Brazil's biofuel mandate are recovered only after 250 years. In sum, Brazil's goal of being gasoline-free will not necessarily result in a better overall climate outcome in the long run, given its high demand for ethanol and utilization of soy for ethanol production. It does however satisfy Brazil's energy security objectives and enables the export of a large percentage of Brazil's oil, creating higher value for its domestic energy resources.

2.1.d Analysis of Environmental and Economic Impacts of Biofuels

Concerns have been expressed about the myriad of unintended and environmental consequences associated with the production and distribution of corn ethanol. One of these concerns is the possible increase in food prices associated with competition for land use. However, this issue is generally overstated. In fact, the National Academy of Sciences (NAS) estimates that although this displacement causes food commodities, primarily corn and soy, to increase in price, a 20-40% price increase in commodities only increases the prices of food containing these products by 1-2%.[28]

On the other hand, biofuel production has unintended environmental consequences both in its production and its utilization. Depending on how the biofuels are produced, and what land-use and land cover changes occur due to their production, the GHG benefits from gasoline displacement may be completely offset.

Furthermore, biofuels can increase water and air pollution. Water quality can be affected by corn production, through eutrophication or hypoxia, due to fertilizer use, decreased soil quality, and other factors. The amount of water used to produce biofuels is also orders of magnitude greater than used in the production of petroleum products. [29] Furthermore, biofuels emit higher quantities of other air pollutants (such as particulate matter, ozone, and sulfur oxides) than gasoline.[30] For example, 10% ethanol-gasoline mix emits more of all air pollutants (except for carbon monoxide) than gasoline alone, while E85 emits more acetaldehyde and formaldehyde than gasoline alone (though emits lower levels of NOx and other air pollutants).[31] Yang *et.al.* (2012) [32] find that gasoline blended with 85% corn ethanol results in a 6-108%

greater environmental impact than gasoline alone (on average 23%), when taking into account full lifecycle impacts on GHG emissions, water quality, and 10 other environmental factors.

In addition to the environmental effects of biofuels production and use, the policies regarding biofuels, such as RFS, come with significant fiscal impacts and social costs. The Congressional Budget Office found in 2010 that the costs of the standard ranged from $1.78/gallon of corn ethanol to $3/gallon of CB, and that the implicit cost per ton of CO_2 reduced is $750/metric ton for ethanol and $275/ton for CB.[33]

A major motivation for the renewable fuel standard was that it would create a technology "pull" sufficient to incentivize the development of the basic technologies for CB, as well as attract the venture capital needed for additional development and commercialization. Unfortunately, there has been little R&D in this area, and the technological advances have not been sufficient. The National Academy of Science conducted a report in 2011 to analyze the impact of RFS2 on the economy and environment. The outlook was dismal: the analysis suggests that the goals set by RFS2 of 16 billion gallons of cellulosic biomass cannot be met absent some major technological innovation and policy changes. NAS also concluded that there is insufficient commercially viable refinery capacity required to produce the mandated amount of CB biofuel.[34]

This is unfortunate: Federal yearly support of $100-$400 million in grants from 2006 to 2008 to help CB producers build production facilities[35] appear to have had minimal impact on the progress of technology development and construction of production facilities. A perverse effect of a mandate that cannot currently be achieved may be reliance on foreign sources for biofuels, thus diminishing the energy security benefits that could have been achieved under the RFS. Also, biofuels are not cost competitive with gasoline, even at today's high gasoline prices. NAS' analysis indicates that biofuels will only be a cost-effective alternative to gasoline under extreme technological innovation in refineries and oil prices of at least $191/barrel.[36]

On the other hand, the RFS may help overcome the possible increase in gasoline prices due to the removal of the ethanol subsidies. While many have speculated that the elimination of ethanol subsidies would lead to higher pump prices, the EPA indicates that the RFS alone could result in a decrease in gasoline prices of approximately 2.5 cents/gallon.[37] It is likely that a portion of the subsidy was passed on to the consumer. Absent any major changes in production, removal of the tax credit, while retaining the RFS mandate, would likely result in an increase of 2 cents/gallon at the pump. On the other hand, if producers were not passing along the subsidies, then there will be no negative impact on the consumer from removal of the tax credit. In any case, the amount of ethanol mixed into gasoline will not change due to the removal of the credit (given the RFS mandate), and a 2 cent/gallon increase would only result in a $10/year increase for the average consumer (under 10,000 yearly VMT and a 20mpg vehicle). Thus, the removal of the credit will most likely have more of an impact on the blender's profits than total gasoline demanded, and may also make it more costly for the producers to meet the RFS standard. However, the RFS could help to alleviate the negative economic impacts from the removal of the ethanol subsidies.

2.2 Alternative Refueling Stations

One of the main barriers to adoption of alternate fueled vehicles is the current lack of refueling stations.[38] Consumers will avoid vehicles if they are not able to refuel or recharge them easily. In the classic chicken and egg conundrum faced by alternative fuels and vehicles, producers will also be less likely to install fueling stations if there is insufficient demand for these alternative fuels. Thus, the federal government has promoted policies to incentivize the construction of alternative refueling stations and associated infrastructure in order to break this unfortunate cycle.

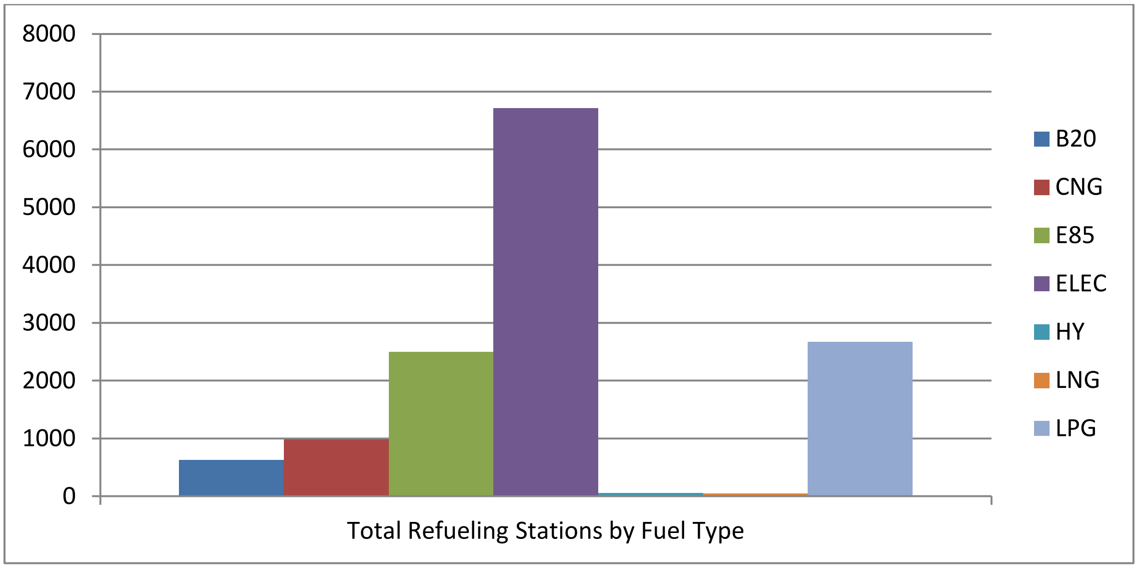
2.2.a US Legislation

The Energy Policy Act of 2005, besides creating RFS1, also sought to promote the installation of alternative fuel refueling stations. This statute provided a tax credit which would cover 30% of the cost of installing an alternative refueling station (of which 85% of the volume has to consist of ethanol, CNG, LNG, liquefied petroleum gas or hydrogen; or 20% of biodiesel; electric charging stations were not included), up to $30,000.[39] This credit was only given to commercial refueling stations - no refueling station on personal property could receive this credit. The 2009 stimulus bill increased the amount of the credit up to 50% of the cost, with a maximum of $50,000.[40] In 2010, the Tax Relief Act extended the alternative fuel vehicle refueling property credit through the end of 2011, but decreased the percentage and total amount of the credit back to EPAct 2005 levels.[41]

EISA also took a (albeit small) step to help in the creation of refueling stations by requiring that the head of each federal agency install at least one alternative fuel pump for service to their vehicle fleet by January 1, 2010.[42] This mandate, while not strictly enforced, required Federal agencies to report through an online reporting tool (Federal Automotive Statistical Tool- FAST) information about the fueling center including amounts of fuel dispensed by type. This information is then compiled by the DOE in order to determine how many alternate fuel pumps are available and how many refueling stations are non-compliant. In June 2011, DOE reported that the percentage of agencies complying with the mandate had increased to 66%, up from 34% in 2010. Enforcement of the mandate could have increased compliance, suggesting that the success of such policies could be improved by incorporating incentives that complement and help support or enforce the mandates- either positive or negative incentives such as tax credits or penalties. The federal fleet mandate for AFVs is discussed in more detail later in this document.

Alternative refueling stations are still limited as can be seen in Figures 4 and 5, and account for less than 8% of all stations in the country (given 2010 levels of US gasoline stations).[43] This suggests that the incentives for building new stations were inadequate, and unfortunately, the lack of refueling stations continues to present a major barrier to adopting alternative fueled vehicles.

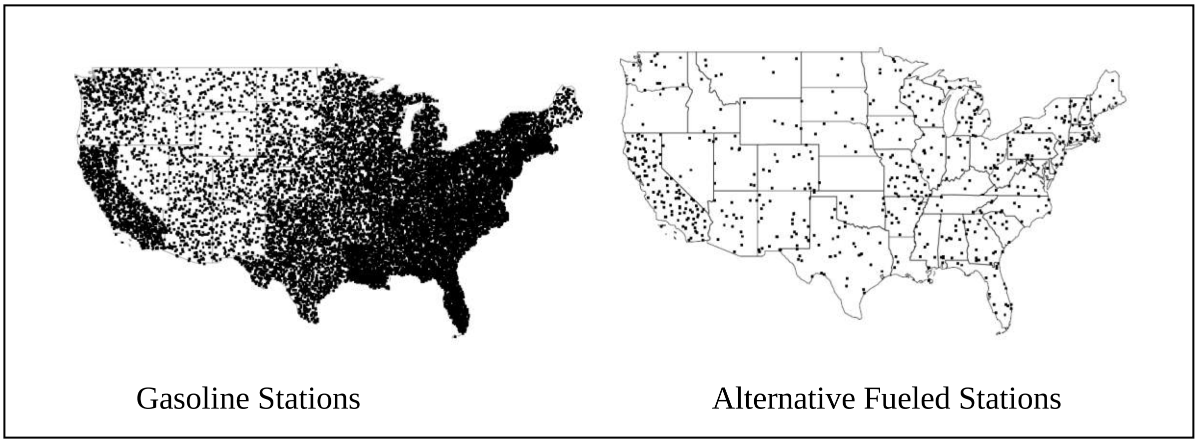
Figure 4. Total Refueling Stations by Fuel Type in 2012



Data from US DOE, Alternative Fuels and Advanced Vehicles Data Center: "Alternative Fueling Station Total Counts by State and Fuel Type"

**The large amount of electric fueling stations is due primarily to an abundance of these in CA

Figure 5. US Refueling Stations 2009



Source: Energy Information Administration. Figures taken from GAO (2000) Report to Congressional Requesters "Energy Policy Act of 1992- Limited Progress in Acquiring Alternative Fuel Vehicles and Reaching Fuel Goals".

**Each dot represents 10 refueling stations in the state (rounded up to the next 10), and the dots do not correspond to specific locations in the state.

2.2.b Natural Gas and Blue Corridors

In Argentina, Brazil and Italy where natural gas is widely used in vehicles, refueling stations are very common. These countries do however, confront inter-country transportation issues; this is especially important for the transportation of goods in heavy duty trucks but presents issues for ease of passenger vehicle travel as well.

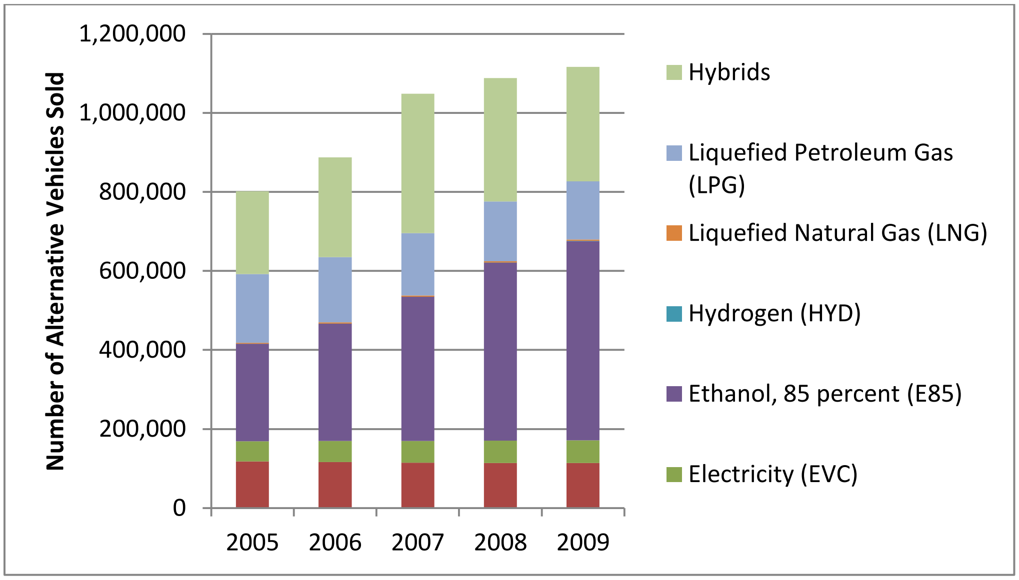
This concern has led to a push for "blue corridors" in South America and Europe -- inter-country pathways that connect countries with natural gas refueling stations. The development of these corridors is facilitated by economic and political arrangements between the countries in question. In South America, this arrangement is MERCOSUR (*Mercado Comun del Sur*, or The Common Southern Market), comprised of Argentina, Brazil, Paraguay, and Uruguay. In Europe, the European Commission serves this function. Both entities are pursuing blue corridors to promote reductions in gasoline consumption and to help stimulate adoption of natural gas heavy duty vehicles in member countries with lower adoption rates.

These corridors allow for a sharing of the investment cost by the two connected countries.[44,45] Both the blue corridor projects in South America and Europe have begun recently (or are still in pilot programs), and as such it is difficult to measure the impact on natural gas adoption or GHG emissions. Nevertheless, these corridors may provide a template for an integrated approach to refueling issues in the US. Most of the refueling stations in the US are centered in large MSAs, which makes it prohibitive to travel very far with AFVs. This is especially problematic for long distance trucking in the US, where the lack of refueling stations has all but prevented alternative fuel adoption by smaller, independent carriers that lack access to or funding for private, company specific refueling infrastructures for alternative fuels. Heavy duty trucks account for 20% of mobile GHG emissions; boosting the adoption of AFVs in this sector could help to significantly mitigate emissions. Blue corridors in the US could similarly help enable interstate travel, especially since incentives and policies vary widely from state to state.

3. Alternative Vehicles

Government efforts to enhance energy security and mitigate mobile emissions have also focused on alternate fueled vehicles. During the Bush administration, policies tended to focus on incentives for AFVs (and later fuel celled vehicles), though policies during the Obama administration have focused more on less fuel-dependent (or independent) vehicles such as electrics, plug-in hybrids, and fuel celled vehicles. However, while these advanced technology vehicles have become more popular over the past few years, they still remain a relatively small portion of the vehicles on the road. Figure 6 shows sales of AFVs and hybrids from 2005-2009. In 2009, sales totaled at less than 1.2 million vehicles, accounting for approximately 11% of all vehicle sales, of which E85 vehicles comprised the largest portion of sales.

Figure 6. Sales of Alternative Vehicles 2005-2009



Data from the US Department of Energy, Alternative Fuels and Advanced Vehicles Data Center: 'HEV Sales by Model', 'AFVs in Use'.

Over the past twenty years, numerous regulations and incentives designed to stimulate the market for alternative fuel and advanced technology vehicles have been implemented. These have included incentives for consumer purchases under the assumption that assistance in developing markets would lower vehicle costs and stimulate additional research. Cost reduction remains a serious issue for these relatively immature vehicles (such as EVs and FCs, although FFVs are very similar in price relative to their internal combustion engine vehicle counterparts).

Range limitations and battery costs are still serious concerns for electric vehicles. The current technological leader in batteries is the nickel-metal hydride (Ni-MH) battery, though the lithium-ion (Li-ion) battery (such as the one used in the Nissan Leaf) has recently emerged as a promising competitor: it is lighter, can be charged more rapidly and doesn't need to be completely discharged prior to recharging. However, Ni-MH batteries are less expensive and are currently the battery of choice for electric vehicles. Table 3 shows the differences in terms of energy and price between Ni-MH and Li-ion batteries compared to conventional internal combustion engine lead acid batteries. Though these numbers may vary by producer, they represent the general trends of power and price across different types of batteries. Energy density is the amount of electricity that can be stored per weight; power density is the proportion of dischargeable energy to chargeable energy; and cycle life is the number of times the battery can be discharged and recharged.

The remainder of this section looks at some of the major regulations and incentives that have been proposed throughout the US with regard to alternative vehicles, both electric and non-electric.

Table 3. Comparison of Battery Types[46]

Battery Type	Lead Acid (conv. car battery)	Ni-MH	Lithium-ion
Energy density (Wh/Kg)	35	60	120
Power Density (W/kg)	180	250-1000	1,800
Cycle life	4,500	2,000	3,500
Cost ($/kWh)	269	500-1,000	1,000-2,000

Sources: Deutsche Bank, 2009; METI, 2009a; Nishino, 2010; The Institute of Applied Energy, 2008; Woodbank Communications Ltd, 2005. Table taken from Lowe *et.al.* (2010)

3.1 Corporate Average Fuel Economy and Greenhouse Gas Standards

The Corporate Average Fuel Economy Standards (CAFE) were established in the Energy Policy and Conservation Act (EPCA); in 2007, EISA amended EPCA and proposed standards for MY 2011-2020 vehicles. The new EISA standards were transformative: they included a 35 MPG mandate by 2020 for light duty vehicles.[47] EISA also required, for the first time, the setting of efficiency standards for medium and heavy-duty trucks, though did not specify a MPG mandate.[48]

Importantly, these new standards decreased the level of credit manufacturers would receive for selling flex-fuel vehicles (FFVs). Previous CAFE standards incentivized the production of FFVs by allowing manufacturers to increase the overall fleet MPG average through the sale of these vehicles regardless of the actual fuel used (as described in more detail in the next section). This was problematic, however: as GAO established in 2000[49] (confirmed later by DOE in 2008[50] and the EPA in 2010[51]), FFVs were primarily being fueled with gasoline in spite of the alternative fuel option. The EISA amendments of EPCA directed NHTSA to phase out this incentive for FFV production completely by 2019. In short, EISA set the highest MPG CAFE standards to date, started the process for regulating the fuel efficiency of medium and heavy-duty trucks, and phased out the credits for AFVs.

However, there are many unintended consequences related to increased fuel efficiency standards, including, for example, the rebound effect and new source bias. The rebound effect is the tendency for individuals to drive more due to cheaper operating costs, as increased fuel efficiency reduces the effective price per mile. This effect has been estimated to be anywhere between 4.5% and 31%,[52] and can offset efficiency gains. New source bias refers to reduced purchases of new vehicles due to the higher vehicle prices associated with more stringent efficiency regulations; the net result is that older, less efficient vehicles tend to stay on the roads longer. NHTSA/EPA estimate that its new National Program – designed to harmonize vehicle regulations, and described in more detail in Section 3.1.c -- will result in $142-182 billion in fuel savings,[53] assuming a 10% rebound effect[54] and a -1 price elasticity of demand for vehicles.[55] This does not, however, take into account the impact on the used vehicle market or scrappage, thus partially ignoring new source bias (though the negative price elasticity picks up some of the reduced demand for these vehicles given higher prices).[56] Even with penalties for manufacturers, concerns remain that the overall costs of improving efficiency could be high enough to encourage non-compliance, reducing the overall benefits of the program.

The story of how current efficiency and emissions standards for mobile sources were set is quite intricate, encompassing actions at both the State and federal level, up to and including Supreme Court decisions. The policy process that led to these standards is described next.

3.1.a Massachusetts vs. EPA

Until 2007, the Clean Air Act (CAA) required the US EPA to regulate air pollutants from mobile sources to protect the public health and welfare. Greenhouses gases had not been determined to be an air pollutant under the CAA, limiting EPA's authority to regulate tailpipe GHGs.[57] In 2003, several organizations petitioned the EPA to regulate GHG emissions from mobile sources, yet EPA denied the petition, saying it lacked authority under the CAA to do so. In response, 12 states, 2 cities, and a number of organizations sued the EPA, to force the agency to regulate GHG emissions from mobile sources, asserting that it did indeed have such authorities under the CAA. In 2007 the US Supreme Court in *Massachusetts vs. EPA*, sided with the petitioners.[58] While the Supreme Court decision was clear, the EPA remained concerned that the costs associated with implementing national standards and regulations for GHG management would be high and ineffective, given the global nature of the problem.

3.1.b CA's Attempt to Regulate GHG Emissions from Mobile Sources

In California, the CA Air Resources Board (CARB) had been regulating non-GHG mobile emissions within the state for decades. The mobile source provisions in the CAA (Title II) intended for emissions standards to be set at a national level to maintain uniformity of regulation across all states, an approach that was beneficial to vehicle manufacturers. Title II however allowed for an exception in Section 209 (b): any state that by March, 30, 1996 had adopted standards that were at least as stringent as the federal standards could receive a waiver to these provisions in the CAA.[59] CA was the only state that adopted regulations prior to 1996, and thereby was the only state eligible for the waiver. However, the waiver could be denied if it was found that: "(A) the protectiveness determination of the State is arbitrary and capricious; (B) the State does not need such State standards to meet compelling and extraordinary conditions; or (C) such State standards and accompanying enforcement procedures are not consistent with section 202(a) of the Act" (Federal Register, 3/6/08, p. 12158).

While CA was successful in obtaining a waiver for other state-based regulations, it took the state several years to acquire a waiver for GHG emissions regulations. In 2002, CA enacted AB 1493, placing CARB in charge of regulating GHG emissions from mobile sources. Under this authority, CARB enacted GHG emissions standards in 2004 requiring a gradual decline in emissions over time for each manufacturer. This spurred California's initial waiver request to the EPA, seeking authority to regulate GHG as air pollutants.[60] Given the lawsuit the EPA was facing at the time, it chose to defer action on CA's waiver petition until EPA's authority to regulate GHG had been either confirmed or denied by the courts. Vehicle manufacturers opposed CA's waiver petition, claiming its standards were excessively stringent relative to the rest of the country. EPA initially denied CA's waiver in 2008, noting that "California does not need its greenhouse gas standards for new motor vehicles to meet compelling and extraordinary conditions" (Federal Register, 3/6/08, p.12156). The EPA claimed that since CA faced the same threat of climate change as the rest of the country, the "compelling or extraordinary conditions" test in article (B) (as detailed above) did not apply. The failure to meet one test was sufficient for the denial of the waiver.

However, since this initial denial, 13 additional states have adopted CARB's proposed GHG standards, and under CA's receipt of the waiver, these states would also be allowed to implement the standards.[61]

3.1.c The National Program

In light of the finding on *Massachusetts vs. EPA*, President Obama announced in May 2009 a plan for the EPA to impose GHG emissions standards for light duty vehicles.[62] The President directed NHTSA, in charge of setting CAFE standards, to work with the EPA to establish the National Program, setting limits of efficiency and GHG standards for motor vehicles and ensuring that regulatory approaches were harmonized. The result of this coordinated approach was a national standard set at the same levels of the CA standard; thus addressing the concerns of automakers about having to satisfy different standards at the national and state levels. Furthermore, having two different sets of regulations could actually result in higher overall emissions. Goulder *et.al.* (2012)[63] find that the effort by the 14 states to adopt CA's GHG standards had negative environmental impacts: adopting states tended to have lower emissions while emissions in non-adopting states actually increased. Given the high standards in the adopting states, manufacturers were able to reach the federal standard faster, allowing them to sell more vehicles with high emissions in the non-adopting states. Thus, overall emissions worsened due to the difference between federal and state regulations. Fortunately, CA accepted the standards for the National Program as consistent with its own.[64] This agreement, along with increasing external pressure from both the President and environmental groups, led to a revision of the waiver request, and subsequently, the EPA granted CA the waiver in June 2009.

The National Program has enabled a uniform national standard for GHG emissions from mobile sources across the country. It also decreased allowances and credits the manufacturer could receive for AFVs and other vehicle technologies (such as air conditioning), though it maintains credits for electric and fuel celled vehicles. I discuss the details of these allowances in more detail below.

3.1.d Light-Duty Vehicles

Although CA was not allowed to regulate GHG emissions from mobile sources until 2009, the CA mobile emissions regulations were used as the basis for current standards issued by the National Program for MY 2012-2016 light duty vehicles. The National Program mandates a fleet average of 34.1 MPG and GHG emissions of 250 grams/mile for MY 2016. It was necessary to lower the MPG requirement from 35MPG in order to solve the problem that the GHG standards provided more allowances to manufacturers than did the CAFE standards. On the one hand, EPCA did not allow CAFE standards to be affected by air conditioner (A/C) credits, while the GHG standards utilized the A/C credits as an allowance to help manufacturers reach the standard. These A/C credits were allowances given to manufacturers who made improvements in the air conditioning system in the vehicle: since A/C is one of the most energy intensive parts of a vehicle, improving the efficiency of these systems was considered by EPA as GHG emission improvements. Furthermore, the 250 g/mile GHG standard would correspond to a 35MPG standard if the manufacturers met the GHG standard through efficiency improvements alone. Thus, in order to coordinate across these two standards and to allow for the fact that the A/C allowances differed across these, the MPG requirement was set slightly lower than proposed in EISA.[65]

As mentioned earlier, FFVs are commonly run on gasoline alone, and these new standards dealt with this issue directly. In previous CAFE standards, FFVs were assumed by EPCA to run 50% of the time on gasoline, and 50% of the time on the ATF. Furthermore, the manner in which emissions for the ATF were calculated was based on a multiplier: each gallon of ATF was counted as 0.15 gallons of gasoline. These two assumptions jointly implied that, for example, an FFV that emits 330 g/mile of CO_2 while utilizing ethanol and 350 g/mile of CO_2 while utilizing gasoline would be estimated as having the following total average emissions:

$$CO_2 = \frac{(330 * 0.15 + 350)}{2} = 199.8 g / mi$$

This provided a major incentive for manufacturers to sell these vehicles, as this allowance facilitated compliance with both the emissions standards and the efficiency requirement. Given the 0.15 conversion factor, this increased the MPG of a FFV by a factor of 6.67: for example, a 15 MPG AFV would be rated at 100 MPG.[66] This diminished greatly the environmental effectiveness of these standards, as it did not take into account the actual fuel utilized by these vehicles. In fact, the National Program's Final Rule cites the Regulatory Impact Analysis of RFS2 as claiming that "Data show that, on average, FFVs operate on gasoline over 99 percent of the time, and on E85 fuel less than 1 percent of the time" (Federal Register 5/7/2010, p.25437).

The new standards pursuant to EISA changed this allowance structure for FFVs, providing the two allowances (the 50/50 assumption and the conversion factor) only for MY 2012-2015 vehicles. For MY 2016 and later, these two allowances were phased out. Also, starting with MY 2016, EPA will assume that the utilization of ATFs is negligible; the manufacturer must provide evidence demonstrating the use of ATFs for vehicles sold or request an alternate weighting value to be determined by the EPA. This leaves the burden of proof on the manufacturer and diminishes the incentive to produce FFVs. Furthermore, the conversion factor no longer holds after 2016 and a vehicle's actual emissions are tested while using an ATF. Finally, the National Program limits the amount of allowances in the average fleet MPG calculation: a manufacturer can only accrue up to 1.2MPG in allowances due to sales of FFVs.[67]

These standards, though they decreased the incentive to produce FFVs, created some flexibility for electric and fuel celled vehicles. EVs, PHEVs, and FCVs are assumed to have emissions of zero g/mile, effectively ignoring upstream and life-cycle emissions. While this benefit is phased out after the manufacturer has sold a certain amount of these vehicles, the regulators did not consider it likely that the limit would be reached within the time frame of the regulation.[68] This was intended to provide incentives to manufacture EVs, to be phased out when economies of scale were achieved.

3.1.e New CAFE Standards and Compliance

In May 2010, President Obama set goals for the next round of CAFE standards, affecting MY 2017-2025 light duty vehicles. The proposed standard is much more stringent, calling on the manufacturers to increase average efficiency to 54.5 MPG by 2025.[69] Because this standard is so difficult for manufacturers to achieve, the proposed standards would actually increase allowances for AFVs and EVs relative to the 2016 rule: one EV (or FCV) would count as 2 EVs/FCVs, and one PHEV would count as 1.6 (though this multiplier is proposed to phase down by MY 2021).[70] This sort of multiplier had been previously ruled out by EPA, as the agency claimed “that the multiplier, in combination with the zero grams/mile compliance value, would be excessive” (Federal Register, 5/7/2010, p. 25401).

This regulation has not yet been finalized and may change after the comment period and subsequent revisions. As it currently stands however, it creates strong incentives for automakers to manufacture EVs, PHEVs and FCVs. The proposed regulation also brings back the zero g/mile allowance for a certain amount of vehicles sold, further incentivizing the production of these vehicles in the beginning of the program. Unfortunately, creating allowances that target very high levels of fuel efficiencies allows manufacturers to sell more vehicles that do not meet the CAFE standards, thus increasing overall fuel consumption.

The regulation may need to implement these allowances for very high efficient vehicles not only because of the stringent standard, but also because of the way in which the CAFE standard is calculated. These standards set a limit on the efficiency that each manufacturer needs to reach, calculated through a sales-weighted harmonic average. What this implies is that the vehicles within a fleet are averaged given the fuel economy over a set of miles, instead of over a set of gallons, as the arithmetic mean would imply. For example, if a fleet has three regular cars and one electric vehicle, with relative efficiencies of 10, 15, 20, and 100MPG, the harmonic average is calculated as:

$$\frac{4}{(1/10)+(1/15)+(1/20)+(1/100)}=17.6MPG$$

whereas the arithmetic average would be calculated as:

$$\frac{10+15+20+100}{4}=36.25MPG\cdot$$

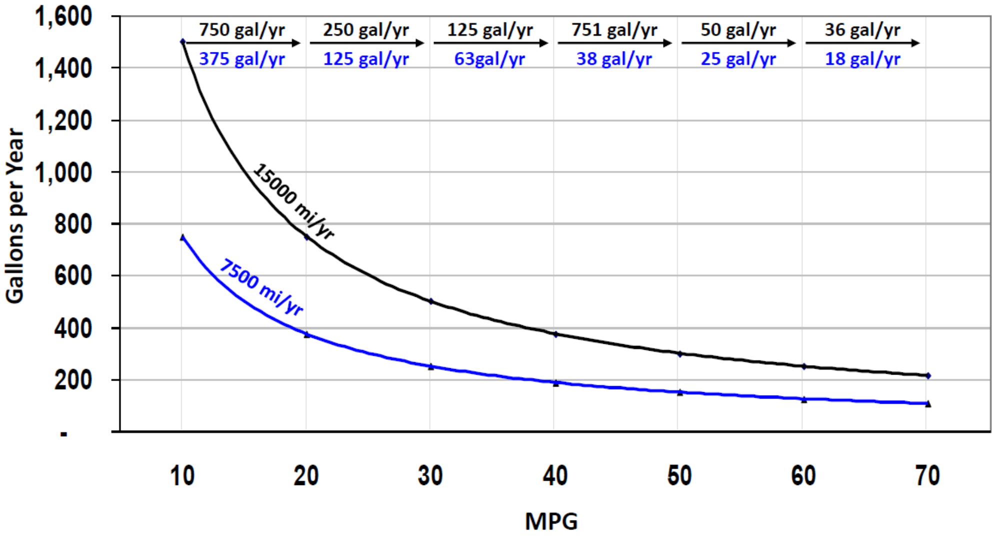
This in essence decreases the ability of a manufacturer to reach a specific goal through efficiency improvements, as the harmonic average mitigates the impact of outliers, and thus decreases the importance of very high fuel efficient vehicles. For example, improving the MPG of the electric vehicle in the above equation could never bring the harmonic average to surpass 18.5MPG: even if its MPG was infinite, the harmonic average would stay at 18.5. Therefore, utilizing harmonic rather than arithmetic averages means that CAFE standards diminish the incentive to produce very highly efficient vehicles (though it does incentivize increasing the MPG of low and middle efficiency vehicles, which can have larger impacts on fuel savings). As such, if the policy wants to incentivize the production of electric vehicles, then allowances in the standard for electric vehicles are essential.

However, increasing fuel efficiency has diminishing returns. For example, replacing a sedan in the fleet with a hybrid equivalent costs the manufacturer around \$3,000[71] given current hybrid technology (though exact costs are unknown, the difference in price between a hybrid car and its non-hybrid counterpart is approximately this amount).[72] On the other hand, replacing an efficient non-hybrid vehicle with an electric vehicle costs anywhere between \$10,000 and \$30,000,[73] mostly due to the cost of the battery (which based on warranty information is projected to need to be replaced more frequently than the battery in a hybrid due to its usage and cycles). Yet, reductions in gasoline consumption are much larger from replacing the sedan with the hybrid than replacing the efficient vehicle with an electric. Consider two vehicles: a 12MPG vehicle and a 30MPG vehicle. Increasing the 12MPG vehicle by 2 miles per gallon would result in fuel savings of 1.19 gallons per 100 miles driven. On the other hand, increasing the

30MPG vehicle to 40MPG would result in 0.08 gallons of fuel saved per 100 miles (assuming no change in VMT- if the rebound effect occurs, then the 40MPG vehicle will be driven more than the 30MPG vehicle, thus reducing even further the amount of gasoline saved).

Figure 7 demonstrates graphically the downward slope of these returns. This figure shows gasoline savings by increases in fuel efficiency (under assumed VMT of 15,000 or 7,500). For example, replacing a 20MPG traditional gasoline vehicle with a 40MPG hybrid vehicle would save 375 gallons (at 15,000 VMT) at a cost of $3,000, while replacing it with a 100MPG electric vehicle would save 600 gallons at an average cost of $20,000. This implies marginal costs of $8/gallon reduced vs. $33/gallon reduced, demonstrating that although total gallons reduced are higher, it is less efficient (in an economic perspective) to replace a traditional vehicle with an EV compared to replacing it with a hybrid. An even larger number of gallons could be saved by replacing a 10MPG vehicle with a traditional gasoline 20MPG vehicle – and without spending thousands of dollars to do so.

Figure 7. Fuel Savings by MPG, VMT



Source: William Chernicoff, Energy & Environmental Research Group Manager, Toyota Motor North America, Inc.

3.1.f Heavy-Duty Vehicles

For the first time, the EPA and NHTSA have created a comprehensive Heavy-Duty National Program of emissions and efficiency. This legislation establishes standards separately for three different types of vehicles;1) Class 7 and 8 combination tractor-trailers; 2) Vocational vehicles; and 3) Medium-duty pickup trucks and vans. These regulations also incentivize the production of alternate fueled and electric vehicles, although less so than the proposed light duty regulations.

Emissions from AFVs are calculated through CO_2 tailpipe emissions testing, while EVs are assumed to have zero emissions. FFVs are treated similarly to current regulations for light duty vehicles – a 50/50 weighting assumption through MY 2015, after which the weighting factor depends on the demonstrated ATF usage by each manufacturer. However, no conversion factor is assumed.[74] Thus, the heavy-duty legislation does less to promote production of AFVs than the light-duty legislation, which is unfortunate given the extremely low level of adoption of these new technologies by the heavy-duty vehicle market.

EPA and NHTSA claim that these improvements to fuel efficiency will save the industry $50 billion in fuel, yet this claim is troubling as the industry has not made these improvements on its own.[75] This under-investment in energy saving technologies that pay back over time has been referred to as an "energy paradox" (see Harrington and Krupnick [2012][76]). The trucking industry and other analysts dispute the availability of fuel saving technologies, and attribute under-investment to hidden costs, such as engineering tradeoffs between fuel efficiencies and torque, or safety tradeoffs.

For the regulations in the heavy-duty sector to be effective in decreasing petroleum consumption, more incentives for alternate fuels and vehicles are necessary than what has been developed in these first efficiency and emissions standards. In fact, merely increasing the fuel efficiency of new vehicles will not necessarily result in a diminished use of gasoline, given rebound effects. Furthermore, hidden costs and technological limitations are present in this industry, causing an under-utilization of efficient technologies. Policy makers need to understand the basis behind the energy paradox and take into account the rebound effect in order to craft policies that are effective in diminishing gasoline consumption.

3.2 Market Stimulation

The government has taken a series of steps to stimulate the market in ways that would encourage wider use of alternative vehicles. These fall into two categories: incentivizing and mandating the adoption of these vehicles by government agencies and consumers; and creating voluntary initiatives and demonstrations to increase awareness and understanding. This section discusses these policies and their impacts on the market for alternative vehicles.

3.2.a Mandated Adoption of Alternative Vehicles

EPAct 1992 presented an important set of incentives and supporting regulations for alternative fuels and vehicles (in addition to ethanol). For example, it established goals for federal agencies to adopt alternative fueled and electric vehicles, under the direction of the US Department of Energy (DOE). This legislation mandated (a soft mandate) that new government fleet purchases contain a minimum of 25% AFVs in 1996, increasing to 75% in 1999.[77] The control of AFV ownership by federal fleets was conducted through voluntary provision of information.[78] DOE claims that since 2003, almost 100% of the federal fleets have complied with or exceeded this mandate, and those that fell short reached agreements with the federal government.[79]

This mandate however had an unfortunate unintended consequence. For much of the period after the passage of EPAct 1992, oil – and therefore gasoline-- prices were very low. It was far less expensive for government AFVs to run on petroleum based fuels than alternative fuels. Consequently, the mandate was largely met but petroleum based fuel consumption did not markedly decrease.[80] DOE recently reported that even if all agencies had complied fully with the mandate, the vehicles would only have replaced less than 1% of gasoline consumed in 2010,[81] illustrating a large net economic cost – the adoption of thousands of higher-priced AFVs with little benefit on the fuel side. Though the price difference between FFVs and traditional vehicles is negligible these days (between $50 and $100[82]), in 1992 it was not. The federal fleet mandate in EPAct 1992 resulted in an extra 200,000 AFV purchases, with little to no GHG emissions benefits.[83] Furthermore, 200,000 vehicles is less than 1% of all vehicle purchases, so it is unlikely that this mandate contributed to the decrease in FFV prices. CAFE standards, which included many credits for the manufacture and use of AFVs, was likely a much more important factor in closing this price gap than the federal fleet AFV mandate.[84]

The fact that these vehicles were primarily used with gasoline led to the adoption of fuel usage mandates in future regulations. EPAct 2005 amended EPAct 1992 to mandate that agencies purchasing FFVs operate them exclusively on alternate fuels. Those agencies not able to use alternative fuels due to lack of fueling stations or other hardships were able to receive a waiver.[85] These waivers were then utilized by the federal government to identify areas where ATFs were not readily accessible. Using the information gathered from these waivers, EISA 2007 mandated a 10% increase in usage of alternate fuels by federal fleets, simultaneously with the refueling station requirement discussed in Section 2.[86]

In order to expand the number of first adopters outside the government, the mandates in EPAct 1992 also affected alternative fuel providers. Alternate fuel producers and refiners were required to purchase a minimum percentage of AFVs per year- increasing to 90% in 1999.[87] In order to enforce these regulations, penalties of $5,000-$50,000 were implemented for non-compliance.[88] These regulations were intended to create an example for the public of AFV usage, as well as to help spur the market. In 2001, the DOE reported a 91% compliance rate amongst for fleets covered by the statute.[89] Regardless of these high compliance rates, the petroleum replacement goals set out by EPAct 1992 of 10% by 2000 and 30% by 2010 were not met.[90] Historical experience suggests that mandating AFVs at the federal fleet level may have more value as a demonstration than as overall decline in petroleum-based fuel consumption.

3.2.b California ZEV Mandates

The state of California has implemented several mandates for the use of zero emission vehicles (ZEVs). Given CA's major problems of transportation pollution in places like Los Angeles, there has been a push over the decades to implement more stringent efficiency and emissions standards. CA has been able to affect standards through the EPA waivers (as discussed in the CAFE standards section of this paper), and has become the earliest promoter of advanced vehicle technologies. In fact, in 1990 California utilized one of these waivers to pass a ZEV mandate, which directed that by 2003 10% of all sales by the large manufacturers must be ZEVs.[91] Unfortunately, the ZEV mandate, while popular among constituents, became a contentious matter and was fought, amended, and changed over the decade-long policy process.

The first set of changes occurred in 1996. As the mandate ramped up ZEV sales from 2% of total vehicle sales in 1998 to 10% in 2003, concerns of manufacturers over meeting intermediate goals resulted in the removal of all mandates prior to 2003, while leaving intact the 10% mandate for 2003. Manufacturers' concerns about meeting the 2003 deadline intensified in 2001, causing the mandate to be changed further- this time, it allowed the manufacturers to meet the ZEV mandate through the production of non-ZEV vehicles, such as Partial Zero Emissions Vehicle (PZEVs) and Advanced Technology PZEVs (AT PZEVs). Soon after, regulators faced a lawsuit preventing them from enforcing the mandate; leading to more regulatory changes and further expansion of the types of vehicles that met the requirements for the mandate. In 2008, the mandate was once again changed to allow the manufacturers to produce a greater number of PHEVs to meet the mandate, but only if they also produced a minimum number of pure ZEVs.[92]

Even though the regulators faced massive opposition to these mandates, in 2009, they increased the requirement for pure ZEVs from 11% in 2009 to 16% in 2018, although the manufacturers were allowed to use a portion of PZEVs and AT PZEVs sold to meet the mandate.[93] The new Advanced Clean Car Rules of 2012 (which set the newest CA ZEV mandates) were even more stringent: credits for non-zero emission vehicles were phased out after 2018.[94]

Lessons Learned from CA's ZEV Mandate History

Both the benefit and drawback of a ZEV mandate is that it places the burden on the manufacturers, tasking them with advance technology and pricing to promote the purchase of ZEVs. While this reduces the burden on the government and consumers, manufacturers feel pressured and will fight to avoid compliance. Indeed, this was the case with the CA ZEV mandates: it was met at every point with lawsuits and opposition from the manufacturers.

Would this have been different had the CA regulators produced significant financial incentives on the consumer demand side? Though the ZEV mandate was never coupled with tax credits or rebates for vehicle purchases, there were a number of federal and state incentives in place after 2007, including tax credits, rebates, and HOV stickers for the purchase of ZEVs. These rebates and tax credits (which are discussed in the next section in more detail) may have simultaneously enabled a more stringent approach and engendered less opposition to the ZEV mandate.

Electric vehicle sales remained relatively flat between 2005 and 2009, averaging approximately 2,000 new vehicles per year with a total of 57,000 by 2009.[95] CA has the majority of these vehicles: in 2009, there were approximately 31,500 electric vehicles in use in the state, which amounted to 55% of the national electric vehicle stock.[96] This demonstrates that though CA is still the leader in ZEV ownership, it was unable to successfully reach any of its goals in terms of percentage of ZEVs purchased.

The history of ZEV regulation in California suggests that mandates, while appealing to governments for both budgetary and policy reasons, are not optimized without complementary incentives. "Sticks without carrots" can reduce compliance and increase opposition to both mandates and ZEVs in general. Also, mandates that are phased in over time tend to encourage lawsuits and the weakening of the original targets or requirements.

3.2.c Consumer Incentives

In addition to incentives and mandates on vehicle manufacturers, the federal and state governments have provided incentives to consumers for purchasing AFVs.

A major goal of EPAct 2005 was to stimulate the production and utilization of alternative vehicles: hybrids, fuel cell vehicles, AFVs, and FFVs. To help market these vehicles, the statute established consumer based incentives in the form of tax credits for their purchase. These tax credits ranged from $2,500-$8,000 for light duty fuel celled vehicles, and up to $40,000 for heavy duty FCVs. The size of the tax credit increased with the vehicle's efficiency, creating an even larger incentive to purchase high fuel efficiency vehicles. For hybrids, the credit ranged from $1,500-$3,000 for light duty vehicles and between $3,000 and $12,000 for heavy duty vehicles, depending on the efficiency increase relative to a non-hybrid equivalent.[97]

These credits were phased down for each manufacturer during a 15 month period, or until its first 60,000 vehicles were purchased. This helped boost purchases of these vehicles, though the economic benefits depended on the popularity of each vehicle. For example, the Toyota Prius tax credit ended within a few months of the regulation, while it was still possible to receive a credit for other vehicles several years later, such as the Chevrolet Malibu Hybrid.

Consumers were already purchasing the Prius in greater quantities than other hybrids, thus the added tax credit may have been more of a windfall than an incentive to these consumers. In fact, in 2004, Toyota had sold over a million Prius'.[98] Providing consumers a credit for purchasing one of the first 600,000 Prius sold in 2005 therefore did not necessarily increase sales.

Incentivizing early adoption of alternative vehicles can help manufacturers achieve economies of scale and help level the playing field for late adopters. On the other hand, certain manufacturers (such as Toyota) who have already commercialized AFVs or ZEVs do not need these types of incentives.

Table 4. Initial Tax Credits for Different 2005 Hybrid Models

Vehicle (Example)	Credit	2005 MSRP	MPG (city/ highway)	2005 MSRP (non-hybrid version*)	MPG (non-hybrid version*)	Yearly Fuel Cost Savings**
Honda Accord Hybrid	$650	$30,655	25/33	$22,715	21/31	$266.19
Honda Insight CVT	$1,450	$19,845	45/49	--	--	--
Honda Civic Hybrid	$1,700	$20,415	39/43	$13,775	25/34	$560.05
Ford Escape 4WD	$1,950	$27,445	30/28	$23,150	19/23	$740.66
Toyota Prius	$3,150	$21,815	48/45	$15,365	28/37	$543.20

MSRP data: cnet.com; MPG data: Edmunds.com

*non-hybrid versions: Honda Accord, Honda Civic, Ford Escape, and Toyota Corolla. Honda Insight has no gasoline equivalent vehicle.

**Cost savings based on 15,000 VMT, $3.5 gasoline price, and EPA 45/55 definition of average efficiency (relative to non-hybrid version)

The American Recovery and Reinvestment Act of 2009 (ARRA, the stimulus bill) provided further incentives to consumers for the purchase of ATVs. These included a consumer tax credit of $2,500 to $7,500 (depending on the size of the battery) for the purchase of electric vehicles. This credit ended after the manufacturer sold 200,000 vehicles.[99] ARRA also provided a consumer tax credit for electric vehicle conversion for 10% of the cost of conversion up to $40,000.[100]

The recession has caused an overall decrease in vehicle purchases, making these tax credits an important stimulus to the economy. During the recession, the government also provided a Cash for Clunkers program to incentivize the purchase of more efficient vehicles. Cash for Clunkers provided consumers with up to $4,500 rebates for turning in an older, low fuel efficient vehicle (a "clunker") to used towards the purchase of a more fuel efficient vehicle.[101] Hybrids or EVs (as long as they cost less than $45,000) were eligible for such purchases. Li *et.al.* (2011)[102] and Mian and Sufi (2010)[103] find that Cash for Clunkers had small impacts on emissions and fuel efficiency; the program did however stimulate sales in the (very) short term, largely by displacing future sales. This suggests that this program was more of an economic stimulus tool than a tool to stimulate advanced technology vehicle markets.

State governments have also provided non-monetary incentives for the purchase of ATVs. In many states, state and local governments provide stickers granting access to High Occupancy Vehicle (HOV) lanes for hybrid, electric and partial zero emission vehicles (regardless of vehicle occupancy). The 1990 Clean Air Act Amendments first implemented these allowances for "Inherently Low Emission Vehicles" (ILEVs), vehicles categorized by the EPA as having low emissions, and which generally ran on alternative fuels. The 1998 Transportation Equity Act for the 21st Century helped states to extend this allowance to individual owners of ILEVs.[104] This allowance was provided in many states- in fact, 9 of 20 states with HOV lanes granted HOV stickers to ILEVs. Several of these states, including California, added hybrids to the list of HOV allowed vehicles.[105] CA currently implements HOV allowances for all electric vehicles sold and for the first 40,000 AT PZEV until January 1, 2015. Between 2005 and 2008, California also issued 85,000 stickers to 3 hybrid vehicle models: the Toyota Prius, the Honda Civic Hybrid, and the Honda Insight.

The HOV allowances for hybrids in California were only available until July 2011. These stickers were valued highly by hybrid vehicle buyers; some research suggests that that individuals were willing to pay as much as $3,200 more for a vehicle that came with such a sticker.[106] However, Diamond (2009)[107] finds that the HOV sticker did not significantly affect hybrid purchases in CA, implying that the HOV allowance was more of a windfall benefit to hybrid owners than a hybrid vehicle market booster.

3.2.d Demonstrations and Voluntary Programs

The federal government has also established several demonstration and voluntary programs designed to encourage adoption of AFVs largely by increasing awareness of and research into their development. EPAct 1992 provided several financial incentives including loan guarantees and grants for trial programs designed to boost AFV demand through demonstration of their use. The Clean Cities Program was such a program, established to help reduce petroleum consumption, and focused on activities at the local level.[108] Clean Cities has been implemented in 100 cities across the nation; it establishes partnerships of local public and private stakeholders, to help in the adoption of advanced vehicle technologies, reduction of gasoline consumption, and fuel economy improvements. The program also provides assistance to fleets for employing alternative vehicles and disseminating information to educate consumers about the benefits of AFVs. Clean Cities claims to have displaced approximately 3 billion gallons of gasoline with alternate fuels, with the largest contributions coming from natural gas and ethanol.[109]

EPAct 2005 also included several voluntary programs to help generate widespread adoption of alternative vehicles, such as fuel cell school buses.[110] In general, the success of these programs is fairly limited and some were never implemented; this was the case with the FC school bus project due to the extremely high costs of capital (a FC school bus costs around $2-3 million compared to $350,000 regular school bus) and hydrogen (2-4 times more expensive than diesel).[111]

EISA 2007 also provided incentives for the creation of voluntary programs to encourage the use of electric vehicles, authorizing $90 million per year for this purpose.[112] The "Plug-in Electric Drive Vehicle Program" provided grants to local and state government agencies and private/non-profit entities to create projects that would encourage the use of EVs and other advanced vehicle technologies. These grants were intended to stimulate R&D of technology in the early stages of adoption. EISA also created the Near-Term Transportation Sector Electrification Program, which authorized $95 million a year for grants to large scale electric transportation projects, including an electric vehicle competition. It also created an electric vehicle education program to encourage the study of EVs in schools and Universities.[113]

Though these sorts of demonstrations and voluntary programs can help to increase understanding and acceptance of alternative vehicles, their impact appears to be limited. Barriers to their adoption are still significant, and until these are overcome, there will likely be fewer alternative vehicles than is socially optimal.

3.3 Technological Advancements and R&D

The federal government has also invested in research to reduce the high cost of AFVs and batteries, so as to help eliminate the barriers to adoption.

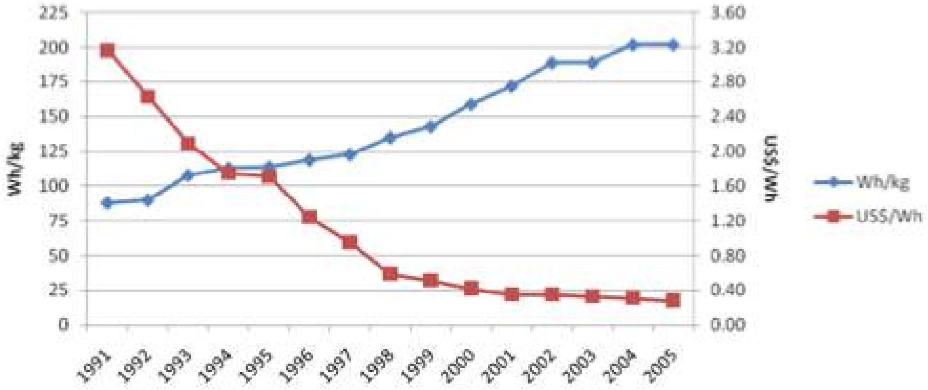
In 2007, the National Academy of Sciences recommended that the Department of Energy establish a program to invest in the development of advanced technologies, called Advanced Research Projects Agency-Energy (ARPA-E). This program was intended to support cutting edge technological research by independent entities, such as Universities, firms and others, to address long-term energy issues.[114]

ARPA-E was authorized in the America COMPETES Act, though it did not receive any funding until October 2009, when ARRA provided the program with $400 million. These funds are used to support 37 different energy projects focusing on renewable energy research, energy storage and fuel-independent vehicles.[115] Together, two rounds of ARPA-E projects have provided funding to advance technology development for advanced vehicles, including EVs, AFVs, and fuel cell vehicles, as well as funding for battery development.

EISA 2007 also implemented a grant program to help develop plug-in hybrid electric vehicles (PHEVs) and EVs, and a $25 billion loan program to aid in the development of infrastructure that produces alternative vehicles and their components.[116] Furthermore, EISA guaranteed loans for the production of EVs and for the production of advanced batteries.[117]

Federal R&D support may be the most important and impactful way to advance the adoption of alternative vehicles. Though cost reduction and performance remain key focus areas for research, the price of Li-ion batteries has decreased over the years, while their energy density has increased, as can be seen in Figure 8. R&D investments can therefore help accelerate cost reductions and performance improvements.

Figure 8. Historical Cost Reductions for Li-ion Batteries, 1991-2005



Source: Farrell, John (2011). “Democratizing the Electricity System: A Vision for the 21st Century Grid”. New Rules Project. http://energyselfreliantstates.org/content/democratizing-electricity-system

4. Conclusion

Over the last three decades, there has been a worldwide push to adopt non-petroleum transportation fuels and to develop vehicles that can run on these alternative fuels. The US has taken a multi-faceted approach to encourage these developments, devising a range of incentives, mandates, tax credits, loan guarantees, demonstration programs and voluntary programs to condition markets, require or encourage manufacturers to produce and consumers to purchase AFVs and EVs. Some policy tools have been complementary but success in general has been relatively limited. Opposition from interest groups, lack of enforcement and monitoring, incoherent policies, low gasoline prices, technological stagnation, lack of refueling stations, and other complications still present substantial barriers to broad deployment and acceptance of AFVs and EVs. Also, these policies have arguably failed at achieving the underlying goals: improving GHG emissions and pollution, decreasing gasoline consumption, and increasing energy security. Questionable or limited progress towards these objectives suggests that federal dollars have not been well spent and that we have yet to find the appropriate mix of government incentives that will enable substantial progress towards these goals.

Providing costly incentives for highly efficient alternative vehicles, such as EVs, PHEVs, and FCVs, is arguably a very inefficient way of reducing GHG emissions, given the high costs to government and vehicle manufacturers and the diminishing returns to gasoline reduction from efficiency increases. Allowances in standards for these vehicles are more costly and less effective policy instruments than focusing on increasing the MPG of the least fuel efficient vehicles.

While it may be less economically efficient to promote electric and other high fuel efficient vehicles, government investments in research to accelerate the advancement of the underlying technologies may be one of the most successful ways to mainstream these vehicles. Focusing on bringing down battery costs, for example, will result in lower vehicle prices, and increased adoption, without having to subsidize or mandate the purchase of the vehicle. Once the costs of electric vehicles have become competitive with internal combustion engine vehicles, adoption will occur on a much greater scale.

Clearly, many of these policies have fallen short of achieving their primary goals and are difficult to implement, especially when the policies are structured in ways that exacerbate opposition from manufacturers. The lack of penalties for non-compliance and the lack of enforcement of existing penalties have also diminished policy effectiveness. Likewise, policies that have long waiting periods prior to their implementation encourage lawsuits and increase uncertainty.

Given the increasing emphasis on promoting these alternative vehicles, it is time to take a step back and ask whether this set of policy tools provides the correct avenue for reaching the goals of environmental improvement and energy security. Stronger compliance mechanisms, coupled with regulatory certainty and a clearer understanding of the technology constraints and market conditions is desirable and could help achieve policy goals. However, the policies detailed in this paper do not address the other externalities associated with driving, such as congestion and accidents, so their scope is somewhat limited. Policies that target driving behaviors, such as a VMT or gasoline tax, for example, could arguably do more to address all the issues mentioned above, and also fit within a much simpler administrative framework. These types of policies have not been adopted due to the public's negative opinion of them. Yet if we spent merely a fraction of the resources that we have placed in promoting alternative fuels and vehicles on instead attempting to change the public's perception (such as an intensive campaign promoting coupling taxes with lump sum rebates), we might have been able to reach a more optimal solution.

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[1] Parry, Ian W. H. and Kenneth A. Small (2005). "Does Britain or the United States Have the Right Gasoline Tax?"*American Economic Review*, Vol. 95, No. 4, pp. 1276–1289.

[2] Williams, Roberton C. III (2005). "An Estimate of the Second-Best Optimal Gasoline Tax Considering Both Efficiency and Equity." Working Paper.

[3] West, Sarah E. and Roberton C. Williams III (2007). "Optimal taxation and cross-price effects on labor supply: Estimates of the optimal gas tax." *Journal of Public Economics*, Vol. 91, No. 3-4, pp. 593–617.

[4] Babcock, Bruce A. (2007). "High Crop Prices, Ethanol Mandates, and the Public Good: Do They Coexist?" *Iowa Ag Review*, Vol. 13, No. 2

[5] Hahn, Robert and Caroline Cecot (2007). "The Benefits and Costs of Ethanol," Working Paper 07-17, AEI-Brookings Joint Center for Regulatory Studies, November 2007.

[6] DOE/EIA: Annual Energy Outlook 2011, Table 58- Light-Duty Vehicle Stock by Technology Type.

[7] Schnepf, Randy and Brent D. Yacobucci (2012). "Renewable Fuel Standard (RFS): Overview and Issues." Congressional Research Service Report for Congress, January 23, 2012, Page 21.

[8] ICM: "Ethanol, the Fuel of the Future" http://www.icminc.com/timeline/1862.html

[9] Cato, Greg (2010). "Clearing the Air: A Policy Analysis of the Ethanol Tax Credit." *Policy Perspectives*, Vol. 17, pp. 71-88.

[10] **TEA-21 - Transportation Equity Act for the 21st Century,** §9003(b)(h)(2)

[11] Yacobucci, Brent D. (2012). "Biofuels Incentives: A Summary of Federal Programs." Congressional Research Service Report for Congress, January 11, 2012.

[12] Elam, Thomas E. (2007). "Fuel Ethanol Subsidies: An Economic Perspective." FarmEcon.com, September 19, 2007.

[13] Yacobucci, (2012).

[14] *Ibid*.

[15] US Energy Information Administration (2011). "Direct Federal Financial Interventions and Subsidies in Energy in Fiscal Year 2010." Independent Statistics and Analysis, US DOE.

[16] EPAct 2005, §1501 (a)(o)(2)(B).

[17] EISA, Title II, §202 (a)(2)(B)(i)(I).

[18] Federal Register, Vol. 77, No. 5, 1/9/2012, page 1339.

---

[19] EPAct 2005, §1501 (a)(o)(4).
[20] *Ibid*, §1501 (a)(o)(2)(B)(iii)(I).
[21] US Department of Agriculture (2011). “U.S. on Track to become World’s Largest Ethanol Exporter in 2011.” http://www.fas.usda.gov/info/IATR/072011_Ethanol_IATR.pdf, page 1.
[22] Wang, Michael, May Wu, Hong Huo and Jiahong Liu (2008). “Life-Cycle Energy Use and Greenhouse Gas Emission Implications of Brazilian Sugarcane Ethanol Simulated with the GREET Model.” *International Sugar Journal*, Vol. 110, No. 1317.
[23] Walter, Arnaldo *et.al.* (2011). “Sustainability assessment of bio-ethanol production in Brazil considering land use change, GHG emissions and socio-economic aspects.” *Energy Policy*, Vol. 39, No. 12, pp. 5703-5716.
[24] Cordonnier, Vanessa (2009). “Ethanol’s Roots: How Brazilian Legislation Created the International Ethanol Boom.” *William & Mary Environmental Law & Policy Review, Vol. 33, Issue 1, pp. 287-317.*
[25] Puerto Rico, Julieta Andrea (2008). "Programa de Biocombustíveis no Brasil e na Colômbia: uma análise da implantação, resultados e perspectivas" (in Portuguese). Universidade de São Paulo. Ph.D. Dissertation Thesis.
[26] Macedo Isaias, M. Lima Verde Leal and J. Azevedo Ramos da Silva (2004). “Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil.” Secretariat of the Environment, Government of the State of São Paulo.
[27] Lapola, David M. *et.al.* (2010). “Indirect land-use changes can overcome carbon savings from biofuels in Brazil” PNAS, Vol. 107, no. 8, pp. 3388–3393.
[28] National Research Council (2011), page. 6.
[29] *Ibid*, pp. 4-5.
[30] *Ibid.*
[31] National Research Council. *Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy*. Washington, DC: The National Academies Press, 2011, pp. 204-206.
[32] Yang, Yi, Junghan Bae, Junbeum Kim, and Sangwon Suh (2012). “Replacing Gasoline with Corn Ethanol Results in Significant Environmental Problem-Shifting.” *Environmental Science & Technology*, doi: 10.1021/es203641p.
[33] Congressional Budget Office (2010). “Using Biofuel Tax Credits to Achieve Energy and Environmental Policy Goals.” July 2010, Pub. No 4044, page VIII.
[34] National Research Council (2011), pp. 2-3.
[35] EPAct 2005, §1512
[36] National Research Council (2011), page 4.
[37] US EPA (2010). “Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis.” EPA-420-R-10-006, page 5.
[38] Krupnick, Alan (2010). “Energy, Greenhouse Gas, and Economic Implications of Natural Gas Trucks.” Resources for the Future Background Paper.
[39] EPAct 2005, §1342.
[40] ARRA 2009, §1123.
[41] Tax Relief Act 2010, §711.
[42] EISA 2007, §246(a).
[43] US DOE, Alternative Fuels Data Center, “Public Retail Gasoline Stations by State and Year”
[44] Papageorgiou, Andreas (2005). “Natural Gas in Argentina.” PREMIA.
[45] United Nations Working Party on Gas Inland Transport Committee (2003). “Blue Corridor Project: on the use of natural gas as a motor fuel in international freight and passenger traffic.”
[46] Lowe, Marcy, Saori Tokuoka and Tali Trigg (2010). “Lithium-ion Batteries for Electric Vehicles: The US Value Chain.” Center on Globalization, Governance & Competitiveness, Duke University. October 5, 2010.
[47] EISA 2007, §102(b)(2)(A).
[48] *Ibid*, §102(k)(1)(B).
[49] United States General Accounting Office (2000). “Energy Policy Act of 1992: Limited Progress in Acquiring Alternative Fuel Vehicles and Reaching Fuel Goals.” Report to Congressional Requesters, page 17.
[50] Department of Energy (2008). “Review of Energy Policy Act of 1992 Programs and the Alternative Fuel Provider Fleet Mandate.” Report to Congress, Prepared in Compliance with Sections 704 and 1831 of the Energy Policy Act of 2005 and Section 501 of the Energy Policy Act of 1992.
[51] EPA (2010), Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis, page 252.
[52] For a review of estimated rebound effects see: Small, Kenneth and Kurt Van Dender (2007). “Fuel Efficiency and Motor Vehicle Travel: The Declining Rebound Effect.” *Energy Journal*, Vol. 28, No. 1, pp. 25-51.
[53] Federal Register, Vol. 75, No. 88, 5/7/2010, page 25347.

---

[54] *Ibid*, page 25379.
[55] *Ibid*, page 25517.
[56] *Ibid*, page 25519.
[57] US EPA (2008). "Advance Notice of Proposed Rulemaking: Regulating Greenhouse Gas Emissions under the Clean Air Act." Docket number EPA-HQ-OAR-2008-0318, June 2008.
[58] McCarthy, James (2007). "CRS Report for Congress: California's Waiver Request to Control Greenhouse Gases Under the Clean Air Act." Congressional Research Service, August 20, 2007, pp. CRS 3-4.
[59] Clean Air Act, Title II, § 209(b).
[60] McCarthy (2007), pp. CRS1-3
[61] *Ibid*, pp. CRS 4.
[62] Federal Register, Vol. 75, No. 88, 5/7/2010, page 25324.
[63] Goulder, Lawrence H., Mark R. Jacobsen, and Arthur A. van Benthem (2012). "Unintended consequences from nested state and federal regulations: The case of the Pavley greenhouse-gas-per-mile limits." *Journal of Environmental Economics and Management*, Vol. 63, No. 2, pp. 187-207.
[64] Federal Register, Vol. 75, No. 88, 5/7/2010, page 25328.
[65] *Ibid*, page 25330.
[66] *Ibid*, page 25432.
[67] *Ibid*, page 25433.
[68] *Ibid*, pp. 25435-25436.
[69] Federal Register, Vol. 76, No. 153, 8/9/2011, page 49759.
[70] *Ibid*, page 48761.
[71] US DOE, Alternative Fuels and Advanced Vehicles Data Center "Benefits of Hybrid and Plug-in Electric Vehicles." http://www.afdc.energy.gov/afdc/vehicles/electric_benefits.html
[72] Interview with William Chernicoff, Energy & Environmental Research Group Manager, Toyota Motor North America, Inc. 3/19/2012.
[73] Lee, Henry and Grant Lovellette (2011). "Will Electric Cars Transform the US Vehicle Market? An analysis of the key determinants." Energy Technology Innovation Policy Discussion Paper Series, Discussion Paper #2011-08, page 10.
[74] Federal Register, Vol. 76, No. 179, 9/15/2011, page 57124.
[75] *Ibid*, page 57125.
[76] Harrington, Winston and Alan Krupnick (2012). "Improving Fuel Economy in Heavy-Duty Vehicles." RFF Issue Brief 12-01, March 2012.
[77] Energy Policy Act of 1992, §303(b).
[78] *Ibid*, §310.
[79] Department of Energy (2008), page 17.
[80] *Ibid*, page 28.
[81] United States General Accounting Office (2000), page 10.
[82] DOE (2011). Statement of Mr. Patrick Davis, Program Director, Vehicle Technologies Program, May 5, 2011. http://www.international.energy.gov/sites/prod/files/ciprod/documents/EE_Final_Testimony(2).pdf
[83] DOE (2008), page 13.
[84] *Ibid*, page 2.
[85] EPAct 2005, §701.
[86] EISA 2007, §400FF (a)(2)
[87] EPAct 1992, §501.
[88] *Ibid*, §512.
[89] Langer, Therese and Daniel Williams (2002). "Greener Fleets: Fuel Economy Progress and Prospects." ACEEE, Report Number T024.
[90] DOE (2008), page 33.
[91] California Environmental Protection Agency Air Resources Board. "Zero-Emission Vehicle Legal and Regulatory Activities – Background", webpage: http://www.arb.ca.gov/msprog/zevprog/background.htm, Accessed 3/1/2012
[92] *Ibid.*
[93] California Environmental Protection Agency Air Resources Board (2009). "California Exhaust Emissions Standards and Test Procedures for 2009 and Subsequent Model Zero-Emission Vehicles and Hybrid Electric Vehicles, In the Passenger Car, Light-Duty Truck and Medium-Duty Vehicle Classes." as of February 13, 2010 (last amended December 2, 2009), incorporated by reference in Section 1962.1(h), Title 13, CCR.

---

[94] California Environmental Protection Agency Air Resources Board (2012). Final Regulation Order: §1962.1 "Zero Emission Vehicle Standards for 2009 through 2017 Model Year Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicle."

[95] Information Administration (2011). "Alternatives to Traditional Transportation Fuels, 2009", Table V1: Estimated Number of Alternative Fueled Vehicles in Use in the United States, by Fuel Type, 2005 – 2009. http://www.eia.gov/renewable/alternative_transport_vehicles/index.cfm

[96] *Ibid*, Table V10: Estimated Number of Electric Vehicles in Use, by State and User Group 2009.

[97] EPAct 2005, §1341.

[98] The Auto Channel, January 4, 2006. "Toyota Reports 2005 and December Sales." http://www.theautochannel.com/news/2006/01/04/205039.html

[99] ARRA 2009, §1141.

[100] *Ibid*, §1143.

[101] Department of Transportation/NHTSA (2009). "49 CFR Parts 512 and 599: Requirements and Procedures for Consumer Assistance to Recycle and Save Program".

[102] Li, Shanjun, Joshua Linn, and Elisheba Spiller (2011). "Evaluating "Cash-for-Clunkers": Program Effect on Auto Sales and the Environment." Working Paper, Available at SSRN: http://ssrn.com/abstract=1594924

[103] Mian, Atif R. and Sufi, Amir (2010). "The Effects of Fiscal Stimulus: Evidence from the 2009 'Cash for Clunkers' Program." Working Paper, Available at SSRN: http://ssrn.com/abstract=1670759

[104] The Transportation Equity Act for the 21st Century, §1216 (a)(5).

[105] Turnbull, Katherine (2005). "Potential Impact of Exempt Vehicles on HOV Lanes". US Department of Transportation Federal Highway Administration.

[106] Shewmake, Sharon and Lovell Jarvis (2011). "Hybrid Cars and HOV Lanes." Working Paper, Available at SSRN: http://ssrn.com/abstract=1826382

[107] Diamond, David (2009). "The impact of government incentives for hybrid-electric vehicles: Evidence from US states." *Energy Policy*, Vol. 37, pp. 972-983.

[108] EPAct 1992, Title VII.

[109] US Department of Energy, Clean Cities Program: http://www1.eere.energy.gov/cleancities/about.html

[110] EPAct 2005, §743.

[111] US Department of Energy (2008). "Fuel Cell School Buses: Report to Congress."

[112] EISA 2007, §131.

[113] *Ibid*.

[114] National Academy of Sciences (2007). Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future. National Academies Press.

[115] US DOE (2009). "DOE Awards $151 Million in Recovery Act Funding for ARPA-E Projects." SunShot Initiative – News, http://www1.eere.energy.gov/solar/sunshot/m/news_detail.html?news_id=15576.

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