The Case for Bi-Fuel Natural Gas Vehicles

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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**

<table>
<thead>
<tr>
<th>Total NGV population - Cars, Buses and Trucks</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD+MD +HD Vehicels</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>11,931,328</td>
</tr>
</tbody>
</table>

Source: Gas Vehicles Report, October 2010

\(^1\) [http://en.wikipedia.org/wiki/Natural_gas_vehicle](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.


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

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


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 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 weight reduces fuel consumption by 0.6 to 0.9 percent. 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 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

<table>
<thead>
<tr>
<th>OEM</th>
<th>Model</th>
<th>Power (hp)</th>
<th>CNG storage kg</th>
<th>Gasoline storage (L)¹</th>
<th>Range (km)</th>
<th>CO2 g/km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiat</td>
<td>Panda 1.2 8V</td>
<td>69</td>
<td>15</td>
<td>30</td>
<td>800</td>
<td>107</td>
</tr>
<tr>
<td>Fiat</td>
<td>Punto Evo 1.4 8V</td>
<td>70</td>
<td>15</td>
<td>45</td>
<td>1000</td>
<td>115</td>
</tr>
<tr>
<td>Fiat</td>
<td>Qubo 1.4 8V</td>
<td>70</td>
<td>15</td>
<td>45</td>
<td>950</td>
<td>114</td>
</tr>
<tr>
<td>Fiat</td>
<td>Fiorino 1.4 8V</td>
<td>70</td>
<td>15</td>
<td>45</td>
<td>960</td>
<td>119</td>
</tr>
<tr>
<td>Mercedes Benz</td>
<td>B 180 NGT</td>
<td>163</td>
<td>19.5</td>
<td>54</td>
<td>1070</td>
<td>149</td>
</tr>
<tr>
<td>Mercedes Benz</td>
<td>E 200 NGT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opel</td>
<td>Zafira Tourer 1.6 CNG Turbo ecoFlex</td>
<td>150</td>
<td>25</td>
<td>14</td>
<td>680</td>
<td>129</td>
</tr>
<tr>
<td>Opel</td>
<td>Comobal 1.4 CNG Turbo ecoFLEX</td>
<td>120</td>
<td>16-22</td>
<td>22</td>
<td>750</td>
<td>134</td>
</tr>
<tr>
<td>VW</td>
<td>Up! CNG</td>
<td>68</td>
<td>11</td>
<td></td>
<td>79-86</td>
<td></td>
</tr>
<tr>
<td>VW</td>
<td>Passat 1.4 TSI EcoFuel</td>
<td>150</td>
<td>21</td>
<td>31</td>
<td>940</td>
<td>117</td>
</tr>
<tr>
<td>VW</td>
<td>Touran 1.4 TSI EcoFuel</td>
<td>150</td>
<td>18-21</td>
<td>11</td>
<td>650</td>
<td>128</td>
</tr>
<tr>
<td>VW</td>
<td>Caddy 2.0 EcoFuel</td>
<td>109</td>
<td>37</td>
<td>13</td>
<td>760</td>
<td>156</td>
</tr>
</tbody>
</table>

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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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. 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

![Figure 2. Example of European NGV Packing](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](http://www.drive-alive.co.uk/fuel_prices_europe.html)


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

![Graph showing payback in years for incremental vehicle costs 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.
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 compete 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.


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.\textsuperscript{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.

\textsuperscript{11} Much of the following discussion was taken from work performed by the CarLab as a subcontractor to TIAX.
Assumptions:

<table>
<thead>
<tr>
<th>Vehicle Make and Model</th>
<th>MSRP</th>
<th>MPG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honda Civic GX</td>
<td>$25,280</td>
<td>28</td>
</tr>
<tr>
<td>Honda Civic Hybrid</td>
<td>$23,800</td>
<td>42</td>
</tr>
<tr>
<td>Honda Civic LX</td>
<td>$18,260</td>
<td>29</td>
</tr>
<tr>
<td>Toyota Camry</td>
<td>$19,720</td>
<td>26</td>
</tr>
<tr>
<td>Toyota Camry Hybrid</td>
<td>$26,150</td>
<td>34</td>
</tr>
<tr>
<td>Toyota Prius</td>
<td>$22,800</td>
<td>50</td>
</tr>
</tbody>
</table>

(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 dedicated NGV and therefore dependent on a convenient fueling infrastructure. Honda did for a period market a home CNG appliance called Phill through Fuelmaker. The appliance is now being marketed 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. 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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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.](image)

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.
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 everyday 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. 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.

![Cumulative Percentage of All Drivers](image)

**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.

\(^{13}\) There is distribution of daily mileages that will limit the penetration of vehicles designed for a daily range of 40 miles.

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 alternative averaging about $3,000 over the vehicle’s lifetime.

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