Prospects for Flexible- and Bi-Fuel Light Duty Vehicles: Consumer Choice and Public Attitudes

Ulrich Kramer*, James E. Anderson**
Ford Motor Company, Research & Advanced Engineering, Europe* & North America**

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\textsubscript{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>
<thead>
<tr>
<th>Types of Alternative Fuel Vehicles</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dedicated-fuel vehicle</td>
<td>Any vehicle engineered and designed to be operated using a single fuel.</td>
</tr>
<tr>
<td>Mono-fuel vehicle</td>
<td>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.</td>
</tr>
<tr>
<td>Bi-fuel vehicle</td>
<td>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.</td>
</tr>
<tr>
<td>Flex-fuel vehicle (FFV)</td>
<td>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.</td>
</tr>
<tr>
<td>Dual-fuel vehicle</td>
<td>Vehicle with two independent fuel systems that can run on both fuels simultaneously. It also may run on one fuel alone.</td>
</tr>
</tbody>
</table>

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-Alcool” 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.

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].](image)

![Figure 2 – E100 History in Brazil [3,4]](image)

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>Brazilian government issued national alcohol program to develop a renewable fuel for vehicle purposes from sugar cane.</td>
</tr>
<tr>
<td>1979</td>
<td>First E100 dedicated-fuel vehicle built: Fiat model 147</td>
</tr>
<tr>
<td>1985</td>
<td>Dedicated-fuel E100 vehicles comprise more than 80% of LDV production.</td>
</tr>
<tr>
<td>1990s</td>
<td>Challenges for dedicated-fuel E100 vehicle market: low oil prices and high sugar prices =&gt; Ethanol shortage in internal market =&gt; Consumers stop purchasing dedicated-fuel E100 vehicles.</td>
</tr>
<tr>
<td>2002</td>
<td>First flexible-fuel vehicle (FFV) demonstrated: Ford Fiesta</td>
</tr>
<tr>
<td>2003</td>
<td>OEMs begin offering FFVs in the market</td>
</tr>
<tr>
<td>2008</td>
<td>FFVs comprise 87% of new LDV registrations.</td>
</tr>
</tbody>
</table>

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].
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.

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.

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.

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]](image)

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 CO₂ 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 CO₂ 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 CO₂ 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.

Furthermore, the volume of ethanol blended into E85 was approximately equal to that blended into E5 gasoline in 2011.

![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.](image)

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.

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.

![Figure 11 – E85 and E5 gasoline consumption in Sweden, 2005 to 2011 [30]](image)
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].

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 complete 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.

Lessons learned:

- 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) CO₂ 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 gasol ine 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].](image)

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\(_3\)H\(_8\), 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 m³), or 150 times current annual global NG consumption [57]. Furthermore, because of its greater hydrogen-to-carbon ratio, it provides a 20-25% TTW CO₂ 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 ft³) [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]

<table>
<thead>
<tr>
<th>Country</th>
<th>No. of CNGVs</th>
<th>No. of CNG Stations</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pakistan</td>
<td>2,740,000</td>
<td>3,285</td>
</tr>
<tr>
<td>2</td>
<td>Iran</td>
<td>1,954,925</td>
<td>1,574</td>
</tr>
<tr>
<td>3</td>
<td>Argentina</td>
<td>1,901,116</td>
<td>1,878</td>
</tr>
<tr>
<td>4</td>
<td>Brazil</td>
<td>1,664,847</td>
<td>1,725</td>
</tr>
<tr>
<td>5</td>
<td>India</td>
<td>1,080,000</td>
<td>571</td>
</tr>
<tr>
<td>6</td>
<td>Italy</td>
<td>730,000</td>
<td>790</td>
</tr>
<tr>
<td>7</td>
<td>China</td>
<td>450,000</td>
<td>1,350</td>
</tr>
<tr>
<td>8</td>
<td>Colombia</td>
<td>340,000</td>
<td>614</td>
</tr>
<tr>
<td>9</td>
<td>Thailand</td>
<td>218,459</td>
<td>426</td>
</tr>
<tr>
<td>10</td>
<td>Ukraine</td>
<td>200,000</td>
<td>285</td>
</tr>
<tr>
<td>11</td>
<td>Bangladesh</td>
<td>193,521</td>
<td>546</td>
</tr>
<tr>
<td>12</td>
<td>Bolivia</td>
<td>140,400</td>
<td>156</td>
</tr>
<tr>
<td>13</td>
<td>Egypt</td>
<td>122,271</td>
<td>119</td>
</tr>
<tr>
<td>14</td>
<td>United States</td>
<td>112,000</td>
<td>1,000</td>
</tr>
<tr>
<td>15</td>
<td>Peru</td>
<td>103,712</td>
<td>137</td>
</tr>
<tr>
<td>16</td>
<td>Armenia</td>
<td>101,352</td>
<td>297</td>
</tr>
<tr>
<td>17</td>
<td>Russia</td>
<td>100,000</td>
<td>244</td>
</tr>
<tr>
<td>18</td>
<td>Germany</td>
<td>91,500</td>
<td>900</td>
</tr>
<tr>
<td>19</td>
<td>Bulgaria</td>
<td>60,270</td>
<td>81</td>
</tr>
<tr>
<td>20</td>
<td>Uzbekistan</td>
<td>47,000</td>
<td>133</td>
</tr>
</tbody>
</table>

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.
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.

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].

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Fuel quantity with energy content of liter of gasoline</th>
<th>Fuel Price, € per liter gasoline equivalent</th>
<th>Fuel Tax, € per liter gasoline equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>1 liter</td>
<td>1.60</td>
<td>0.665</td>
</tr>
<tr>
<td>Diesel</td>
<td>0.92 liter</td>
<td>1.37</td>
<td>0.432</td>
</tr>
<tr>
<td>CNG</td>
<td>0.66 kg</td>
<td>0.68</td>
<td>0.120</td>
</tr>
<tr>
<td>LPG</td>
<td>1.31 liter</td>
<td>0.96</td>
<td>0.120</td>
</tr>
</tbody>
</table>

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).

<table>
<thead>
<tr>
<th></th>
<th>Ford Focus CNG</th>
<th>Ford Focus LPG</th>
<th>Ford Focus FFV (E85) Hypothetical*</th>
<th>Ford Focus Gasoline</th>
<th>Ford Focus Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.0l NA 126 hp</td>
<td>2.0l NA 141 hp</td>
<td>2.0l NA 126 hp</td>
<td>2.0l NA 145 hp</td>
<td>2.0l TC 136 hp</td>
</tr>
<tr>
<td>Fuel Price € / liter or kg (CNG)</td>
<td>1.03</td>
<td>0.73</td>
<td>1.06</td>
<td>1.60</td>
<td>1.48</td>
</tr>
<tr>
<td>Yearly Mileage / km</td>
<td>Yearly fuel costs / €</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15,000</td>
<td>880.65</td>
<td>1,040.20</td>
<td>1,558.20</td>
<td>1,728.00</td>
<td>1,296.30</td>
</tr>
<tr>
<td>30,000</td>
<td>1,761.30</td>
<td>2,080.50</td>
<td>3,116.40</td>
<td>3,456.00</td>
<td>2,592.60</td>
</tr>
<tr>
<td>45,000</td>
<td>2,641.95</td>
<td>3,120.75</td>
<td>4,674.60</td>
<td>5,184.00</td>
<td>3,888.90</td>
</tr>
<tr>
<td>Yearly Mileage / km</td>
<td>Pay Back Period / years</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15,000</td>
<td>4.0</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
<td>4.0</td>
</tr>
<tr>
<td>30,000</td>
<td>2.0</td>
<td>0.7</td>
<td>0.7</td>
<td></td>
<td>2.3</td>
</tr>
<tr>
<td>45,000</td>
<td>1.3</td>
<td>0.5</td>
<td>0.5</td>
<td></td>
<td>1.3</td>
</tr>
</tbody>
</table>

* 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 CNG 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.

Lessons learned:

• 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, monofuel 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 monofuel 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.

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 CO₂ 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) CO₂ reductions versus gasoline. With bio-methane or e-methane close to 100% fossil CO₂ 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, monofuel 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.

5. ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of our colleagues in preparing this paper: Leandro Benvenutti, Tim Wallington, and Wulf-Peter-Schmidt.

6. ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEV</td>
<td>Battery Electric Vehicle</td>
</tr>
<tr>
<td>CNG</td>
<td>Compressed Natural Gas</td>
</tr>
<tr>
<td>CNGV</td>
<td>CNG Vehicle</td>
</tr>
<tr>
<td>ECU</td>
<td>Engine Control Unit</td>
</tr>
<tr>
<td>ETBE</td>
<td>Ethyl Tertiary Butyl Ether</td>
</tr>
<tr>
<td>FAME</td>
<td>Fatty Acid Methyl Esters (Biodiesel)</td>
</tr>
<tr>
<td>FFV</td>
<td>Flexible Fuel Vehicle</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
</tr>
<tr>
<td>LPG</td>
<td>Liquefied Petroleum Gas</td>
</tr>
<tr>
<td>LPGV</td>
<td>LPG Vehicle</td>
</tr>
<tr>
<td>MTBE</td>
<td>Methyl Tertiary Butyl Ether</td>
</tr>
<tr>
<td>NG</td>
<td>Natural Gas</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>TTW</td>
<td>Tank to Wheel</td>
</tr>
<tr>
<td>WTT</td>
<td>Well to Tank</td>
</tr>
<tr>
<td>WTW</td>
<td>Well to Wheel</td>
</tr>
</tbody>
</table>

7. CONTACT INFORMATION

Ulrich Kramer  
Ford Motor Company  
Research and Advanced Engineering Europe  
Powertrain Research & Advanced  
Spessart Strasse, D-ME/5-B8  
D-50725 Cologne, Germany

James E. Anderson  
Ford Motor Company  
Research and Advanced Engineering  
Systems Analytics and Environmental Sciences Department,  
PO Box 2053, Mail Drop RIC-2122  
Dearborn, MI 48121

8. REFERENCES


40 Verband der Automobilindustrie (VDA, Association of German Automobile Manufacturers), personal communication, 2011.
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,


