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Issues Affecting Adoption of Natural Gas Fuel in Light- and Heavy-Duty Vehicles

GA Whyatt

September 2010



Pacific Northwest
NATIONAL LABORATORY

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Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

This report provides a preliminary examination of the incentives and barriers for adopting natural gas as the fuel for light-duty passenger cars, heavy duty combination trucks, and fleet vehicles of all types. In all cases the primary incentive to switch from gasoline or diesel fuel to natural gas is the potential savings in fuel costs. Additional benefits at a national level include a reduction in foreign oil imports and reduced vehicle emissions. Barriers to application of CNG to passenger vehicles include the cost premium for the vehicle, significant competition from hybrid vehicles, limited original equipment manufacturer vehicle selection, high cost and poor selection for U.S. Environmental Protection Agency-approved vehicle conversions, and a limited public refueling infrastructure. The purchase and maintenance costs for operating a compressor at home to refuel from a residential gas source is less cost effective than using a public refueling station and provides fuel at a lower cost than gasoline only in regions of the country with the lowest natural gas prices. Heavy-duty vehicles using liquefied natural gas (LNG) with a high-pressure direct injection system (HPDI) engine have improved driving range, efficiency, and power compared to a similar vehicle using CNG with a spark-ignited engine. However, use of LNG makes the lack of a refueling infrastructure even more critical because CNG stations far outnumber LNG stations. Despite the fact that an LNG-equipped truck is much more expensive than a diesel truck, the payback in terms of fuel cost is more rapid than a passenger vehicle because of the higher number of miles travelled per year and the much lower fuel mileage, which increases the potential fuel cost savings. The most attractive opportunity for natural gas vehicles is for fleet vehicles operating in regions with low natural gas prices because of 1) the ability of the vehicles to return to a captive refueling infrastructure and 2) the relatively high number of miles driven per year. Displacing a major fraction of gasoline and diesel vehicles will require significant incremental investments in the natural gas infrastructure. Incremental investments to reach a 20-percent penetration of the vehicle fuel market (the point at which a market may become self-sustaining) assuming an LNG/CNG refueling station infrastructure are estimated to be ~\$87 billion for production and distribution, ~\$68 billion for refueling stations and ~\$72 billion for liquefaction capacity. Cost would increase proportionally if 56-percent market penetration is assumed, which would be necessary to displace vehicle fuel attributable to imported oil. While investments in natural gas production will occur without additional incentives as demand increases, the same may not be true for public refueling stations, which require that a threshold number of CNG vehicles be on the road before the stations become profitable. Measures that may help develop the refueling infrastructure are incentivizing private refueling stations to provide public access, incentivizing public refueling station construction, and encouraging bi-fuel vehicles that can utilize a limited CNG refueling infrastructure where available but still operate in areas where CNG refueling stations are not available. The potential impact on oil imports is about 2.6 times greater for on-road gasoline vehicles than for on-road diesel vehicles. This is due to a combination of a larger fraction of a barrel of oil being converted to gasoline combined with a higher percentage of gasoline being used for on-road vehicles. However, the greatest impact is obtained by use of natural gas to displace both gasoline and diesel fuel. The higher cost of natural gas vehicles leads to their introduction to the vehicle fleet being primarily limited to new vehicles which have a longer remaining life over which the fuel cost savings can be realized. As a result, the rate at which the overall vehicle population can be shifted to natural gas will be limited by the time required to retire the existing conventional vehicle population. A higher price differential in fuel prices could accelerate the rate of adoption by making it economical to retire existing vehicles earlier.

Acknowledgments

Funding for this report was provided through the Vehicle Technology Program, located within the Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy.

Acronyms and Abbreviations

AT-PZEV – Advanced Technology-Partial Zero Emission Vehicle, CARB emission rating
bsfc – brake specific fuel consumption, mass of fuel consumed relative to mechanical work produced
bi-fuel – the ability to switch between fuels, for example operate on either gasoline or natural gas
dual-fuel – simultaneously uses two fuels, for example a pilot injection of diesel to ignite natural gas
CARB – California Air Resource Board
CNG – compressed natural gas
DOE – Department of Energy
DOT – Department of Transportation
E85 – refers to a vehicle capable of operating on gasoline ethanol blends up to 85% ethanol
EERE – Energy Efficiency and Renewable Energy, office within DOE
EIA – Energy Information Administration
EPA – Environmental Protection Agency
GGE – gallons of gasoline equivalent, see appendix E
GDE – gallons of diesel equivalent, see appendix E
GVWR – Gross Vehicle Weight Rating
HPDI – High pressure direct injection, type of natural gas engine
IRS – Internal Revenue Service
ISO – International Organization for Standardization
INGAA – Interstate Natural Gas Association of America
ISL-G – a spark ignited natural gas SEGR engine produced by Cummins Westport
LHV – lower heating value, heat of combustion (ref 25°C) with water formed as vapor
LNG – liquefied natural gas
LNG/CNG – LNG refueling station which also provides CNG refueling by vaporizing LNG
LPG – liquefied petroleum gas
Net Energy Content – equivalent to LHV, uses 60°F reference temperature
NFPA – National Fire Protection Association
NGVA – Natural Gas Vehicles for America
NO_x – oxides of nitrogen, including NO and NO₂
OEM – Original Equipment Manufacturer
PM10 – particulate matter measuring 10 microns or less
SCR – Selective Catalytic Reduction, a method of reducing NO_x in exhaust gases
SEGR – Stoichiometric cooled Exhaust Gas Recirculation
SVM – Secondary Vehicle Manufacturer

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1.0 Introduction

There are a number of motivations for displacing gasoline or diesel-fueled engines with natural-gas-fueled engines in the United States—potential fuel cost savings, reduced dependence on imported foreign oil, and reduced engine emissions (e.g., carbon dioxide, nitrogen oxide, etc.). This report examines the incentives and barriers to adopting natural-gas-fueled engines to power light-duty gasoline and heavy-duty diesel vehicles. In addition, factors specific to fleet vehicles also are discussed. Displacing the following vehicle types with natural-gas-fueled vehicles is specifically discussed:

- Gasoline-fueled, light-duty, vehicles used primarily for personal transportation
- Diesel-fueled, heavy-duty, vehicles used for transporting freight
- Gasoline-fueled (e.g., cars, pickups, small vans, taxis, etc.) or diesel-fueled (e.g., buses, garbage trucks, dump trucks, cement trucks, delivery trucks) fleet vehicles that return to a common depot for refueling.

Included is an assessment of the relative feasibility of providing the natural gas refueling supply required if significant market penetration into each market segment were achieved. The report does not address the validity of the overall “Pickens Plan”¹ and the economic feasibility of displacing natural-gas-fueled electrical generation with wind and solar power.

¹ The Pickens Plan (August 24, 2010) for the United States is composed of four basic elements: 1) generate 22 percent of electricity from wind plus additional from solar, 2) enhance the electrical grid, 3) increase residential and commercial building energy efficiency, and 4) use natural gas as transportation fuel, thereby reducing foreign oil imports by one-third within 10 years.

2.0 Natural Gas in Light-Duty Vehicles

2.1 Engine Types Replacing Gasoline Engines in Light-Duty Vehicles

Natural-gas-fueled vehicles with spark-ignited engines may be either “bi-fuel” indicating an ability to switch back and forth between gasoline and natural gas or “dedicated” meaning that the gasoline fueling hardware is completely removed and the engine may run on natural gas only. A bi-fuel engine offers the advantage of allowing the use of gasoline when refueling with natural gas is not available. However, bi-fuel engines or conversions of gasoline engines that are accomplished simply by altering the fuel system result in an engine that will have lower power and efficiency when operating on natural gas than when fueled by gasoline. However, because of the high octane rating of natural gas, an engine constructed to run exclusively on natural gas can have a higher compression ratio, which improves the engine efficiency to a level similar to that of a gasoline engine. The only non-conversion, dedicated compressed natural gas (CNG) car available in the United States is the Honda Civic GX. Table 2.1 provides comparative information between the dedicated CNG-fueled (GX) and gasoline-fueled (LX) versions of the Honda Civic.

Table 2.1. Comparison of Engine Performance for Gasoline-Fueled and CNG-Fueled Honda Civics

	Civic LX, Gasoline	Civic GX, CNG
Displacement, cc	1799	1799
Compression Ratio	10.5	12.5
Horsepower	140	113
Torque at 4300 rpm	128	109
Combined Mileage, mpg	29	28

Conventional natural-gas-fueled engines can be classified as stoichiometric in that the oxygen and methane are added in a stoichiometric ratio. A stoichiometric engine contains a low oxygen content in the exhaust and may use the same three-way catalytic converter used with gasoline engines.

Lean-burn engines, available for natural-gas-powered generators, offer a potential to increase efficiency while reducing engine NO_x emissions. In the lean-burn engine, significant excess air is added that reduces combustion temperatures and NO_x formation at the engine. At low power, the ability to admit more air into the engine reduces throttling losses. Typically, a turbo charger is used to increase the power level above the level in a stoichiometric, non-turbocharged engine. The combustion chambers may use non-uniform charges or pre-combustion chambers to achieve reliable ignition near the lean limit. The additional complexity and addition of the turbocharger increases the cost of the engine; however, this engine design offers an option to improve power and efficiency relative to the gasoline engine. The VW 1.4-L TSI CNG engine¹ uses direct injection with twin charging and other engine enhancements to provide similar power, torque, and mileage on either gasoline or CNG. This performance is achieved by adjusting the boost pressure and ignition timing depending on the fuel.²

¹ Offered on the Passat Ecofuel bifuel vehicle, which is not available in the United States.

² VW presentation by Norbert Krause, September 29, 2009.

An additional natural-gas-fueled engine type, the high-pressure direct injection engine, is discussed later in this report when considering diesel engine replacement.

The Honda Civic GX is the only car in the United States that can be purchased direct from the manufacturer with an engine configured to run on CNG. However, it is possible to have secondary manufacturers convert vehicles with gasoline engines to run on natural gas.

2.2 CNG Fuel Storage Density and Weight Compared to Gasoline

Gasoline can be stored on a vehicle at approximately atmospheric pressure in a thin-walled, light-weight (~1 lb/gal depending on construction¹) tank. The shape of the tank can be adjusted as needed to fit the space available, thus minimizing the impact on cargo space. Regular gasoline has a density of about 6.1 lb/gal and a net energy content of about 114,000 BTU/gal. Diesel fuel is similarly easy to store and has a density of about 7.1 lb/gal and a net energy content of 129,500 BTU/gal. Hence, a full 10-gal tank of gasoline/diesel will weigh slightly more than 71/81 lbs, respectively, and will occupy a space only slightly greater than the fuel volume.

Compressed natural gas is stored on a vehicle in a high pressure cylinder at fill pressures up to 3600 psig. Natural gas cylinders are constructed in several different ways. Approximately 90 percent of CNG cylinders in use today are Type-1 cylinders.² Type-1 cylinders are constructed of solid steel walls. The cylinders are heavy but cost less than half that of a composite cylinder.³ Type-2 tanks are “hoop-wrapped” using a glass or carbon fiber composite along the straight sides of the cylinder. The wrapping shares the stresses with the wall, thereby allowing a thinner wall to be used, which saves weight but increases cost. Type-3 cylinders have a full composite wrap over a relatively thin metal liner. The composite wrap carries the majority of the pressure load. Type-3 cylinders are lighter in weight than Type-1 and -2 cylinders but are more expensive to produce. Type-4 cylinders have a full composite wrap over a plastic liner.

Faber, an Italian manufacturer of CNG vehicle tanks, provides the following estimates for weight savings in a 140-L (water volume) tank relative to a standard CrMo steel tank:⁴ Type 1 using modified CrMo steel, 10 percent; Type 2 steel with glass fiber, 15 percent; Type 2 with carbon fiber, 35 percent; Type 3 steel with carbon fiber, 48 percent. In addition, the weight may be affected by the configuration of the tank. In most cases a longer, smaller-diameter tank will weigh less than a shorter, larger-diameter tank. Table 2.2 provides some metrics for actual Type-1 and Type-3 tanks designed for use in natural-gas-fueled vehicles.

In comparison, a gasoline tank would provide a fuel+tank mass of about 7.1 lbs/gallon capacity with a volume ratio only slightly less than 1. The most common type 1 tanks weigh 4 to 5 times as much as the same capacity gasoline tank (compared with tanks full), and occupy about 3 times the volume in the vehicle. Using the type 3 carbon composite tanks reduces the weight to a little more than twice that of the

¹ Keoleian, GA, S. Spataro, R Beal, Feb. 1998, “Life Cycle Design of a Fuel Tank System”, EPA 600/R-97-118. Data for a 31-gal tank indicated 1.27 lb/gal for a metal tank and 0.80 lb/gal for a plastic tank. Does not include mounting hardware, heat shields, etc.

² <http://www.americancng.com/>

³ Ibid

⁴ <http://www.faber-italy.com/cng.htm>

Table 2.2. Data for Specific Automotive CNG Tanks

Cylinder Diameter, (in.)	GGE ^(a) Capacity	Fuel+Tank Mass Per GGE, (lbs/gge)	~GGE Per Volume ^(b) of Fuel + Tank
Type-1 Steel Tanks at 3600 psig (Data from American CNG)			
9.6	3.0	35.9	0.27
9.6	5.4	33.8	0.29
12.7	10.9	30.3	0.29
14.0	10.9	36.3	0.29
Type-3 Carbon-Composite Tanks at 3600 psig (Data from Luxfer Gas Cylinders)			
12.7	3.0	15.2	0.20
14.2	10.5	15.2	0.24

(a) Gasoline Gallon Equivalent, provides the energy storage equivalent expressed in gallons of gasoline.
(b) Volume calculated as a right circular cylinder for simplicity while recognizing that volume exterior to the curved portion of the cylinder end is difficult to use.

gasoline tank but the volume occupied increases to four to five times that of the gasoline tank. As a result of these higher volumes and weights to hold fuel, most CNG-fueled vehicles have smaller fuel tanks and shorter vehicle ranges when compared to gasoline-fueled vehicles.

Liquefied natural gas (LNG), which will be discussed later as it applies to heavy trucks, offers an improvement to storage density when compared to compressed natural gas. However, LNG is probably not suitable for use in consumer cars that might be parked in a home garage. If not driven regularly, the warming of the LNG tank will increase pressure in the tank, resulting in methane venting. The National Fire Protection Association (NFPA) 57 code¹ requires that LNG tanks be constructed so that they can avoid venting for 72 hours. Any planned period of non-use for a vehicle for three days or more would require removal of the fuel from the tank to avoid venting. In addition, LNG is not odorized so LNG vented in an enclosed space, which would constitute a hazardous condition, might not be detected.

2.3 Incentives for Acceptance – Light-Duty Vehicles

2.3.1 Fuel Prices: CNG vs. Gasoline, Private Station vs. Public Station, Regional Differences

The primary economic incentive for consumer adoption of natural-gas-fueled vehicles is the potential savings in fuel cost relative to gasoline-fueled vehicles. On average, the cost of CNG at a retail filling station is about one-third less than gasoline. However, the savings can vary from 24 percent to 53 percent depending on the region of the country. Data from the April 2010 Clean Cities Alternative Fuel Price Report is provided below in Table 2.3.

In addition, in some regions the price of CNG at private stations is significantly lower than the price at public stations. The national average difference between public and private stations is \$0.61/GGE for natural gas compared to only \$0.07 for gasoline. The price difference for natural gas is largest in areas where gas prices are low already. It is likely that, if CNG-fueled vehicles were to be broadly adopted so

¹ NFPA 57 Liquefied Natural Gas Vehicular Fuel Systems Code, 2002 Edition, section 4.3.5.

the number of vehicles refueled per station increases, the price difference between public and private stations would approach a value similar to that for gasoline. A comparison between public and private station prices by region is provided in Table 2.4.

Table 2.3. Regional Price Comparison for CNG and Gasoline for Retail Filling Stations¹

Region	Average CNG Price, \$/GGE	Gasoline, \$/gal	Savings, \$/GGE	Savings, %
New England	\$2.20	\$2.88	\$0.68	23.6%
Central Atlantic	\$2.21	\$2.90	\$0.69	23.8%
Lower Atlantic	\$1.82	\$2.75	\$0.93	33.8%
Midwest	\$1.73	\$2.84	\$1.11	39.1%
Gulf Coast	\$2.06	\$2.71	\$0.65	24.0%
Rocky Mountain	\$1.31	\$2.80	\$1.49	53.2%
West Coast	\$2.23	\$3.02	\$0.79	26.2%
National Average	\$1.90	\$2.84	\$0.94	33.1%

Table 2.4. CNG Prices at Private and Public Stations by Region²

Region	Private Station	Public Station	Savings at Private Station	% Savings at Private Station
New England	\$2.30	\$2.17	-\$0.13	-6.0%
Central Atlantic	\$2.11	\$2.30	\$0.19	8.3%
Midwest	\$1.24	\$1.86	\$0.62	33.3%
Rocky Mountain	\$0.96	\$1.58	\$0.62	39.2%
West Coast	\$1.79	\$2.26	\$0.47	20.8%
National Average	\$1.44	\$2.05	\$0.61	29.8%

As a result, while the cost of CNG is about two-thirds that of gasoline on a national average basis, the cost of CNG in the Rocky Mountain region could be as low as one-third the cost of gasoline. This difference in price signal leads to an uneven regional incentive for adopting CNG vehicle technology.

It should be noted that market prices for natural gas vary with the time of year based on supply and demand for the gas. Prices typically show some increase in the winter due to use in heating with a smaller increase in the summer due to electrical generation for cooling.

2.3.1.1 Costs of Home Refueling

According to the U.S. Energy Information Administration, 52 percent of households used natural gas as their primary heating fuel in 2005. Thus, about half of households have the option of purchasing a compressor and using their home natural gas supply for a CNG-fueled car.

¹ Data source: http://www.afdc.energy.gov/afdc/price_report.html. DOE-EERE, April 2010.

² Data source: http://www.afdc.energy.gov/afdc/price_report.html. DOE-EERE, April 2010, data was not available for Lower Atlantic and Gulf Coast Regions.

The home-fueling approach faces several disadvantages. First, because the price of natural gas delivered to the home includes a cost for the residential distribution piping network, the home-refueling approach starts with a price disadvantage compared to a commercial fueling station, which would benefit from commercial pricing. In addition, the pressure of natural gas delivered to a residential connection is very low (<0.5 psig), which increases the compression work that must be performed to bring the gas to the ~3000 to 3600 psig needed to refill a vehicle fuel tank. The capital expense and maintenance of the refueling appliance must be considered in the fuel cost. The capital cost contribution to the fuel cost is higher for a compressor that operates only a few hours a day. Offsetting these disadvantages is the fact that home refueling can be accomplished using a slow-fill approach, refueling the vehicle over a period of hours, eliminating the need for high-pressure storage outside the vehicle and/or a high-capacity compressor. This section examines the cost of refueling a CNG vehicle using a home refueling compressor.

Residential Gas-Price Disadvantage

Data on natural-gas prices by customer type and state are provided by the Energy Information Administration. Natural-gas prices are lower for commercial customers than for residential customers, and even lower still for industrial customers. Commercial customers pay between 10 and 50 percent less for natural gas compared to residential customers. The data trend over the last few years is shown in Figure 2.1.

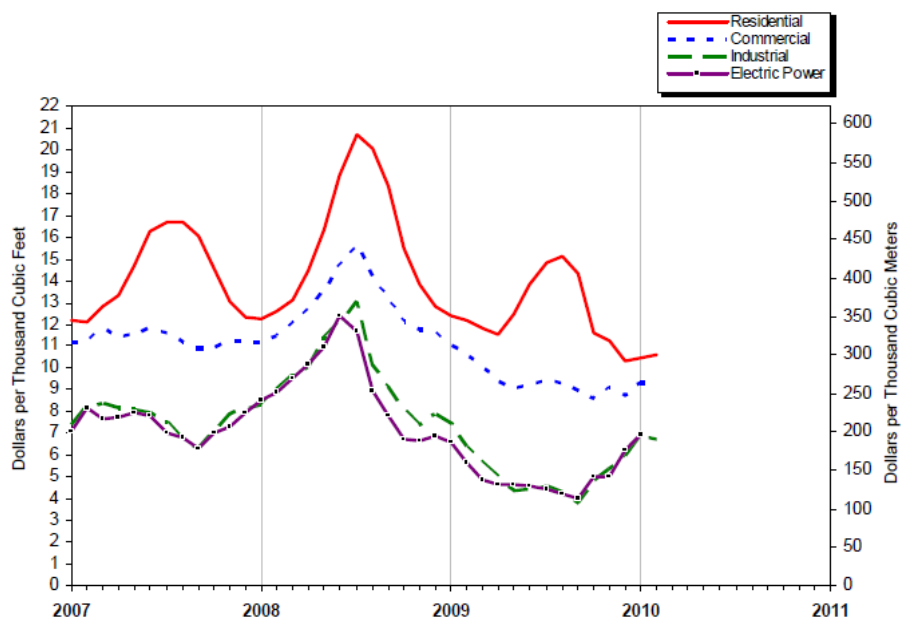


Figure 2.1. Average Natural-Gas Prices by Customer Type ¹

¹ http://www.eia.doe.gov/oil_gas/natural_gas/data_publications/natural_gas_monthly/ngm.html, Figure 3.

As was seen in the retail CNG prices, residential gas prices vary significantly with location. Averaging 2009 monthly EIA data for each state excluding Hawaii¹ and then averaging states provides an approximate national average price of \$14.15/1000 ft³ with state averages ranging from \$8.88/1000 ft³ in Utah to \$21.59/1000 ft³ in Florida. Residential consumer prices for natural gas in California averaged 9.32\$/1000 ft³. Prices to commercial customers vary similarly with a 2009 average monthly price of \$10.40 and a high of \$16.70 (New Hampshire) and a low of \$6.01/1000 ft³.

Compressor

Fuelmaker Corporation, owned by Honda, previously manufactured the “Phill”, a compressor intended for home refueling of natural gas vehicles. In April 2009, Fuelmaker declared bankruptcy. In May 2009, Fuelmaker’s assets and technology were purchased by MTM/BRC, which is headquartered in Cherasco, Italy. The small natural-gas compressors will now be sold under the name BRC FuelMaker. IMPCO is the North American Importer/Distributor for all BRC FuelMaker small, natural-gas compressors. Data received from BRC Fuelmaker prior to the reintroduction of the Phill indicates a delivery rate of 0.42 GGE/h, average power consumption of 800 W, and a maximum pressure of 3600 psig. A \$2000 rebuild is required after 6000 hours of service. Pricing information suggests an initial price of ~\$4589 not including tax or installation. The BRC FuelMaker version of the Phill is expected to be introduced in the near future.²

Impco also offers its FMQ-2-36, which has a higher fill rate of 0.9 GGE/h, is capable of 3600 psig, and draws an average of 1.0 to 1.5 kWe during the fill. Pricing information received from IMPCO technologies indicates that the equipment required would cost \$9881. Details are provided in Table 2.5.

Table 2.5. Purchased Equipment for a Home CNG Vehicle Fueling Appliance Installation

Part#	Description	Price
FMQ-2-36	Vehicle Refueling Appliance 3600psi	\$8,778
50.114	Single Breakaway Outlet Assembly	\$415
50.118	Lock Assembly	\$65
H4.5F-36	Fill Hose 15'	\$230
P36	Fill Nozzle	\$393
	Total	\$9,881

¹ The average 2009 monthly price for natural gas in Hawaii was \$36.93, which is much higher than any other state.

² Website <http://www.impcotechnologies.com/fuelmaker.asp> on 9/8/2010 indicates the Phill will be back on the market in the “near future”.

Estimated Home Refueling Cost

To arrive at an estimated home-refueling cost, we assumed that a Honda Civic GX is refueled at home using a Fuelmaker model FMQ-2-36¹. We also assumed that the compressor cost is spread evenly over 10 years of operation during which it refuels a Honda Civic GX driven 15,000 mi/yr.² In addition to the purchase cost, the compressor requires major maintenance at 4000 hours of operation that is expected to cost \$983. The Civic GX traveling 150,000 miles at a combined mileage rate of 28 mpg requires 5357 GGE, indicating a single major maintenance event would occur during the period. The capital cost and maintenance cost spread evenly over the fuel delivered contributes $(\$9881 + \$983)/5357 \text{ GGE} = \$2.03/\text{GGE}$. This value would be higher if the time value of money were included in the analysis.

An electrical power consumption rate of 1.5 kWe while compressing at 0.9 GGE/h results in power consumption of 1.67 kW-h/GGE. The electrical cost would then cost about \$0.18/GGE with a range of approximately \$0.11/GGE to \$0.32/GGE depending on location.³

The price for the natural gas itself would average \$1.79/GGE, with the cost ranging from \$1.13 to \$2.74 depending on location.

The estimated cost per GGE using a home-refueling appliance is shown in Table 2.6. The cost has been calculated for electrical and natural-gas costs that are at the low, average, and high end of state averages. Low values assume low-end rates for both gas and electricity while high values assume high rates for both gas and electricity.⁴ In addition, the calculations were repeated for a 30,000-miles/year assumption for which two compressor maintenance events are required. The 30,000-mile/year case might represent an extreme high-mileage driver or perhaps two vehicles being refueled with one appliance.

The analysis is repeated in Table 2.7 for data available for the Phill.

Table 2.6. Estimated Cost (\$/GGE) for CNG Delivered to Vehicle Using a FMQ-2-36 Compressor for Home Fueling of a Honda Civic Driven 15,000 and 30,000 Mi/Yr

Cost Element Contribution	15,000 Mi/Yr			30,000 Mi/Yr		
	Low	Avg	High	Low	Avg	High
Compressor Purchase	1.84	1.84	1.84	0.92	0.92	0.92
Compressor Installation	0.19	0.28	0.37	0.09	0.14	0.19
Compressor Maintenance	0.18	0.18	0.18	0.18	0.18	0.18
Electrical Power	0.11	0.18	0.32	0.11	0.18	0.32
Cost of Natural Gas	1.13	1.79	2.74	1.13	1.79	2.74
Tax Credit	0.00	-0.19	-0.37	0.00	-0.09	-0.19
Total	3.42	4.23	5.38	2.41	3.17	4.27

¹ Reintroduction of a version of the “Phill” appliance, expected in the July/August 2010 time frame, may provide a less expensive option. However, performance and pricing details are being finalized and were not yet available at the time this report was written.

² This is at the high end of average ranges. Energy Information Administration data for 1994 indicate average annual mileage is 11,200 mi/yr for a sedan. New vehicles, which are driven more than older vehicles, averaged 14,300 mi/yr. <http://www.eia.doe.gov/emeu/rtecs/chapter3.html>.

³ Electrical power cost obtained from DOE report# DOE/EIA-0226 (2010/04). Data is average residential rate by state for January 2010. Average value obtained by averaging state averages.

⁴ There is a weak correlation between residential prices for natural gas and electricity. However, in California, natural gas prices are two-thirds the national average while electricity is 1.5 times the national average.

Table 2.7. Effective Fuel Price (\$/GGE) for the Phill Refueling Appliance

Cost Element Contribution	15,000 Mi/Yr			30,000 Mi/Yr		
	Low	Avg	High	Low	Avg	High
Compressor Purchase	0.86	0.86	0.86	0.43	0.43	0.43
Compressor Installation	0.19	0.28	0.37	0.09	0.14	0.19
Compressor Maintenance	0.75	0.75	0.75	0.93	0.93	0.93
Electrical power	0.13	0.20	0.36	0.13	0.20	0.36
Cost of natural gas	1.13	1.79	2.74	1.13	1.79	2.74
Tax Credit	0.00	-0.19	-0.37	0.00	-0.09	-0.19
Total	3.01	3.83	5.00	2.68	3.45	4.57

Other Factors

Federal tax credits are currently available to encourage purchase of home -refueling devices. These credits, previously worth 30 percent of the cost up to a maximum of \$1000, were increased to 50 percent and a \$2000 maximum as part of the American Recovery and Reinvestment Act for installations occurring in 2009 and 2010.¹ The tax credits expire December 31, 2010. The installation cost of the refueling device would be expected to run \$1000 to \$2000 depending on location of the natural gas and electrical service relative to the intended installation location. Each \$1000 saved via tax credit/spent on installation would decrease/increase the average fuel cost by \$0.19/GGE for the 15,000-mile case or \$0.09/GGE for the 30,000 mile case.

Based on Tables 2.6 and 2.7, the effective price of fuel obtained using a home compressor is higher than the range of \$1.58/GGE to \$2.30/GGE seen at existing public refueling stations. Hence, if CNG refueling stations are available, it would not be cost effective to purchase and install a home compressor for home refueling. In addition, for a 15,000 mile/year driver for which the average price is \$3.60/GGE or \$3.99/GGE (depending on compressor), the economic incentive for using natural gas in place of gasoline is eliminated. Only in regions where the natural gas prices are lowest would the effective price of CCG fuel from a home compressor be lower than current gasoline prices (see Table 2.3).

2.3.2 Federal Tax Incentives

The Energy Policy Act of 2005 provides a federal tax credit that applies to the purchase of an OEM dedicated natural-gas-fueled vehicle or to conversion of a gasoline-fueled engine vehicle to a dedicated natural-gas-fueled vehicle. The tax credit expires December 31, 2010. The tax credit for light-duty vehicles, defined as a gross vehicle weight rating (GVWR) of less than 8500 lb, is applicable to up to \$5000 of either the added cost of buying an OEM dedicated natural-gas fueled vehicle or the cost of converting a gasoline vehicle to a dedicated natural-gas-fueled vehicle. The credit does not apply to bi-fuel conversions that maintain the ability to operate the vehicle on gasoline. The amount of the credit is either 50 percent or 80 percent of the added costs depending on the vehicle emissions. Light-duty vehicles meeting EPA's Tier 2, Bin 2 standard qualify for the 80 percent credit. The Honda Civic GX qualifies for the maximum tax credit of \$5000 x 0.80 (i.e., 80 percent) = \$4000. Additional details on the federal tax credit are provided on the Natural Gas Vehicles for America (NGVA) website.²

¹ NGVA website. <http://www.ngvc.org/>

² <http://www.ngvc.org/incentives/federalTax.html>.

2.3.2.1 Refueling Infrastructure Credits

For businesses, tax credits are available that provide \$50,000 or 50 percent, whichever is less, of the cost of natural-gas-refueling equipment placed in service during 2009 and 2010. A similar tax credit for home-refueling devices covers either \$2000 or 50 percent of the cost, whichever is less. These credits were extended and increased in value as part of the American Recovery and Reinvestment Act of 2009. The credit expires December 31, 2010.

2.3.2.2 Fuel Credits

In addition to the federal tax credits described above, a credit for sellers of CNG or LNG existed from October 1, 2006, through December 31, 2009. For CNG, this tax credit was worth \$0.50/GGE to the seller of CNG for vehicle fuel. These tax credits are no longer in effect.

2.3.3 State Incentives

Many states offer incentives in the form of tax deductions or credits, reduced license fees, reduced vehicle sale taxes, and lower registration fees. Some states also permit certain alternative fuel vehicles to operate in high-occupancy-vehicle lanes during peak rush-hour traffic periods. In some cases, these incentives can make a significant difference in the overall tax incentive offered. Transeco Energy, a company providing CNG vehicle conversions, has summarized information on state tax incentives. The various credits are summarized below in Table 2.8 along with links for additional information. A more comprehensive table incorporating other alternative fuels, regulations, etc., is provided by the Alternative Fuels and Advanced Vehicle Data Center.¹

Table 2.8. Summary of State-Level Tax Incentives²

State	Description	Link
Colorado	Alternative fuel vehicle (AFV) tax credit is available ranging from \$1,947 to \$13,779, depending on vehicle weight	http://www.afdc.energy.gov/afdc/progs/state_summary.php/CO
Georgia	AFV tax credit is available up to \$2500	http://www.afdc.energy.gov/afdc/progs/state_summary.php/GA
Kansas	AFV tax credit is available ranging from \$2,400 to \$40,000, depending on vehicle weight	http://www.afdc.energy.gov/afdc/progs/state_summary.php/KS
Louisiana	AFV tax credit is available worth 20 percent of the cost of converting the vehicle	http://www.afdc.energy.gov/afdc/progs/state_summary.php/LA
Montana	AFV tax credit is available for 50 percent of the cost of converting the vehicle up to \$1000, depending on the weight of the vehicle.	http://www.afdc.energy.gov/afdc/progs/state_summary.php/MT
Oklahoma	AFV tax credit is available for 50 percent of the cost of converting the vehicle and also for 10 percent of the vehicle cost up to \$1,500	http://www.afdc.energy.gov/afdc/progs/state_summary.php/OK
Oregon	AFV tax credit is available in the amount of \$750 for the cost of converting the vehicle.	http://www.afdc.energy.gov/afdc/progs/state_summary.php/OR

¹ <http://www.afdc.energy.gov/afdc/laws/matrix/tech>.

² Descriptions and links obtained from website http://www.transecoenergy.com/pages/Tax_incentives.htm.

Table 2.8. (contd)

State	Description	Link
South Carolina	AFV tax credit is available worth 20 percent of the federal tax credit	http://www.afdc.energy.gov/afdc/progs/state_summary.php/SC
Utah	AFV tax credit is available for 50 percent of the cost of converting the vehicle up to \$3,000	http://www.afdc.energy.gov/afdc/progs/state_summary.php/UT
Washington	AFV are exempt from sales tax	http://www.afdc.energy.gov/afdc/progs/state_summary.php/WA

2.3.4 Reduced Emissions and Foreign Oil Dependence

Gasoline represents 43 percent of the volume of products derived from a barrel of crude oil and approximately 97 percent of the gasoline is used in on-road vehicles. Appendix F provides additional discussion of the impacts of gasoline displacement by natural gas on reducing imported oil.

Some consumers may consider driving a lower-emission vehicle as an incentive for converting to a natural-gas-fueled vehicle. While noting the emissions will vary with engine design, the EPA¹ in 2002 estimated that use of CNG as a vehicle fuel has the following potential emission benefits relative to use of gasoline:

- Reduction of carbon monoxide emissions by 90 to 97 percent
- Reduction of carbon dioxide emissions by 25 percent
- Reduction of nitrogen oxide emissions by 35 to 60 percent
- Potential reduction of non-methane hydrocarbon emissions by 50 to 75 percent
- Emission of fewer toxic and carcinogenic pollutants, and little particulate matter.

In addition, a dedicated CNG system has no evaporative emissions from the fuel system.

Clearly, with proper design, natural-gas-fueled engines can provide reductions in emissions relative to gasoline-fueled engines. EPA estimates that the full fuel cycle carbon emission for the Civic GX to be 5.4 tons/yr compared to 6.3 tons/yr for the gasoline-fueled model (i.e., the LX). This represents a 14-percent reduction in greenhouse gas emissions.² In addition, the Civic GX qualifies for the Advanced Technology Partial Zero Emission Vehicle (AT-PZEV)³ rating indicating its tailpipe emissions meet Super Ultra-Low Emission Vehicle⁴ standards and are 90 percent cleaner than average new model vehicles.

However, improper conversion of gasoline-fueled engines can lead to increases in emissions especially with respect to nitrogen oxide emissions. Kalam et al. (2005) studied emissions from a four-cylinder, bi-fuel, gasoline/CNG spark ignited engine on a dynamometer operating at steady load. The results showed that operation on CNG reduced carbon monoxide and hydrocarbon emissions but

¹ EPA420-F-00-033, March 2002, www.epa.gov.

² www.eere.energy.gov/afdc/vehicles/natural_gas_calculator.html.

³ AT-PZEV, CARB rating, implies Super Ultra-Low Emission Vehicle tailpipe emissions, zero evaporative emission and a 15 year / 150,000 mile warranty on its emission control components.

⁴ Super Ultra Low Emission Vehicle, California Air Resources Board (CARB) rating.

increased nitrogen oxide emissions. Dondero and Goldemberg (2005) examined 21 gasoline-fueled vehicles that had been converted from gasoline to bi-fuel capability in Brazil. They found that emissions, when operating on natural gas, were reduced on average by 53 percent for carbon monoxide, 66 percent for non-methane hydrocarbons, and 20 percent for carbon dioxide. However, they also found that overall hydrocarbon emissions increased 162 percent and nitrogen oxide emissions increased 171 percent. In India, Kathuria (2004) examined pollutant data at the busiest intersection in Delhi from 1999 through 2003 to determine the effects of CNG vehicle adoption, which began in 2001. The study found a significant decline in carbon monoxide emissions, marginal reduction in suspended particulate and PM10 particulates, and an increase in nitrogen oxide emissions following the CNG conversion. Similarly, Chelani and Devotta (2007) examined pollutant levels in Delhi obtained at 10 monitoring stations from 2000 through 2003. Pollutant profiles establish that the emissions in Delhi are dominated by mobile sources. The study was undertaken to determine the impact of natural-gas-fueled vehicles following adoption of CNG vehicles in 2001. The study found a 34.8 percent reduction in sulfur dioxide, a 2.8 percent reduction in suspended particulates, and a 7 percent reduction in PM10 particulates. However, introduction of CNG vehicles resulted in a 13 percent increase in nitrogen oxide levels.

2.4 Barriers to Acceptance – Light-Duty Vehicles

2.4.1 Vehicle Refueling Infrastructure

The inadequate number of natural-gas-refueling stations is a barrier to acceptance of CNG-fueled vehicles by consumers. Similarly, the low number of natural-gas-fueled vehicles needing public refueling stations makes investments in natural-gas-refueling stations unprofitable. The effect of refueling station concentration and other issues related to penetration of natural-gas-fueled vehicles has been examined by Yeh (2007), who compared the experience of CNG-fueled vehicles in Argentina, Brazil, India, New Zealand, and the United States. Yeh identified two conditions that need to be addressed if sustained use of natural-gas-fueled vehicles is to be achieved. First, there must be on the order of 1000 vehicles per refueling station for the stations to be profitable. Second, the number of natural-gas-refueling stations must be at least 10 to 20 percent the number of gasoline-refueling stations to provide driver convenience. Natural gas infrastructure will be discussed further in Section 5.

2.4.2 Availability of OEM CNG-Capable Vehicles

The Honda Civic GX is the only OEM dedicated CNG vehicle available to consumers in the United States. There are no OEM bi-fuel CNG vehicles available. Worldwide, there are a large number of OEM vehicles capable of operating on CNG. About two-thirds of the vehicles are in a bi-fuel configuration, which allows operation on either gasoline or CNG. A listing of the vehicles available worldwide is provided in Appendix C. The lack of bi-fuel vehicles in the U.S. market is unfortunate because bi-fuel vehicles offer an option for consumers who have at least one source of CNG fuel but who are worried about the limited refueling infrastructure. Because CNG prices are generally lower than gasoline prices, consumers would have an incentive to use natural gas whenever possible and revert to gasoline only when necessary. Engines offered in Europe appear to maintain high efficiency when operating on either gasoline or CNG fuel. The VW 1.4-L TSI engine is a twin-charged (i.e., supercharged and turbocharged), direct-injection gasoline engine. The “Ecofuel” variant of the engine has a number of design features to enhance performance while running on natural gas, and is offered in a bi-fuel configuration on several vehicles. The Passat Ecofuel is a bi-fuel vehicle equipped with three under-floor steel CNG tanks and an

8-gal gasoline tank; in the configuration, the vehicle achieves ~35 mpg in the European cycle on either fuel. This Passat Ecofuel offers a driving range of 295 miles on CNG plus an additional 285 miles on gasoline. Currently, U.S. tax credits for CNG vehicles do not apply to bi-fuel vehicles.

From 1997 through 2004, Ford Motor Company produced approximately 30,000 CNG vehicles including dedicated CNG versions of the Crown Victoria sedan, F150 pickup truck, and E250 van. Other dedicated CNG vehicles offered by vehicle manufacturers between 2000 and 2005 included the Chevrolet Silverado and Express, the GMC Savana, the Dodge Ram van and wagon, the Toyota Camry, and the Honda Civic. A number of vehicles were offered in a bi-fuel configuration as well. Ford withdrew from producing natural-gas-fueled vehicles following the 2004 model year citing that the vehicles were not selling well enough to justify the program.¹ After offering the CNG versions of the 2005 Chevrolet Silverado and GMC Sierra, GMC ceased offering CNG vehicles, leaving the Honda Civic GX as the only OEM CNG-fueled vehicle offered in the United States.

Looking forward, a couple of additional options may be added to the selection of CNG vehicles. In May 2010, General Motors announced it will offer fleets CNG and LPG powered versions of the Chevrolet Express and the GMC Savana full-size vans later this year.²

In October 2010, Vehicle Production Group LLC (VPG) will begin producing a dedicated CNG-fueled OEM van that is wheelchair accessible and designed for commercial use. The CNG-fueled van will have a range of 250 miles.³

In addition, Ford will begin offering the Transit Connect as a commercial vehicle suitable for use as a taxi or delivery van. While the Transit Connect will not be offered as an OEM CNG-fueled vehicle, Ford will provide engine-preparation packages on all Transit Connect models and the required calibration specifications for the CNG conversion. If the Ford specifications are followed, the conversion will not void Ford's engine warranty.⁴ In March 2010, Altech-Eco Corp. (Asheville, North Carolina) announced that it received an EPA certificate of conformity for natural gas conversion of the Transit Connect.⁵ Transit Connect is just one of several Ford vehicles that offer CNG conversion capability. Ford has shipped more than 3000 CNG/LPG-prepped engines for its E-Series vans with 5.4-L and 6.8-L gasoline engines. A similar package will be introduced for Ford's F-Series Super Duty trucks.

2.4.3 Availability of Retrofits

During the mid-1990s, observations that some gasoline-fueled vehicles that were converted to natural gas fuel had worse emissions than the original gasoline engines led EPA to exercise more stringent control over natural gas conversions of gasoline vehicles.⁶ EPA then issued the Addendum to Memorandum 1A in September 1997, requiring more stringent emissions testing for AFV conversions.⁷ As a result, current EPA regulations intended to prevent tampering with pollution controls on vehicles

¹ <http://www.cleanenergyfuels.com/articles/09-26-04.html>.

² <http://www.automotive-fleet.com/Channel/Green-Fleet/News/Story/2010/05/GM-to-Offer-Fleets-CNG-LPG-Full-Size-Vans.aspx>.

³ <http://www.ngvglobal.com/mv-1-paratransit-cng-taxi-production-set-for-october-2010-1117>.

⁴ <http://www.ngvglobal.com/ford-offers-cng-prep-package-for-transit-connect-2011-0209>.

⁵ <http://www.automotive-fleet.com/News/Story/2010/03/CNG-System-for-Ford-Transit-Draws-EPA-OK.aspx>.

⁶ <http://www.afdc.energy.gov/afdc/vehicles/conversions.html#certification>.

⁷ <http://www.afdc.energy.gov/afdc/vehicles/conversions.html#certification>.

require companies that provide gasoline-to-natural gas conversions to obtain a Certificate of Conformity from EPA (or an Executive Order from CARB) for the specific conversion kit/engine family.¹ This is a process similar to what is done for new vehicles. The testing confirms that the emissions meet limits and that the system works with the OEM on-board diagnostics. This process can include submitting data and potentially a converted vehicle for confirmatory testing by EPA. The overall process can cost \$200,000, which the company performing the conversions must recoup from the sale of vehicles using the particular engine family covered. The certification only applies to a given model year.² Carrying the certification for a given engine conversion into a future year requires additional paperwork and payment of an additional fee. Typically, conversions are done on new or nearly-new vehicles to maximize the vehicle life over which the costs for the conversion can be recovered through fuel costs. As a result of this and the cost of carrying certifications from year to year, most manufacturers only offer conversions on a small subset of potential vehicles and only for new or nearly-new vehicles. The selection of engines for which conversions are available is limited. NGVA describes the selection as follows:

“Currently, there are six SVMs offering EPA- certified systems (two also have CARB certifications) for eight GM and Ford light-duty engine families covering about twenty-five vehicle models (and various iterations of the same base models). Presently, these include the GM 3.5L, 3.9L, 4.8L, 6.0L engines and the Ford 2.0L, 4.6L, 5.4L and 6.8L engines. Note: Not all vehicles with these engines are covered in the engine test groups for which certifications have been granted. In addition, there are no certified natural gas engine conversion systems available in the U.S. for any other light-duty vehicle brand.”

An up-to-date list of all currently available EPA- and CARB-certified engine retrofits along with secondary vehicle manufacturer contact information is maintained by NGVA.³

2.4.3.1 Non-EPA Approved CNG Conversion Kits

In addition to companies performing natural gas conversions that are EPA- or CARB- certified, there are websites offering relatively lower cost, do-it-yourself, CNG conversion kits. In addition, some converters do not appear to limit conversions to EPA- or CARB-certified conversions. Consumers using these conversion kits for their vehicles would appear to run the risk of being in violation of EPA anti-tampering regulations with respect to the vehicle emissions systems. A few examples of do-it-yourself conversions are described below:

¹ This section is a brief summary of a more thorough discussion of EPA regulations surrounding retrofit of gasoline vehicles provided in the document “Frequently Asked Questions About Converting Vehicles to Operate on Natural Gas” available on the NGVA website. More detailed information is provided in the source document if required.

² The EPA has recently proposed (EPA-420-F-10-002, May 2010, Office of Transportation and Air Quality) changes to these rules that may make it easier to retrofit older vehicles. The EPA announcement reads:

“The U.S. Environmental Protection Agency (EPA) is proposing to amend the current regulations for aftermarket fuel conversions, which took effect on September 21, 1994 (40 CFR part 85 subpart F). This proposal updates regulations that apply to manufacturers of light-duty vehicle and heavy-duty highway vehicle and engine clean alternative fuel conversion systems. The proposed revisions would streamline the compliance process while maintaining environmentally protective controls.”

³ www.ngvamerica.org/pdfs/marketplace/MP.Analyses.NGVs-a.pdf.

- *Energy and Water Solutions.* Energy and Water Solutions¹ in Syracuse, Utah, offers non-EPA/CARB certified conversion kits for all cars with four- to eight-cylinder engines at prices ranging from \$650 to \$750. The fuel tank is not included in the price. They cite an injunction² as eliminating EPA requirements. A Type-2, 7.4-GGE, International Organization for Standardization [ISO]-approved (not U.S. Department of Transportation [DOT]-approved) tank can be purchased for \$999. A Type-2, 5.2-GGE, DOT-approved tank also is available for \$999.
- *All Things CNG.*³ Conversion kits are available for four- and eight-cylinder engines from \$1095 to \$1395. These kits convert the vehicle to a bi-fuel capability. The wording of their disclaimer, which is reproduced below, appears designed to avoid responsibility for any failure to comply with EPA regulations.

“Our compressed natural gas systems are over the counter performance parts for off road use. All Things CNG LLC cannot give any legal, regulatory, or other advice regarding your personal use of the products that they distribute. Buyer accepts full responsibility for understanding and adhering to the regulations of his or her jurisdiction. The company grants you freedom and privacy to do as you please with the CNG kits once they become your property, and as such will not be held liable for any Buyer failure to adhere to regulatory standards.

“The Compressed Natural Gas Kits that we offer are not certified by any US regulatory agency. As such, no representation is made to the availability of any government incentive or rebate. Additionally, they should only be used in accordance with the laws and regulation of the jurisdiction(s) in which the kits will be located.”

- *CNG United.* CNG United⁴ is a distributor for Auto Gaz Centrum⁵ and sells conversion kits for four- and 8-cylinder engines, completely installed for \$2395 to \$4190. A 9.6-GGE tank costs \$2395. EPA certification does not appear to be a discussed on the website.

2.4.4 Natural-Gas-Fueled Vehicle Cost

The 2010 Honda Civic GX, with a base Manufacturer's Suggested Retail Price (MSRP) price of \$25,340, costs \$6935 more than the nearly identically equipped Civic LX with an MSRP of \$18,405. Due to the very low emissions of the Civic, it would qualify for tax credits equal to 80% of up to \$5000 in incremental cost or \$4000 in this case. This makes the incremental cost for the consumer to \$1935. Honda estimates the 5-year maintenance and repair cost for the GX to be \$3083 vs. \$2050 for the LX, which effectively adds \$1033 to the cost differential for a total of \$2968. A rational consumer would then try to recover these costs through lower fuel costs.

¹ On the Web at <http://www.ewsews.com/cnghome.html>.

² Available at <http://icreatewow.com/pdf/InjunctionRandyLieber.pdf>.

³ Webpage at www.Allthingscng.com.

⁴ <http://cngunited.com/>.

⁵ <http://en.agcentrum.com.pl>.

2.4.4.1 Natural Gas Vehicle Cost, Conversions

The incremental costs associated with having a secondary vehicle manufacturer convert a gasoline engine to natural gas is significantly higher than the incremental cost seen in the Civic GX which comes directly from the OEM configured for natural gas. The NGVA website provides the following “ballpark” costs for several conversions:

- Crown Victoria/Lincoln Town Car/Mercury Marquis with 13 GGE: \$13,500
- E350 cargo/passenger van with 20 GGE fuel: \$15,500
- F150/250/350 pickup truck with 20 GGE: \$16,500. With 30 GGE: \$18,500
- E450 cutaway shuttle van with 24 to 38 GGE: \$18,500 to \$22,500
- Sierra/Silverado 1500/2500HD pickup truck with 11 GGE: \$12,500. With 20 GGE: \$15,500
- Savana/Express G1500/2500 cargo/passenger van 12 to 20 GGE: \$12,500 to \$16,000.

These costs would be reduced by tax credits as discussed above depending on vehicle weight and emissions rating. However, even with tax credits, the conversion introduces a significant capital expenditure that will require the vehicle be driven many miles in order to recover the conversion cost over a reasonable time period.

2.4.4.2 Cost of EPA Compliance for Conversion Kits

The non-EPA/CARB-approved conversions and kits are significantly less expensive than the EPA/CARB-approved kits and conversions. Similarly, Dondero and Goldemberg (2005) reported that conversion kits purchased in Brazil range in cost from \$800 to \$1400 (2005 U.S. dollars), suggesting that it is possible to reduce the cost of converting gasoline engine vehicles. The cost differential may indicate that the cost of compliance with EPA regulations is a significant contributor to the high cost of converting gasoline-fueled vehicles to natural gas. While an OEM manufacturer can spread compliance costs over a large number of vehicles, a company in the business of converting gasoline-fueled vehicles to natural gas must recover their compliance costs over a small number of vehicles. Consumer decisions are made one vehicle at a time meaning that costs to comply prohibit making a conversion. While fleet vehicles may be ordered in large enough numbers to bring the per vehicle cost to tolerable levels, the compliance costs significantly increase the costs of the vehicles, and the types of vehicles available limit consumer selection.

2.4.4.3 CNG Cylinder Costs

In addition to the cost of compliance discussed above, the cost of the CNG cylinder is a significant factor in the higher cost for the CNG vehicle. Figure 2.2 shows the trend in retail costs by capacity for various types of CNG cylinders. CNG manufacturers typically only provide quotes for quantities of 100 or more of a specific cylinder, and do not provide price information on their cylinders. Hence, it is difficult to assess the degree of discount that might be received by an OEM manufacturer purchasing a large number of CNG tanks.

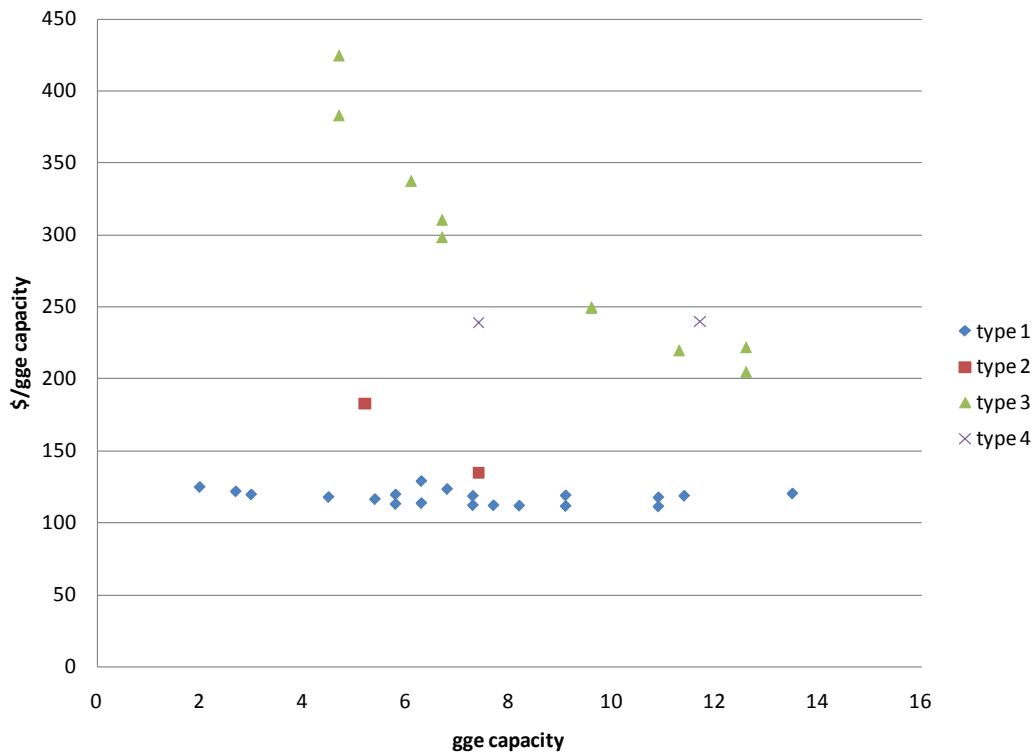


Figure 2.2. Retail CNG Cylinder Cost as a Function of Tank Capacity and Tank Type. Data is obtained from several vendor websites.¹

2.4.5 Technological Competition and Vehicle Attributes

In making a decision to purchase a natural-gas-fueled vehicle, consumers, will compare the costs (purchase price, maintenance cost, fuel cost) and vehicle attributes (power, cargo, fueling convenience) to other vehicle technologies. Natural-gas-fueled vehicles have several hurdles to overcome including reduced power and cargo space. This section examines the comparison of natural-gas-fueled vehicles to hybrid technology and diesel technology.

2.4.5.1 Comparison to Hybrid Vehicles

The Honda Civic is offered in gasoline (LX), gasoline-electric hybrid, and natural gas (GX) models. This provides one data point to compare changes in vehicle costs and attributes as the gasoline engine is replaced by either natural gas or hybrid drive. Table 2.9 was assembled using a tool from the Honda website to display key attributes of the three versions of the Civic.

¹ Data available at the following websites: <http://www.americancng.com/cylindersAccessories.html>, <http://www.ewsews.com/cngprices.html>, and <http://cngunited.com/products/cng-tanks-and-cylinders>.

Table 2.9. Comparison of Data for Gasoline, Hybrid, and Natural Gas Models of the Honda Civic¹

Model	2010 Civic GX, Natural Gas, with AT	2010 Civic Hybrid, CVT	2010 Civic LX, AT, Conventional
MSRP	\$25,340	\$23,800	\$18,405
Price, Comparably Equipped	\$26,050	\$24,510	\$19,115
Est. 5-yr maint & repair cost	\$3,083	\$2,019	\$2,050
MPG city/highway	24/36	40/45	25/36
Engine displacement	1.8 L	1.3 L	1.8 L
Horsepower@rpm	113@6300	110@6000	140@6300
Torque@rpm	109@4300	123@1000	128@4300
Fuel capacity, gal	7.8	12.3	13.2
Range city/highway (calc), mi	187/281	492/554	330/475
Fold-down rear seat	Yes	No	Yes
Cargo volume, ft ³	6.0	10.4	12.0
Curb weight, lb	2,910	2,877	2,754
Emission Rating	AT-PZEV	AT-PZEV	ULEVII

As seen in Table 2.9, the hybrid version of the Civic provides a number of advantages relative to the natural-gas-fueled version. These include:

- *Fuel Consumption.* The natural-gas-fueled vehicle uses 67 percent more fuel in the city and 25 percent more fuel on the highway compared to the hybrid. This means that in the city, there would be a fuel cost disadvantage for the natural-gas-fueled vehicle. The fuel cost differential for highway driving would be much reduced.
- *GHG Emissions.* Based on the difference in mileage, the hybrid would be expected to have lower greenhouse emissions than the natural-gas-fueled vehicle in the city.
- *Power/Torque.* The hybrid provides improved torque with nearly identical horsepower from a smaller displacement engine relative to the natural-gas-fueled engine.
- *Vehicle Range.* The range of the natural gas vehicle is only 38 percent that of the hybrid in the city and 51 percent on the highway.²
- *Cargo Space.* The cargo volume is significantly reduced. (Although the rear seat does fold down; a feature that which is not available in the hybrid).
- *Cost.* The difference in the purchase cost plus 5-year maintenance costs amounts to a \$2604 cost advantage for the hybrid prior to application of any tax credits.
- *Other.* In some areas, natural-gas-fueled vehicles may use the high occupancy vehicle lane.

Based on the comparison above the natural gas version of the Civic would have trouble competing with the gasoline hybrid version even if natural gas fueling stations were available. Of course, except for the increased cost of the vehicle, there is nothing preventing the combination of a natural gas engine with hybrid technology.

¹ Data generated by tool located at <http://automobiles.honda.com> is intended for making vehicle comparisons.

² The range is determined by multiplying fuel capacity times the mileage. Values in the city/highway are 492/554 miles for the hybrid and 187/281 miles for the natural-gas-fueled vehicle.

2.4.5.2 Diesel Cars in the United States

The use of diesel engines in cars offers an option for reducing fuel consumption relative to spark-ignited, gasoline-fueled cars. Diesel-powered cars could compete with natural-gas-powered cars for consumers who are particularly motivated by savings in fuel costs. At present, relatively few passenger cars are offered in the United States with diesel engines, and all the offerings are from European manufacturers (i.e., Audi, BMW, Mercedes, and Volkswagen). This is likely due to a combination of higher fuel prices in Europe creating a higher emphasis on fuel efficiency coupled with stricter diesel emission standards in the United States. Details on the diesel passenger vehicles and pickups available in the U.S. market and their fuel mileage are provided in Appendix A. Compared to gasoline engines that do not require premium fuel, diesel engines offer mileage increases amounting to more than 30 percent for city driving and more than 40 percent for highway driving. Examples of price premiums for Volkswagen vehicles equipped with diesel engines over vehicles equipped with gasoline engines are ~\$5100 for the Jetta and ~\$3500 for the Toureg. While the mileage boost provided by a hybrid is greater, combinations of elements of hybrid vehicles and diesel vehicles may become available if fuel prices become high enough and/or incentives were offered. For example, the Volkswagen Polo Blue Motion, currently sold in Europe, has a 1.2-L turbocharged diesel with start/stop technology and regenerative braking, and it gets a combined 71 mpg on the European cycle.¹ The price in the United Kingdom starts at approximately \$22,364.² Similarly, a Volkswagen Golf Blue Motion with a 1.6-L TDI engine that achieves 62 mpg is available in Europe.³ Most engines are using selective catalytic reduction (SCR) with urea to meet emissions limits. The Jetta achieves emissions with a nitrogen oxide storage catalyst⁴ without additional fluid addition.

2.4.5.3 CNG Cylinder Safety

The potential for a high-pressure, natural-gas cylinder to rupture is low, but the potential impacts of such a failure are catastrophic and may affect some consumers purchase decisions. A number of measures are taken to assure safety of CNG tanks. Each tank has a limited life, typically 15 to 20 years, after which it must be removed from service and replaced. CNG tanks must⁵ be periodically inspected so that tanks affected by corrosion or abrasion can be removed from service. CNG tanks are equipped with a temperature-triggered pressure relief valve designed to vent the tank in a controlled fashion during a vehicle fire. However, isolated incidents of CNG tanks exploding have occurred when the tanks were heated in a way that failed to trigger the thermal pressure relief protection. For example, in 2003 the CNG tank in a Ford Crown Victoria involved in a fire exploded. This event led to a recall to add insulation to the CNG tanks⁶. Similarly, in 2007, a Civic GX involved in an arson fire in Seattle, Washington, exploded violently, leading to a recall to add insulation to the tanks of those vehicles.⁷

¹ http://www.caranddriver.com/reviews/car/09q4/2010_volkswagen_polo_bluemotion_diesel-quick_spin

² Based on February 18, 2010, article at <http://www.carsuk.net/vw-polo-bluemotion-2010-launched/>. Value of £14,445 converted to US dollars using the exchange rate as of February 18, 2010.

³ http://www.greencarreports.com/blog/1036712_the-62-mpg-2010-volkswagen-golf-tdi-we-wont-get-in-the-u-s.

⁴ A NO_x storage catalyst stores NO_x on the catalyst during extended lean exhaust operation and then releases and reduces the NO_x during short periods of rich exhaust conditions.

⁵ Federal Motor Vehicle Safety Standard (FMVSS) 304 (49 CFR 571.304), Compressed Natural Gas Fuel Container Integrity, inspection required every 36,000 miles or at 36 months, whichever comes first.

⁶ http://www-odi.nhtsa.dot.gov/cars/problems/defect/results.cfm?action_number=EA03001&SearchType=QuickSearch&summary=true.

⁷ www.seattle.gov/fire/publications/cng/CNGAutoFire.ppt

3.0 Natural Gas in Heavy-Duty Vehicles

Although the technology of natural-gas-fueled engines for heavy trucks has been evolving over time, earlier studies that examined natural-gas-fueled, Class-8 trucks provide some assessment of performance relative to diesel trucks. In a test conducted on Class-8, heavy-duty waste transfer trucks between 2001 and 2003, 12 diesel trucks were compared to 12 LNG trucks (Chandler and Proc 2004). The LNG trucks were powered by the prototype HPDI LNG engine. The LNG engines operated at a rate of 100,000 miles per month and accumulated 1.8 million miles through June of 2003. At this stage of development, the LNG engine showed 10.5 percent reduction in fuel economy. Fuel costs for LNG were high in large part because of the transportation costs to transport it from Wyoming to San Francisco. Maintenance costs were 2.3 times higher for the LNG vehicles. Many of the maintenance problems were related to loss of vacuum on the insulation of the LNG tanks and contaminants in the LNG affecting the LNG pumps.

In another study (Chandler et al. 2000), eight LNG-fueled, Class-8 trucks were operated by Raley's Supermarkets, and their performance was compared to diesel trucks in their fleet. The LNG trucks were found to have 33 percent lower fuel economy, leading to higher fuel costs. The use of a throttled and spark-ignited engine with a low compression ratio (10.5:1) was a major factor in the lower efficiency. The LNG trucks also were found to have an overall operating cost of \$0.383 per mile compared to \$0.192 per mile for equivalent diesel trucks.

3.1 Natural Gas Engine Options for Heavy-Duty Vehicles

There are a number of different engine configurations that can be used with natural gas for heavy-duty vehicles. CNG-fueled engines can be spark-ignited as in conventional gasoline-fueled engines, or they can be compression-ignited as in a conventional diesel engine. When using compression ignition, there needs to be a pilot injection of ~5 percent or more diesel fuel in addition to the natural gas to initiate ignition. Spark-ignited engines can be further broken down into lean-burn or stoichiometric engines. Most truck engines are turbocharged. Introduction of natural gas at low pressure can be performed downstream of the turbocharger. Some compression ignition engines use HPDI, which injects the natural gas at very high pressure at the end of the compression stroke just after injection of the pilot diesel injection. High-pressure natural gas (~4500 psi) for injection is obtained by pumping LNG to high pressure and then vaporizing it by heating.

A tool allowing identification of heavy-duty natural gas vehicles and engines is maintained by DOE's Advanced Fuels and Advanced Vehicle Data Center.¹ Of a total of nine engines listed that may operate on CNG and or LNG, only three are currently listed as meeting 2010 emission requirements. These engines are summarized in Table 3.1.

¹ <http://www.afdc.energy.gov/afdc/vehicles/search/heavy/#>.

Table 3.1. Natural Gas Engines for Heavy-Duty Vehicles Meeting 2010 EPA Requirements

Manufacturer	Emission Solutions, Inc	Cummins-Westport	Baytech ^(a)	Westport Innovations
Model	Phoenix NG	ISL-G	-	GX
Type/Ignition	Stoichiometric/spark	Stoichiometric/spark	-/spark	HPDI/pilot injection
Displacement (L)	7.6	8.9	8.1L	15
hp range	175-265	250-320	-	400-450

(a) Baytech indicates that it has EPA 2010 certification for its 8.1-L engine (<http://www.baytechcorp.com/>). DOE website does not yet reflect this. Available in dual-fuel configuration

In addition to the engines listed in the Table 3.1, Doosan Infracore America indicates its 11.1-L, ~285-hp, lean-burn, spark-ignited GX12-S engine will meet 2010 EPA limits with adaptation of SCR technology.¹ However, it is unclear whether the 2010 compliant engine including SCR system is currently available.

Finally, Clean Air Power is working with Navistar to develop a dual-fuel version of the MaxxForce 13 Engine for the North American market. The developers state, “The development program will utilize Clean Air Power's Dual-Fuel™ combustion technology to deliver an engine that achieves the U.S. Environmental Protection Agency (EPA) 2010 emissions standard.”² While the horsepower of the natural gas version is not available, the diesel version of the MaxForce13 produces 410 to 475 hp.

Currently only the Westport GX engine can produce more than 320 hp when fueled with natural gas. Even the GX engine at rated at 400 to 450 hp is relatively low in the power range compared to a diesel engine with the same displacement. For example, the 15-L Cummins ISX 2010 diesel is available in horsepower ratings ranging from 400 to 600 hp. The Westport GX engine requires LNG in order to work with the HPDI engine. Hence, if running on CNG, the power of a natural gas truck in the U.S. is currently limited to a maximum of about 320 hp offered by the Cummings Westport ISL-G engine.

3.1.1 Dual-Fuel Engines

Dual-fuel diesel engines may offer a route to utilize CNG with diesel fuel while still achieving high power levels when required. In a dual-fuel diesel engine, natural gas can be introduced at low pressure downstream of the turbo. Ignition occurs when diesel fuel is injected as in a normal diesel engine. However, unlike an engine that uses only a pilot injection, the dual-fuel engine can switch to full diesel operation or conceivably could adjust the diesel:natural gas ratio to satisfy operating requirements. The engine can operate on diesel only but not on natural gas only. The ability to operate on diesel fuel would lessen concerns over not being able to find a CNG refueling station. However, this approach has some drawbacks. First, the weight and volume of the CNG tanks is significant and would need to be in addition to normal dimension diesel tanks if operation on diesel fuel only is anticipated. Second, the operating characteristics of the engine when operating in a dual-fuel mode would be expected to have some undesirable operating characteristics compared to conventional diesel-only engines. Sahoo et al. (2009) recently reviewed the literature on performance characteristics of dual-fuel diesel engines. Several

¹ http://usa.doosaninfracore.co.kr/Product/CE_engine.aspx#.

² <http://www.cleanairpower.com/>.

researchers have noted that while dual-fuel diesel engines show reduced nitrogen oxide emissions, and dramatically reduced soot emissions, there is a small loss in maximum power, a large reduction in engine efficiency at low load, and increases in engine carbon monoxide and unburned hydrocarbon emissions.

The reduced efficiency at less than full load is perhaps the most serious drawback to the dual-fuel diesel approach. While increases in carbon monoxide or unburned hydrocarbons could potentially be addressed by treating the exhaust, the reduction in efficiency will translate into larger natural gas tanks on the vehicle, and could even result in greater carbon dioxide emissions and increases in total fuel cost.

Papagiannakis and Hountalas (2004) collected operating data on a dual fuel engine and provide a plot¹ comparing brake-specific fuel consumption (bsfc), expressed as g/kWh, for an engine operated in dual-fuel and diesel-only modes. Test data were collected at 1500 rpm and 2500 rpm at BMEP² representing 20, 40, 60 and 80% of full engine load. The mass of natural gas injected ranged from 74 and 86 percent of the total fuel mass injected. The data indicate that while bsfc is similar at 80% load the dual fuel engine efficiency drops continuously relative to the diesel engine as the engine load is reduced. At 20% of full load, bsfc was found to be about 60% higher at 2500 rpm and 90% higher at 1500 rpm. It should be noted that Papagiannakis and Hountalas express the fuel consumption rate in terms of fuel mass, and if compared in terms of fuel energy content, the relative weighting of natural gas consumption would increase by 13.7 percent due to the higher specific energy content of the natural gas.³

Compared to the dual-fuel engine, the diesel provides higher specific power and lower specific fuel consumption. Sahoo et al. (2009)⁴ provides a critical review of dual fuel diesel engines. Mansour et al. (2001) present data showing the variability with engine speed at full load⁵. As engine speed is reduced from 2450 rpm at full load, the spread between dual-fuel and diesel engine performance in terms of specific power and specific fuel consumption widens. At 2450 rpm the dual fuel engine had ~17% lower power with 33% higher bsfc compared to diesel only operation. However, at ~1500 rpm the dual fuel engine experienced ~44% lower power with 84% higher in bsfc relative to diesel only operation. The extent of reduction in specific power and increase in bsfc at low speed and low loads appear to be a significant disadvantage for this type of engine.

The same trend in efficiency has been seen for diesel generator sets using a dual-fuel diesel and producer gas fuel.⁶ Data collected by Singh et al. (2007) are summarized in Table 3.2. Data collected by Uma et al. (2004) are summarized in Table 3.3.

¹ Refer to figure 3 in the Papagiannakis and Hountalas (2004) reference

² BMEP is brake mean effective pressure and represents the pressure that, if imposed on the pistons uniformly from the top to the bottom of each power stroke, would produce the measured power output. The formula relating it to torque for a four-stroke engine is $BMEP = 150.8 \times (\text{torque in ft-lb}) / (\text{displacement, in}^3)$. A derivation of the formula is provided at http://www.epi-eng.com/piston_engine_technology/bmep_performance_yardstick.htm.

³ Energy values for fuels used in Papagiannakis and Hountalas (2004) are 48.6 MJ/kg for natural gas and 42.74 MJ/kg for diesel.

⁴ Within Sahoo et al., the source of the information is referenced to Mansour C, Bounif A, Aris A, Gaillard F. Gas–Diesel (Dual-Fuel) Modeling in Diesel Engine Environment. International Journal of Thermal Science 2001; 40(4):409–24.

⁵ Refer to Figure 3 from Mansour et al. 2001

⁶ Producer gas consisting primarily of carbon monoxide, hydrogen, methane, and nitrogen obtained through gasification of coal or biomass.

Table 3.2. Comparison of Fuel Consumption for Diesel/Producer Gas Dual-Fuel Compression Ignition Engine Driving a Generator. Data from Singh et al. 2007.

Engine Load % of Full Load	Diesel Mode Energy Consumption MJ/kWh	Dual Fuel Mode, Liquid Fuel Replacement, %	Dual Fuel Mode Energy Consumption, MJ/kWh	Percent Increase in Energy Consumption for Dual Fuel Mode
63	11.07	62.7	19.55	76.6
84	10.15	68.0	15.39	51.6
98	10.35	22.2	11.61	11.2

Table 3.3. Comparison of Fuel Consumption for Diesel/Producer Gas Dual-Fuel Compression Ignition Engine Driving a Generator. Data from Uma et al. 2004.

Engine Load kW	Diesel Mode Energy Consumption MJ/kWh	Dual-Fuel, Pilot Rate Relative to Diesel-Only Rate %	Dual-Fuel Mode Energy Consumption MJ/kWh	% Increase in Energy Consumption for Dual-Fuel Mode
10	22.8	35.8	34	49.1
20	15.5	18.1	18	16.1
30	14.0	15.3	15	7.1
40	13.1	30.3	16	22.1

While there is scatter in the available data, there appears to be a consistent trend of higher fuel consumption, particularly at lower engine loads. Maintaining efficiency in this type of engine may require more complex engine controls. Possible solutions to this issue include fueling some but not all cylinders at low load so that the cylinders being fired are at high load, or perhaps transitioning to a high-fraction diesel fuel when the engine is operating under unfavorable conditions.

Clean Air Power¹ has been developing the dual-fuel diesel/natural gas engine. They offer two products: 1) “Genesis,” which is a relatively simple retrofit that provides 50 to 60 percent fuel substitution and 2) “Hawk,” which requires an intimate integration with the ECU and can achieve up to 90 percent fuel substitution. In January 2009, Clean Air Power announced that it had signed a letter of intent with Volvo Powertrain to incorporate their technology into Volvo truck engines. The engines are expected to be more efficient than spark-ignited natural gas engines. In February 2010, Clean Air Power announced that it had entered into a concept-development agreement with Navistar Inc. to develop a MaxxForce 13 Natural Gas/Diesel Engine that will meet EPA 2010 emissions standards. Hence, a dual-fuel engine option may be available in the near future.

Because the load on the engine during steady-state pulling is likely to be a fraction of the maximum engine load, improvement in engine technologies or operating strategies are needed to avoid suffering the loss in efficiency at low load when applied to long-haul trucks.

Sahoo et al. (2009) also present data showing the dual-fuel engine has higher levels of carbon monoxide and hydrocarbon emissions than does the diesel engine. Although these emissions are higher, this issue could be addressed downstream of the engine using emissions controls.

¹ <http://www.cleanairpower.com/dualfuel.php>.

3.1.2 Lean-Burn, Spark-Ignited Engine

A lean-burn, spark-ignited, natural-gas-fueled engine with a downstream oxidation catalyst is one possible choice for heavy-duty vehicles. This approach was used in the B Gas Plus and C Gas Plus engines produced by Cummins Westport Inc. These engines are more efficient than stoichiometric engines but have higher nitrogen oxide emissions. Spark-ignition eliminates the need for pilot injection of diesel fuel. Unlike dual-fuel engines, lean-burn, spark-ignited engines cannot operate on diesel fuel. This type of engine eliminates need for a diesel fuel tank and fuel system, but the engine is less efficient than a diesel engine. With the introduction of EPA's 2010 emission standards the B Gas Plus and C Gas Plus engines are no longer offered in the United States.

3.1.3 Stoichiometric Cooled Exhaust Gas Recirculation Engine

In the stoichiometric cooled exhaust gas recirculation (SEGR) engine, exhaust gases are cooled before mixing with fuel and air provided to the engine. The cooled exhaust gases lower the combustion temperature and limit NO_x production. For its ISL-G engine, which uses SEGR, Cummins Westport claims improved fuel economy and power density compared to lean-burn or conventional stoichiometric engines. Because combustion is stoichiometric, a conventional three-way catalyst can be used on the exhaust. The ISL-G meets EPA's 2010 emission standards without the need to add particulate filtration or SCR nitrogen oxide reduction to the exhaust treatment.

3.1.4 High-Pressure, Direct-Injection Engine

In a HPDI engine, natural gas is injected at very high pressure (e.g., 4500 psi) late in the compression stroke. Diesel fuel equivalent to about 5 percent of the total fuel is injected with the natural gas as a pilot ignition source. The engine operates in a manner similar to a diesel engine with very similar power and torque curves. To provide HPDI, LNG is pressurized to high pressure and then vaporized prior to injection. This approach greatly reduces the difficulties associated with compressing the gas to 4500 psi, but as a result, the HPDI engine must operate on LNG and cannot run on CNG. Engine efficiency can be within a few percent of the efficiency of a diesel engine. The Cummings Westport GX engine is an example of an HPDI engine.

3.2 LNG and CNG Fuel Storage on Heavy Trucks

3.2.1 Storage Density and Weight

For natural-gas-fueled trucks equipped with a HPDI engines, fuel must be stored on board in the form of LNG. For other trucks, a decision needs to be made as to whether the fuel will be stored as liquid and then vaporized as it is fed to the engine or stored as CNG. The primary advantage of LNG is a higher storage density meaning that, for a given fuel storage space on the vehicle, an LNG vehicle will have greater range between refueling. LNG also provides a weight advantage if Type-1 or Type-2 cylinders are used for CNG. Using Type-3 or Type-4 construction for CNG cylinders saves significant weight and brings the storage weight for CNG more in line with that of LNG. Table 3.4 compares the relative weight and volume characteristics of commercially-available LNG and CNG storage tanks.

Table 3.4. Comparison of LNG and Type-3 CNG Storage Tanks

Manufacturer/Model/Type	Diameter, in.	Length, in.	Capacity, gde	Tank Weight, lbs	Tank Weight, lbs/gde	Tank Volume, gal/gde
LNG Tanks						
Chart/HLNG-52	20	57	26.6	245	9.2	2.9
Chart/HLNG-72	24	57	37.6	320	8.5	3.0
Chart/HLNG-119	26	76	62.5	505	8.1	2.8
Chart/HLNG-150	26	90	76.2	615	7.9	2.7
CNG Tanks						
Dynetek/W205/type 3	16.1	83.1	16.2	185	11.4	4.5
Dynetek/V234/type 3	15.2	100.1	18.2	170	9.0	4.2
Dynetek/V294/type 3	15.2	123.1	23.6	234	9.9	4.1
Dynetek/W320/type 3	15.9	123.1	25.7	236	9.2	4.1
Worthington/Alt820G/type 3	21.0	85.8	25.8	386	15.0	5.0
Lincoln/Tuffshell/type 3	21.2	120	40.3	380	9.4	4.6

The first thing to note is that the tank weights and tank volumes for both LNG and CNG are significantly larger than the weights and volumes required for diesel fuel. Although data were not gathered for diesel tanks, the values would be only slightly greater than 1 gal total volume per gallon of diesel fuel, and the weight would be on the order of 1 to 2 lbs per gallon of capacity. If Type-3 or Type-4 tanks are used, the weight penalty is relatively minor compared to that of LNG tanks. In terms of storage density, the CNG takes up about 1.5 times as much space as the LNG, meaning that the range would only be two-thirds that of the LNG vehicle if the same space is occupied.

LNG is stored in double-wall vessels with vacuum insulation between the shells to limit heat conduction into the tank. The LNG is typically stored in the tank at about 50 psig so a fuel pump is not needed to deliver the fuel from the tank. After the LNG tank is filled, the LNG slowly absorbs heat through the insulation, which results in increases in both liquid volume and vapor pressure. Data from the National Institute of Standards and Technology for liquid methane are provided in Figure 3.1.

The volume increase of the liquid phase is an important factor for LNG. At approximately -162°C the pressure is 14 psia. If the liquid is provided at a temperature of -140°C with a vapor pressure of 64 psia, it occupies a volume that is 8.8 percent greater. As the LNG warms to -121°C, the vapor pressure increases to 166 psig and the liquid expands to occupy a volume 19.5 percent greater than the volume at -162°C. The LNG fuel tank must be designed with a pressure capacity and freeboard volume sufficient¹ to prevent venting of methane for 72 hours following filling the tank without consumption by the vehicle.

¹ Required by NFPA57, Section 4.3.5.

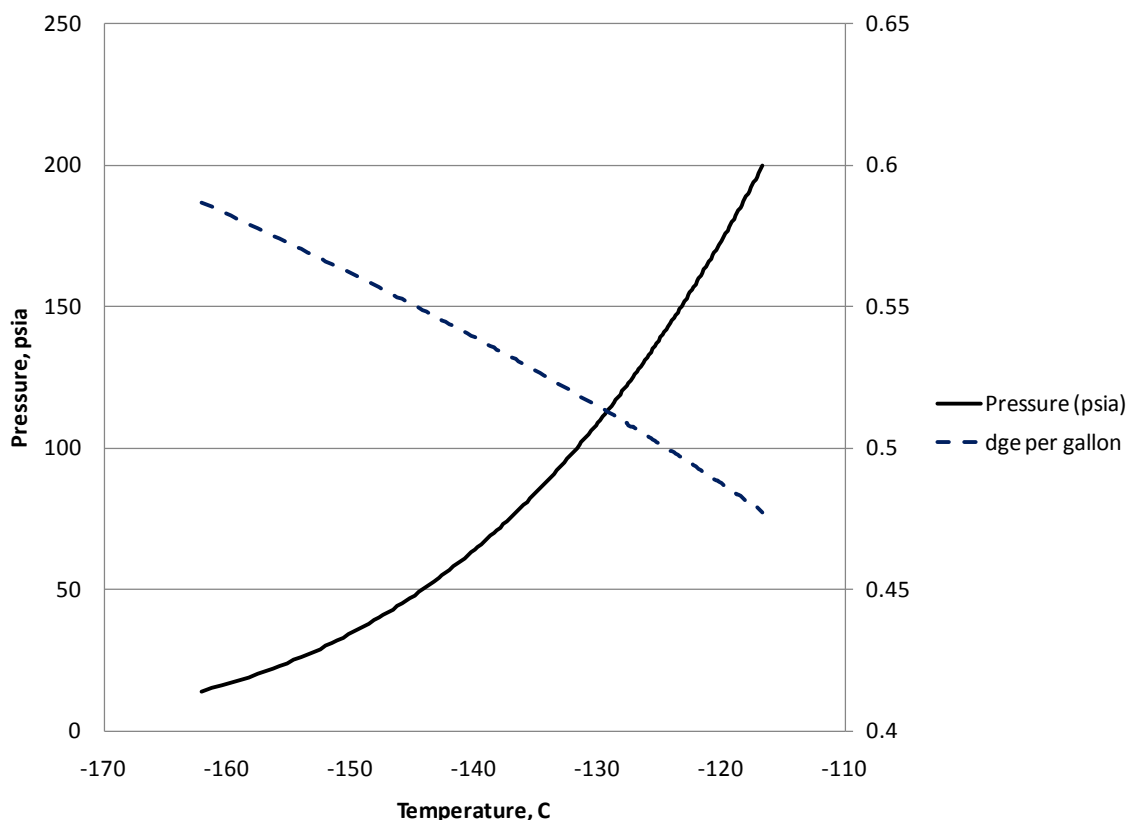


Figure 3.1. Equilibrium Pressure and Storage Density for Liquid Methane. Storage density is based on liquid methane density, lower heating value (LHV), and a value of 129,500 BTU/gal for diesel. Methane data are from the National Institute of Standards and Technology.¹

Another important consideration in the selection between LNG vs. CNG is the source of the LNG and cost of liquefaction. Appendix B provides a discussion of technologies used to produce LNG. LNG can be obtained from import terminals where it is offloaded from LNG tankers, it can be produced in utility peak-shaving plants, or it can be produced in a dedicated facility using natural gas supplied by pipeline. If obtained from an import terminal, the LNG is delivered to a receiving terminal where it is vaporized and introduced as gas into a natural gas pipeline. To be economically feasible, the LNG must be produced in a location where the gas price is low enough to allow sale of the LNG at the local pipeline natural gas price. Hence, near operating import terminals, LNG would be available at approximately the same price as CNG. LNG might also be obtained from utility peak-shaving plants. A peak-shaving plant takes pipeline natural gas and liquefies it for storage near the point of consumption to ensure adequate supply during periods of high use (e.g., during extremely cold weather). Once the desired quantity of stored LNG is achieved, the plant capacity might be diverted to providing LNG for vehicle use. However, this supply would be interrupted when the peak shaving-plant needs to operate for its original intended purpose. The third option would be to build dedicated LNG plants that operate using pipeline natural gas. Currently, Clean Energy operates two LNG plants that liquefy natural gas obtained from pipelines. One of these plants, sized at 100,000 gal/day with 800,000-gal storage, is located about 60 mi north of Houston, Texas. The other plant is located in Boron, California, and is sized for 160,000 ga/day

¹http://webbook.nist.gov/cgi/fluid.cgi?ID=C74828&TUnit=C&PUnit=psia&DUnit=mol%2Ffl&HUnit=kJ%2Fmol&WUnit=m%2Fs&VisUnit=uPa*s&STUnit=N%2Fm&Type=SatT&RefState=DEF&Action=Page.

with 1.5-million-gal storage, and is designed to be upgradable to 240,000 gal/day. LNG is transported from the production plant to the fueling station using 12,000 gal trailers.

In areas where pipeline natural gas is available, the price of LNG would be expected to be higher than CNG because the capital expenditure for the liquefaction plant, the higher cost of truck vs. pipeline transport, and the energy cost of performing the liquefaction (~9 percent for a nitrogen recycle plant). If LNG is produced from pipeline natural gas, it would likely be produced at a centralized plant and then transported via tanker trucks to refueling stations. Experience from Cryostar suggests a source of LNG can on average supply areas within about 250 miles from the production plant. During truck transport, the LNG is typically at low pressure (<50 psig). The LNG refueling station consists of a vacuum insulated storage tank, a heater used to saturate the liquid at a specific pressure, and a pump for delivering the liquid to a vehicle. Current LNG refueling station practice is to receive LNG with a vapor pressure <50 psig and then heat it to reach a saturation pressure in the range of 50 to 120 psig. The liquid is pumped into the LNG vehicle storage tank. The vapor space of the fueling tank is condensed by the introduction of cooler liquid from the station. If the station and truck are used regularly, venting of natural gas is minimized. Having the natural gas in liquid form makes it relatively easy to provide CNG from the same station. LNG is pumped to high pressure, vaporized, odorized, and delivered to tanks from which vehicles are fueled. The vaporizer consists of a heat exchanger that can either be heated by ambient air or by hot water. If hot water is provided by burning a portion of the gas, the process consumes about 2 percent of the gas delivered.

A possible alternative technology for producing small quantities of LNG has been developed at Idaho National Laboratory.¹ The technology uses the natural gas as a refrigerant as it is let down in pressure for distribution in order to convert a fraction of the gas to liquid. This type of technology may allow economical production while demand for LNG is too low to justify a larger scale plant.

3.2.2 Safety Implications for Use of LNG vs CNG in Trucks

LNG is inherently more hazardous than natural gas. Spills of LNG can lead to a heavier-than-air vapor cloud that can travel from the spill site and then ignite some distance away. In contrast, CNG is lighter than air so it rises when spilled, which reduces the hazard. In addition, LNG is not odorized so smaller leaks may not be detected. Finally, an LNG station has a higher inventory of gas onsite at any one time than a pipeline-fed CNG station. The increased hazard is reflected in the NFPA setback distances of 10 ft for CNG (NFPA 52) and from 10 to 75 ft for LNG tanks depending on size.

The use of LNG to power trucks will result in a significant increase in trucks hauling LNG to fueling stations. This increases the potential for accidents involving LNG transport trucks. While the overall safety record of LNG truck transport is good, in 2002 a natural gas tank truck exploded violently in a boiling-liquid, expanding-vapor type explosion. The accident, which occurred in Spain, was evaluated in detail by Planas-Cuchi et al. (2004). The tanker rolled to its side, which damaged the tank insulation. Flames appeared immediately between the cab and trailer and after about a 20-minute delay, the tank exploded. The explosion broke the tank and trailer into several pieces and created projectiles. The truck cab and motor were blown to a distance of 257 m. The explosion created a large white cloud that then ignited, creating a fireball. The heat radiation from the fireball caused first- and second-degree burns to bystanders 200 m away.

¹ <http://www.inl.gov/lng/factsheets/index.shtml>.

There also would be a potential for crashes involving LNG tanker trucks, resulting in the tank being penetrated and LNG being spilled on the ground. In such an event, the natural gas would rapidly boil off and generate a vapor cloud. Unlike CNG, which would rise from the release point, the low temperature of the LNG vapor creates a heavier-than-air cloud that would stay close to the ground and would flow downhill and be influenced by wind. As the LNG mixes with air, its concentration enters the flammable range of 5 to 15 percent so ignition is possible. While a transition to detonation is unlikely in a non-enclosed space, the thermal radiation from a deflagration could be significant, could cause burns to people in the vicinity, and could ignite combustible materials some distance from the location of the release.

Similarly, penetration of an LNG vehicle fuel tank below the liquid level could result in rapid ejection of LNG and formation of an ignitable vapor cloud. Compared to a tanker truck, the potential hazard for a vehicle fuel tank is limited because of the smaller LNG volume involved in a single incident. LNG tanks are not as strong as CNG tanks and, thus, may be more easily penetrated. However, LNG tanks are pressure vessels that are much stronger than conventional diesel-fuel tanks, making a penetration of an LNG tank less likely than for diesel-fuel tank for a similarly mounted tank.

CNG tanks on board a vehicle store natural gas at high pressure, typically up to 3600 psig, and can release significant energy if the tank suddenly fails. Such failures are rare; however, they do occur. In August 2010 in Seoul, South Korea, a bus with CNG tanks mounted under the floor experienced a tank rupture while driving in traffic. The bus was heavily damaged and 17 people were injured, including one serious injury in which the person lost both feet. Fortunately, the released CNG did not ignite. Video of the tank failure was captured on a security camera.¹ The bus was one of 7234 CNG buses operated in Seoul. This was the eighth Korean bus to experience a CNG tank failure since 2005.²

Hazards associated with LNG stations are greater than those associated with pipeline-supplied CNG stations. The increased hazard is related to the greater inventory of natural gas in the station at any one time and in the ability of LNG to form an ignitable vapor cloud that travels laterally across the ground rather than rising. Safety in design and operation of LNG vehicles and refueling is addressed by NFPA 57, which requires a drainage containment system to catch any liquid draining from the LNG tank and establishes a minimum distance between the edge of the drainage system and any buildings or property lines. This distance is set at 50 ft for storage tanks with capacities between 15,001 and 30,000 gal and 75 ft for storage tanks with capacities between 30,001 to 70,000 gallons. For reference, the Clean Energy refueling station adjacent to the Ports of Long Beach and Los Angeles contains two 25,000 gal LNG storage tanks.

Appendix D provides an overview of LNG accidents that have involved explosions or fires. The most serious U.S. accident occurred in 1944 in Cleveland Ohio. In that accident, a tank with a capacity of ~1.3 million gal of LNG failed because inadequate nickel content in the alloy used in the tank. When the tank failed, LNG spilled into a containment berm that was not large enough to contain the entire contents of the tank. As a result, LNG overflowed the berm. Vaporizing LNG formed a vapor cloud that ignited, resulting in ~130 deaths and destruction of 70 homes and two factories over an area of approximately 1 square mile.³ While this particular accident scenario can easily be avoided by proper

¹ <http://jalopnik.com/5610184/korean-cng-bus-explosion-caught-on-camera>

² http://www.koreatimes.co.kr/www/news/nation/2010/08/117_71205.html

³ For more information, see [http://www.ircrisk.com/blognet/post/2010/03/29/LNG-Explosion-Levels-One-Square-Mile-\(Cleveland-1944\).aspx](http://www.ircrisk.com/blognet/post/2010/03/29/LNG-Explosion-Levels-One-Square-Mile-(Cleveland-1944).aspx).

design of the LNG tank and mitigated by providing a berm sufficient to hold the entire tank contents, it clearly illustrates the potential hazard associated with improper storage of large volumes of LNG. NFPA 57 requires that vehicle fueling stations incorporate a berm sufficient to hold the entire tank contents if there is one tank. If a berm serves several tanks, the berm must have sufficient capacity to contain the contents of the largest tank. In addition, the facility design must incorporate measures to prevent the failure of one tank leading to failure of a second tank.

The potential hazard associated with storage of large volumes of LNG has spurred local opposition to these facilities, which has in some cases hindered efforts to site large LNG terminals. For example, after a six-year effort to develop a an LNG import terminal at Bradwood Landing, which is 25 mi east of Astoria on the Columbia River, the project was abandoned because of local opposition. It is possible that such opposition might be seen for efforts to site liquefaction plants where large quantities of LNG might be stored (although much lower quantities than for a LNG-receiving terminal) or perhaps even to refueling stations.

3.3 Incentives for Application of Natural Gas to Heavy-Duty Vehicles

3.3.1 Fuel Price

As was the case for light-duty vehicles, the primary incentive for acceptance of heavy-duty vehicles is reducing the cost of the fuel. The incentive varies with location primarily because of variations in the cost of natural gas. Table 3.5 provides the savings per gallon and as a percentage for various regions of the United States. The effect of the fuel price advantage will be decreased somewhat depending on the efficiency of the natural-gas-fueled engine employed. Comparative data for LNG intended for vehicular fuel are sparse, but use of LNG will still offer a significant reduction in fuel price relative to diesel fuel.

Table 3.5. Regional Price Comparison for CNG and Diesel Fuel for Retail Refueling Stations¹

Region	CNG Avg Price, dge	Diesel, \$/gal	Savings, \$/GGE	Savings
New England	\$2.45	\$3.09	\$0.64	20.7%
Central Atlantic	\$2.46	\$3.19	\$0.73	22.9%
Lower Atlantic	\$2.03	\$3.04	\$1.01	33.2%
Midwest	\$1.93	\$3.05	\$1.12	36.7%
Gulf Coast	\$2.30	\$3.02	\$0.72	23.8%
Rocky Mountain	\$1.46	\$3.08	\$1.62	52.6%
West Coast	\$2.49	\$3.19	\$0.70	21.9%
National Average	\$2.12	\$3.07	\$0.95	30.9%

Because of the much lower miles per gallon and greater number of miles driven, the savings realized on a per-vehicle basis for heavy-duty trucks is significantly greater than for light-duty vehicles. Data from the DOT are provided in Table 3.6.

¹ Data from DOE-EERE, April 2010. Available at: http://www.afdc.energy.gov/afdc/price_report.html.

Table 3.6. Average Vehicle Miles and Fuel Consumption for 2007¹

	Average Miles Traveled Per Year	Average Miles Per Gallon	Fuel Consumed Gallons Per Year
Combination trucks	65,290	5.1	12839
Two-axle four+-tire trucks	12,040	8.2	1474
Buses	8,360	6.1	1371
Two-axle, four-tire trucks	10,952	18.0	609
Passenger cars	12,293	22.5	547

Hence, compared to passenger cars and even compared to other trucks and buses, combination trucks consume significantly more fuel, thus potentially increasing the return on investment through fuel price savings when converted to natural gas.

In addition, a significant fraction of the miles driven by combination trucks are logged by trucks driven a large number of miles per year. Table 3.7 provides information on the breakdown of total miles driven by the annual miles driven for the vehicle.

Table 3.7. Distribution of Total Miles for Combination Trucks by Annual Miles Driven (2002)²

Annual Miles	Percent Of Total Miles Driven
<30,000	16.6%
30,000-49,999	10.0%
50,000-75,000	13.7%
>75,000	59.7%

The data show that ~60 percent of the total miles driven by combination trucks are accounted for by trucks that drive more than 75,000 miles per year. These trucks offer perhaps the greatest potential payback from reduced cost of fuel using natural gas.

3.3.2 Tax Incentives

For heavier-duty vehicles, the amount of the incremental cost to which the credit applies increases with gross vehicle weight rating as shown in Table 3.8. The maximum credit is equal to either 50 percent or 80 percent of the incremental cost up to the maximum value based on the emissions performance. The Internal Revenue Service (IRS) does not offer guidance on the emissions levels that trigger the 50 percent or 80 percent credit level, but it has approved specific engines for specific amounts on a case-by-case basis. For engines on vehicles with GVWRs >14,000 and that use two fuels simultaneously, the credit is either 90 percent of the normal credit amount if the engine consumes <10 percent diesel fuel or 75 percent of the normal credit if the engine consumes between 10 and 25 percent diesel fuel during operation.

¹ DOT Table VM-1, data for 2007, available at <http://www.fhwa.dot.gov/policyinformation/statistics/2007/vm1.cfm>.

² 2002 Vehicle Inventory and Use Survey, available at <http://www.census.gov/svsd/www/vius/2002.html>.

Table 3.8. Maximum Basis for Calculating Federal Tax Credits. Credit is either 50 percent or 80 percent of the amount based on emissions.

Vehicle Rating, GVWR, lbs	Maximum Incremental Cost For Calculating Credit
<8,500	\$5,000
8,501-14,000	\$10,000
14,001-26,000	\$25,000
>26,001	\$40,000

In the case of a Class-8 truck using the Westport HPDI engine that uses diesel pilot injection (<10 percent), the tax credit is 90 percent x 80 percent x 40000 = \$28,800. This is confirmed by the IRS website.¹ Additional details on the federal tax credit are provided on the NGVA website.² The tax credit expires December 31, 2010.

3.3.3 Reducing Emissions and Dependence on Foreign Oil

While important factors at the national level, reducing emissions and foreign oil dependence are secondary factors for the person making a decision about purchasing a natural-gas-fueled, heavy-duty truck. Distillate fuel oil accounts for 25 percent of the products refined from crude oil refining, and 65 percent of the distillate fuel oil is consumed as diesel fuel in on-road vehicles. This translates to about 16 percent of crude oil consumption being linked to on-road, diesel-fueled vehicles. Additional information on crude oil refining and product consumption is provided in Appendix F.

3.3.3.1 Reducing Emissions

The lower carbon content of the natural gas fuel offers the potential to reduce greenhouse gas emissions (carbon dioxide). Some of the benefit may be reduced if the efficiency of the natural-gas-fueled engine is lower than that of the diesel engine. A comparison of energy usage and greenhouse emissions was conducted on diesel-fueled and CNG-fueled refuse trucks operating in Madrid, Spain (Lopez et al. 2009). The study compared a turbocharged, multipoint-injection, CNG-fueled engine to an identical displacement direct-injection turbocharged diesel engine. The study found that, on a tank-to-wheels basis, the CNG-fueled trucks consumed 4 percent more energy (expressed as MJ/km) but had carbon dioxide emissions that were only 84 percent that of the diesel-fueled trucks.

There is general agreement that the mass of particulates emitted from a natural-gas-fueled engine will be lower than a diesel engine in the absence of exhaust after-treatment. Emissions from the vehicle, however, may or may not be lower depending on whether the engines are equipped with oxidation catalysts and particulate filters. Also, when accelerating, natural-gas-fueled engines may emit higher particle number rates, even if the particle mass rate is less because of the smaller size. Jayaratne et al. (2010) examined a number of studies involving natural-gas-fueled buses and concluded that, when accelerating in first gear, the particle number emissions of the natural-gas-fueled engines is an order of magnitude higher than for diesel buses. Because of the small size of ultra-fine particles (<100 nm), they

¹ <http://www.irs.gov/businesses/article/0,,id=201039,00.html>

² <http://www.ngvc.org/incentives/federalTax.html>

do not contribute to exhaust opacity or contribute significantly to total particulate mass. However, they are of concern as they penetrate deep into the human lung and are more toxic than larger particles.

With the introduction of EPA's 2010 emission limits, emissions of nitrogen oxides and particulates from diesel trucks are very low, which reduces the emissions-related incentives for adopting natural-gas-fueled engines.

3.4 Barriers to Use of Natural Gas in Heavy Vehicles

3.4.1 Refueling Infrastructure

The use of natural gas fuel in heavy-duty trucks is limited by the lack of refueling infrastructure. This is particularly true for trucks using an HPDI type engine that must be refueled using LNG.

Table 3.9 shows the breakdown of miles driven by on-road combination trucks based on the primary range of operation. This table shows that about half of the miles driven are by combination trucks with an operating range greater than 200 miles and that 30 percent of the miles driven are by trucks operating over a range of more than 500 miles.

Table 3.9. Miles Driven by Combination Trucks Broken Down by Primary Range of Operation.¹

Primary Range of Operation, Mi	Percent of Miles Driven
<50	23.6%
51-100	14.6%
100-200	12.1%
200-500	19.3%
>500	30.4%

About half the miles driven by heavy-duty, combination trucks are spent on interstate highways. Combination trucks spend a greater fraction of their time on interstate highways and in particular on rural interstate highways when compared to other vehicle classifications. This is illustrated in Table 3.10.

Table 3.10. Fraction of Travel on Interstate Highways²

	Percent of Total Miles on Urban Interstate	Percent of Total Miles on Rural Interstate
Combination trucks	21.6%	29.4%
Two-axle, six-tire trucks	12.4%	8.8%
Buses	15.1%	14.1%
Two-axle, four-tire trucks	15.4%	7.4%
Passenger cars	16.0%	7.3%

¹ Data from Table 7 of the 2002 Vehicle Inventory and Use Survey

² Calculated from DOT data available at <http://www.fhwa.dot.gov/policyinformation/statistics/2007/vml.cfm>

The distribution of miles driven and fuel consumed in heavy trucks is skewed towards high consumption by trucks driven large numbers of miles per year with a large fraction of those miles being driven over large distances on interstate highways. The Kenworth T800 LNG-fueled truck is offered in configurations offering vehicle ranges between 300 and 500 miles¹. To be a practical alternative, a truck operating over a 500-mile or greater range must have refueling available.

One concept for overcoming the refueling infrastructure issue is to build LNG stations along major highways. For trucks with routes limited to highways served by LNG stations, this could provide the incentive to purchase LNG trucks, and then stations could become profitable as more LNG-fueled trucks are driven. To be feasible, this approach requires that the initial construction must be subsidized because the high capital cost of a refueling station cannot initially be recovered over the small number of vehicles initially using the station.

Significant gains have been made in the feasibility of using natural gas to fuel fleet vehicles. Incentives to make private fueling infrastructure available for public use might begin the process of forming a network of fueling stations that would encourage adoption of natural-gas-fueled vehicles. In the case of heavy-duty trucks, there is the added desire to refuel using LNG rather than CNG, which is more commonly used in fleet vehicles. Use of CNG would further reduce the range of heavy trucks.

Larger freight companies may be able to make use of LNG in limited regions by relaying trailers at the edge of LNG-served regions. In this case, freight trailers would be transported using LNG-fueled trucks within the regions served by LNG stations. The freight would then be handed off to diesel trucks for the remainder of the trip. Similarly incoming freight would be transferred from diesel trucks to LNG-fueled trucks within the served area.

Another concept is to use dual-fuel engines that can transition to full diesel operation when LNG is not available. This would result in efficiency losses at low engine load, as well as a shorter range when LNG is the fuel as the space available for fuel is split between the diesel and LNG tanks.

Because of the limited LNG refueling infrastructure, application of natural gas to heavy-duty trucks has largely been limited to fleet vehicles that can refuel when they return to a common point as part of their operating cycle.

3.4.2 Availability of Vehicles

Unlike the case for passenger vehicles, there is a wide selection of heavy trucks that can be purchased in a natural-gas-fueled configuration. These include:

- *Cummings Westport*. Heavy Class-8 trucks operating on LNG powered by the Westport GX HPDI engine suitable for line or regional hauling (T800LNG, T800Short Cab, W900S) as well as a Class-7/8 truck powered by the Cummins Westport ISL-G engine suitable for regional haul and vocational applications (T400).
- *Peterbilt*. LNG- or CNG-vehicles with the spark-ignited ISL-G engine include models suitable for garbage trucks or other low cab forward designs (Model 320), suitable for dump trucks and cement

¹ Kenworth brochure, assumes 6 mpg

trucks (Model 365), and line and regional hauling (Models 382, 384).¹ In addition, Model 386, powered by the HPDI Westport engine is available as a Class-8 truck that can be fitted with detachable sleepers.²

- *Freightliner M2-112*. Medium-duty truck powered by the ISL-G engine and available in CNG/LNG-fueled truck or tractor configurations. Can be configured as a tractor for GVWR up to 66,000 lbs.³
- *Mack*. The Terra Pro is powered by an ISL-G engine and is suitable for refuse truck applications. The Terra Pro is eligible for a \$32,000 tax credit⁴.
- Sterling Set Back 113 – Class 8 truck powered by the ISL-G, suitable for port drayage operations.
- Autocar Xpeditor – A low cab forward truck which were among the first CNG trucks to be applied to port drayage service at the Los Angeles port area. Also has been applied to refuse trucks. In May, 2010, Autocar announced it was approaching a production level of 1000 natural-gas-fueled trucks over the previous 18 months.⁵ Natural-gas-fueled trucks account for ~30 percent of total Class-8 truck production.⁶

3.4.3 Vehicle Purchase Price

Currently, natural-gas-fueled vehicles are more expensive to purchase than an equivalent diesel truck. Table 3.11 shows an assessment of purchase prices for heavy-duty diesel trucks.

Table 3.11. Purchase Comparison Prior to Application of Any Incentives⁷

	Diesel	HPDI Truck
Base Truck	\$84,000	\$84,000
Westport HD System	-	\$60,000
Extended Warranty	\$4,400	\$8,000
Total without Incentives	\$88,400	\$152,000

Hence, the natural-gas-fueled truck starts with a cost disadvantage \$63,600. Because taxes are based on the cost of the truck, federal and state taxes may increase the cost differential to \$76,100.⁸ A tax credit of \$28,800 can reduce the difference to \$47,300. This cost differential must then be recovered from fuel-cost savings.

¹ March 2010 Peterbuilt brochure

² July 2007 Peterbuilt brochure

³ <http://www.lafreightliner.com/alternative-fuel-trucks.htm>

⁴ <http://macktrucks.com/default.aspx?pageid=4597>

⁵ <http://www.autocartruck.com/refuse/NewsArticle.aspx?NewsID=49>

⁶ <http://www.autocartruck.com/Voc/TruckTractors.aspx>

⁷ Source data available at <http://www.slideshare.net/westportinnovations/westport-corporate-update-presentation-20090615>

⁸ The Westport presentation assumed 12 percent federal tax and 8 percent state tax. State taxes will vary by state.

3.4.4 Technological Competition

The major competitor to the natural-gas-fueled truck is, of course, the diesel truck. Implementation of EPA 2010 emission limits for nitrogen oxides and particulates make the Cummins-Westport ISL-G powered trucks attractive because the CNG-fueled engine can meet emission limits using only a three-way catalyst, which is much simpler than the particulate filter and SCR nitrogen oxide reduction required for diesel engines. The downside to the spark-ignited ISL-G engine is a small decrease in engine efficiency. The Westport HPDI dual-fueled engine is almost as efficient as a diesel engine, but it requires emission control equipment that is similar to the equipment used on diesel engines.

Hybrid technology is also becoming available for heavy trucks. For example, the Walmart fleet is testing diesel/electric hybrids, including five Peterbilt Model 386 trucks and one Arvin Meritor Prototype.¹ However, hybrid technology provides the greatest benefit for vehicles that stop and start frequently so that regenerative braking can be effective. Hence, the benefit of hybrid technology is expected to be greater in buses, delivery vans, garbage trucks, and utility trucks. For a heavy truck transporting goods over long distances on an interstate highway, fuel savings associated with hybrid technology would be modest.

¹ <http://walmartstores.com/pressroom/news/8949.aspx>

4.0 Factors Specific to Natural Gas in Fleet Vehicles

The introduction of natural-gas-fueled vehicles as fleet vehicles has several potential advantages relative to other vehicle applications. Fleet vehicles often are driven significantly more miles per year than consumer vehicles. This allows greater savings per year on fuel costs to offset the higher capital costs of the vehicles. Many fleet vehicles operate over a limited range and return to a common depot one or more times a day. This common depot could be the location of a dedicated refueling station that supports the fleet. Concentrating vehicles in a fleet can allow a more economical repair capability as parts inventories and repair expertise supports a number of vehicles. Finally, in some cases, conversion to an alternative fuel may be mandated for a fleet of vehicles by regulations, making the economics of the conversion a secondary concern.

Fleet vehicles considered for conversion to natural gas may include light-duty, gasoline-fueled vehicles such as taxis and shuttle buses, medium-duty vehicles such as city/school buses and garbage trucks, or heavy-duty Class-8 trucks hauling freight. Prior experience with CNG- or LNG-fueled vehicles in the various categories is reviewed below.

4.1 Taxis

A major portion of the U.S. taxi fleet consists of used Ford Crown Victoria sedans previously used as police vehicles. Advantages of the Crown Victoria include adequate space for passengers and their luggage, durability in a high-mileage commercial setting, low purchase cost, and a simple and inexpensive maintenance. The spacious back seat is a particular advantage in major cities where a partition is required between the driver and passengers.

The business model under which taxis operate in the United States may affect how CNG-fueled taxis are adopted. About 90 percent of taxi drivers are not conventional employees. The driver leases the vehicle from the company by paying a fee to take the taxi for a shift and pays for driver permits, passenger pickup fees, road tolls, and fuel. The company is responsible for the vehicle purchase, maintenance, and insurance, and provides dispatching services and processing of fares paid using credit cards, vouchers, or other non-cash methods. In cases where the vehicle is driver-owned, the driver is responsible for purchasing and maintaining the vehicle, so the fees charged per day for those items are eliminated. In the leased vehicle arrangement, increased costs for vehicle purchase and maintenance are passed to the driver in the form of higher daily lease fees that the driver must then make up through savings in fuel costs. For hybrid cabs, the increase in fees to the driver is about \$15 per vehicle-day.¹

The high monthly mileage for the average taxi (~5000 miles) should make any fuel-saving alternative vehicle technology more attractive compared to service as a consumer vehicle. Most of the inroads made by alternative vehicle technology into taxi fleets have been for hybrids, primarily the Ford Escape and Toyota Prius. A number of fleet operators have concluded that hybrid vehicles are more expensive to purchase and maintain for use as taxis. For example, expenses for the 167 Escape hybrids operated by Gotham Yellow LLC were estimated to be \$3611 per year higher than the Crown Victoria.² The expenses included higher purchase cost, higher cost to convert to a taxi, higher costs for parts, more

¹ "Analysis of Alternative Fuels & Vehicles for Taxicab Fleets" July 31, 2009, pg 10. Taxicab, Limosine & Paratransit Association. Available at <http://www.tlpa.org>

² Ibid, pg 19

repairs with a lower percentage performed in-house, more down-time and need for standby vehicles, and higher repair costs for vehicles involved in accidents. The higher cost to maintain the vehicles reduces the benefit obtained from lower fuel consumption. Some of the higher maintenance costs are related to the fact that the currently used hybrid vehicles are not intended to be used as commercial vehicles. Introduction of commercial CNG-fueled vehicles suitable for use as taxis may avoid some of these issues. The Crown Victoria was previously offered as an OEM CNG-fueled vehicle, but this option was discontinued in 2004. The Ford Transit Connect appears to be the most likely commercial vehicle to be applicable as a CNG-fueled taxi.

An incentive provided in some locations for CNG-fueled taxis is to allow them to go to the front of the taxi queues at the airport. This practice is currently being used at San Francisco International, Boston's Logan International, Dallas/Fort Worth, Dallas Love Field and San Jose's Mineta Airport.¹ This practice effectively boosts the earnings potential of taxi drivers with CNG-fueled vehicles at the expense of other taxi drivers who are operating conventional vehicles.

4.1.1 Current Use of CNG Taxis

CNG-fueled vehicles have made inroads in several major cities. As of March, 2010, 57 percent of San Francisco's taxi fleet is composed of hybrid or CNG-fueled vehicles. CNG-fueled vehicles account for 131 of 1378 total taxis or about 10 percent of the total. In San Francisco, adoption is in part driven by a law requiring taxi companies to reduce greenhouse gas emissions by 20 percent from 1990 levels by 2012.²

California Yellow Cab, serving Orange County, California, recently placed an order for 25 Ford Transit Connects that it intends to convert to CNG fuel. The converted Transit Connects will join almost 100 more CNG-powered taxis already deployed by the cab company.³

Yellow Cab Cooperative, San Francisco's largest taxi operator, has awarded Clean Energy Fuels Corporation a 10-year contract to supply compressed natural gas (CNG) fuel, and provide operations and maintenance for a newly expanded Clean Energy CNG station located south of the City center at 1200 Mississippi St.⁴

New York City has over 250 CNG fueled taxis.⁵ Several additional examples of cities with CNG taxis operating are shown in Table 4.1.⁶

¹ <http://www.leftlanenews.com/cng-fueled-taxi-cabs-bumped-to-front-of-airport-lines.html>

² <http://www.ngvglobal.com/san-francisco-alternative-fuel-taxis-cut-ghgs-and-dollars-0322>

³ <http://green.autoblog.com/2010/06/08/california-yellow-cab-orders-up-25-cng-powered-ford-transit-conn/>

⁴ http://www.businesswire.com/portal/site/home/permalink/?ndmViewId=news_view&newsId=20081229005054&newsLang=en

⁵ <http://www.epa.gov/oar/recipes/natgas.html>

⁶ <http://www.cngnow.com/EN-US/AmericaOnCNG/Fleets/Pages/YellowCab.aspx>

Table 4.1. Examples of CNG Taxi Numbers in Several Cities

City	Number of CNG Taxis	Company
Bloomfield/New Haven Connecticut	140	Yellow Cab, Metro Taxi
Chicago, Illinois	100	Yellow Cab
Dallas Fort Worth, Texas	10, plus 50 planned	Yellow Cab
Long Beach, California	Plans for 100-200 orders	Long Beach Yellow Cab
Orange County, California	160	Yellow Cab of Greater Orange County

4.2 Corporate Fleet Vehicles

Interest in natural-gas-fueled vehicles has been particularly strong for corporate fleet vehicles. A 2009 survey of 135 companies with fleets ranging from 70 to 72,000 vehicles, conducted by the Alternative Fuels Vehicle Institute, found that nearly half of the companies plan to purchase alternative fuel vehicles in the next three years.¹ The top four factors most often cited as being very important to purchase decisions were in order of frequency: 1) the right vehicle to meet the need, 2) availability of fuel in the area, 3) overall payback, and 4) environmental concerns.

Several recent announcements tend to confirm a high level of interest in CNG-fueled corporate fleet vehicles.

4.2.1 AT&T

AT&T recently announced that it expects to spend an estimated \$350 million to purchase about 8000 CNG-fueled vehicles as part of a long-term strategy to bring its alternative-fuel fleet to more than 15,000 vehicles by 2019.² The CNG-fueled vehicles will replace gasoline-powered service vehicles over the next 5 years. The vehicles will be domestic OEM gasoline-powered vehicles converted to run on natural gas. AT&T is working with natural gas companies to provide 40 new CNG fueling stations to refuel the vehicles.

4.2.2 UPS

In January 2010, UPS announced that, over the prior month, it had deployed 245 CNG-fueled delivery trucks to its offices in Denver, Colorado, (140) and the California cities of San Ramon (18), Fresno (16), West Los Angeles, (59) and Ontario (12).³ In April 2010, UPS announced deployment of 200 next-generation hybrid electric delivery trucks in eight U.S. cities.⁴

¹ <http://www.afvi.org/>

² <http://www.att.com/gen/press-room?pid=4800&cdvn=news&newsarticleid=26598>

³ <http://pressroom.ups.com/Press+Releases/Archive/2010/Q1/UPS+Deploys+245+New+%22Green%22+Trucks>

⁴ <http://pressroom.ups.com/Press+Releases/Archive/2010/Q2/UPS+Deploys+200+Hybrid+Electric+Vehicles>

4.2.3 Verizon

Verizon announced in June 2010 that it intends to add 501 Ford E-250 cargo vans converted by BAF to operate on CNG.¹ Vans are primarily used by technicians who install and maintain telephones and FiOS television and Internet services for homes and businesses. Verizon also recently added 576 Chevrolet Silverado Hybrids to its fleet.

4.2.4 Chesapeake Energy

As of May 2010, Chesapeake Energy Corporation plans to convert 1000 light-duty trucks in its corporate fleet to CNG in the next 18 months, and an additional 2300 within 4 years. Nine public CNG stations will be built this year in Oklahoma and two in Arkansas.²

4.2.5 Shuttle Vans

Supershuttle International has ordered 40 new CNG-fueled vans to be operated at San Francisco International Airport through BAF, Clean Energy's subsidiary. A 5-year agreement with Clean Energy Fuels provides for refueling CNG SuperShuttle Vans operating at additional major airports in Dallas/Fort Worth, Denver, New York City, Phoenix, California, Los Angeles, Burbank, Ontario, Orange County, and San Diego.³

Funding from the New York State Energy Research and Development Authority assisted the Albany International Airport in providing shuttle vans and pickup trucks powered by CNG.⁴

4.2.6 Garbage Trucks

As of 2008, there were over 2000 natural-gas-fueled refuse trucks operating in the United States.⁵ In addition to the federal tax credit, many states have air quality programs to assist purchases of new natural-gas-fueled trucks. Prior studies have compared natural-gas-powered and diesel powered refuse trucks.

A study (Chandler et al 2001) of five LNG-fueled refuse trucks operated from 1998 to 2000 by Waste Management found fuel economy to be 9 to 12 percent lower during emission testing of the vehicles and 27 percent lower in the field (although this may have been influenced by the load carried by the trucks). The overall fuel cost for the LNG-fueled trucks was much higher, in part due to high LNG cost. Overall, the LNG-fueled trucks cost 80 percent more to operate per mile.

¹ <http://www.automotive-fleet.com/Channel/Green-Fleet/News/Story/2010/06/Verizon-Adds-CNG-Fueled-Ford-Cargo-Vans-to-Fleet.aspx>

² <http://www.automotive-fleet.com/Channel/Green-Fleet/News/Story/2010/05/Chesapeake-Energy-Recognized-for-Natural-Gas-Efforts.aspx>

³ <http://www.automotive-fleet.com/Channel/Green-Fleet/News/Story/2010/05/Clean-Energy-to-Provide-Natural-Gas-for-SuperShuttle.aspx>

⁴ <http://www.nyserda.org/programs/Transportation/afv.asp>

⁵ Jan 2008 Presentation "Natural Gas Powered Refuse Trucks" by Raymond Burke, VP Clean Energy Fuels

In addition, in 1999 there was a test of LNG/diesel dual-fuel refuse trucks by the Los Angeles Bureau of Sanitation. The trucks were equipped with a 110-gal LNG tank and a 48-gal diesel tank in place of the normal 65gal diesel tank. This demonstration involved engine technology being developed by Clean Air Power. When hauling light loads, the engine used a skip-fire technique to remove fuel from some cylinders.¹

There are a number of recent announcements related to natural-gas-fueled refuse trucks being purchased or put into service:

- In June 2010, the Montgomery County Department of Environmental Protection's Division of Solid Waste Services in Rockville, Maryland, put into service the first 20 of 100 refuse and recycling collection trucks powered with CNG.² In addition, Montgomery County plans to have all its vehicles operating on natural gas by 2012.³
- In Bridgeport, Connecticut, refuse truck operator Enviro Express announced it will purchase 18 new LNG-powered tractors and build a LNG/CNG refueling station that will be open to the public.⁴ Through the project, Enviro also will fuel four heavy-duty dump trucks that the City of Bridgeport will re-power with CNG-fueled engines with assistance from the same award.⁵ The effort is part of a four-year, \$26.8 million program called the Connecticut Clean Cities Future Fuels Project. The funding was provided by the American Recovery and Reinvestment Act of 2009.
- In Montgomery County, Maryland, the county has begun implementing a plan to achieve a goal to have all refuse and recycling trucks running on natural gas by 2012.

4.2.7 Delivery Trucks

Application of natural gas to fuel fleet delivery trucks also has been examined. A study of UPS delivery trucks fueled by CNG was performed from 1997 through 2000 at two sites (Chandler et al. 2002.). At both sites, the mileage of the CNG-fueled trucks was 27 to 29 percent lower than that of the diesel trucks. The total operating costs at one site were found to be 19 percent higher, and at the other site, they were 2 percent lower. An oil carryover problem with the natural gas compressor was a major factor in the difference in operating costs.

4.2.8 Buses⁶

Several head-to-head studies have been made of natural-gas-fueled buses compared to diesel-powered buses. In the first study (Chandler et al. 2006a), the fleet included 260 CNG-fueled buses and 125 hybrid buses. The miles-between-road-call values were 5000 for the CNG-fueled buses and 7000 for the hybrid buses, both of which are above the required level of 4000. The CNG-fueled buses experienced fuel

¹ www.afdc.energy.gov/afdc/pdfs/35115.pdf

² <http://www.government-fleet.com/News/Story/2010/06/Montgomery-County-Deploys-New-CNG-Trash-Trucks.aspx>

³ <http://moneymorning.com/2010/07/02/natural-gas/>

⁴ http://www.nhregister.com/articles/2010/06/15/business/ee1_gas0609061510.txt

⁵ <http://www.automotive-fleet.com/News/Story/2010/06/AGT-Enviro-Partner-for-Natural-Gas-Fuel-Station.aspx?interstitial=1>

⁶ Some of the references listed are provided and additional information on fleet experience is provided by EERE at http://www.afdc.energy.gov/afdc/fleets/fleet_experiences.html

economies that were 25 percent lower than that of the diesel buses, while the hybrid buses averaged 45 percent higher mileage. Because of natural gas prices, including the compression costs being slightly higher than the diesel-fuel costs (1.78 \$/GGE vs 1.70 \$/gal), the fuel costs were highest for the CNG-fueled buses. Propulsion related maintenance costs for the hybrid were 9 percent higher than the CNG-fueled buses.

In a second study (Chandler et al. 2006b), the performance of 40-foot, CNG-fueled transit buses operated by the Washington Metropolitan Area Transit Authority were compared over 12 months to the performance of diesel buses. The study found that the total operating costs were very similar for the two types of buses. Fuel economy of the CNG-fueled buses was 16 to 18 percent lower, and fuel costs, when electrical compressor power was accounted for, were nearly the same. Engine and fuel-system related maintenance costs were 11 percent higher for the CNG-fueled buses.

An earlier feasibility study that compared the costs of changing a 200 bus fleet over to CNG or adding diesel particulate filters to the buses to control emissions found it was much more economical to work with the diesel-powered buses (Lowell et al. 2003). The most important factor in the higher cost was a \$20 million cost to upgrade the bus depot to accommodate natural-gas-fueled buses. Ignoring the facility costs, the CNG-fueled buses would have been about 20 percent more expensive to operate.

Since these studies were done, important changes have occurred. The first is implementation of EPA's 2010 emissions standards. Although these standards add costs to diesel engines, requiring inclusion of an SCR and a particulate filter, it also eliminates some of the non-financial reasons to prefer natural-gas-fueled engines (i.e., to reduce particulate and nitrogen oxide emissions). Second, natural-gas-fueled engines have improved in efficiency over time.

Natural-gas-fueled buses have been introduced to a number of bus fleets across the country. Valley Metro, serving metropolitan Phoenix, Arizona, operates one of the largest CNG- and LNG-fueled bus fleets. As of July 2007, Valley Metro operated a total of 649 natural-gas-fueled buses. Approximately 85 percent of fuel use is in the form of LNG with the remainder CNG. As of June 2010, Sante Fe Metro is operating an all CNG-fueled transit fleet of 30 buses. Reasons cited for converting to CNG are lower fuel costs relative to the cost of diesel fuel and lower original purchase costs compared to hybrid vehicles. Pierce Transit, serving Tacoma and the surrounding Pierce County area in Washington, is operating a fleet of 200 CNG-powered transit buses.¹ This is only a partial listing of bus fleets adopting natural gas as a fuel.

¹ http://www.afvi.org/newsletter_apr10.html#Story2

5.0 Implications for Natural Gas Infrastructure

5.1 Natural Gas Supply and Distribution Infrastructure

A key element of the plan promoted by T. Boone Pikens is “Using America’s natural gas to replace imported oil as a transportation fuel.” In 2008, the United States consumed 7117 million barrels of oil. Of this total, 3108 million barrels were domestically produced with the balance of 4009 million barrels being imported.¹ Thus, in 2008, about 56 percent of our oil was provided by imports.

Using natural gas to significantly reduce dependence on gasoline or diesel fuel will result in a significant increase in the consumption of natural gas. The degree of our increase in natural gas consumption will depend on the amount of gasoline or diesel fuel that is displaced. Table 5.1 provides a summary of the consumption of natural gas for 2009. The energy values are converted to GGE to allow comparison on an equivalent energy basis to gasoline and diesel fuel consumption. For comparison, consumption of gasoline and diesel with <15 ppm sulfur are summarized in Table 5.2.

Table 5.1. 2009 U.S. Natural Gas Consumption²

Sector	Billion ft ³ /yr	% of Delivery to Customers	Million GGE/Day
Residential	4761	22.7%	105.9
Commercial	3113	14.9%	69.3
Industrial	6142	29.3%	136.6
Electric Power	6888	32.9%	153.2
Vehicle Fuel	32	0.2%	0.7
Total Delivered to Customers			465.7
Pipeline and Plant Use	1898		42.2
Total Gas Production	22834		507.9

Table 5.2. 2009 U.S. Gasoline and Diesel Consumption³

	Thousands of Barrels/Day	Million GGE/Day
Gasoline	8986	377.4
Low Sulfur Diesel(<15 ppm S)	2861	136.8
Total, gasoline+diesel (<15 ppm S)		514.2

Based on these figures, natural gas deliveries would need to increase by a factor of $(514.2+465.7)/465.7 = 2.10$ over current production to provide the energy content currently provided by gasoline and diesel fuel. If the objective is only to displace the currently imported fraction,⁴ the increase in natural gas consumption would be $(514.2*0.56+465.7)/465.7 = 1.64$. This increase would be in

¹ <http://tonto.eia.doe.gov/country/index.cfm?view=production>

² http://www.eia.doe.gov/oil_gas/natural_gas/data_publications/natural_gas_monthly/ngm.html

³ http://tonto.eia.doe.gov/dnav/pet/pet_cons_psup_dc_nus_mbbbl_m.htm

⁴ It should be noted that reductions in consumption of diesel fuel and gasoline would not necessarily result only in reductions in imports. If natural gas were to displace 56 percent of the U.S. gasoline and diesel fuel consumption, the oil sources displaced would be based on economic considerations and would displace some mix of domestic and imported oil sources depending on cost.

addition to any increase in natural gas consumption related to current uses such as for electrical power generation.

Because of improved extraction of natural gas from shale deposits, domestic natural gas production has been increasing over the last several years while imports from Canada have been falling and exports slowly rising. Figure 5.1 illustrates this using monthly production, import, and export values with a 12-month moving average for each. Over the last 4 years, the domestic monthly production has increased from ~1.50Tcf to ~1.75Tcf, which represents an increase of ~17 percent.

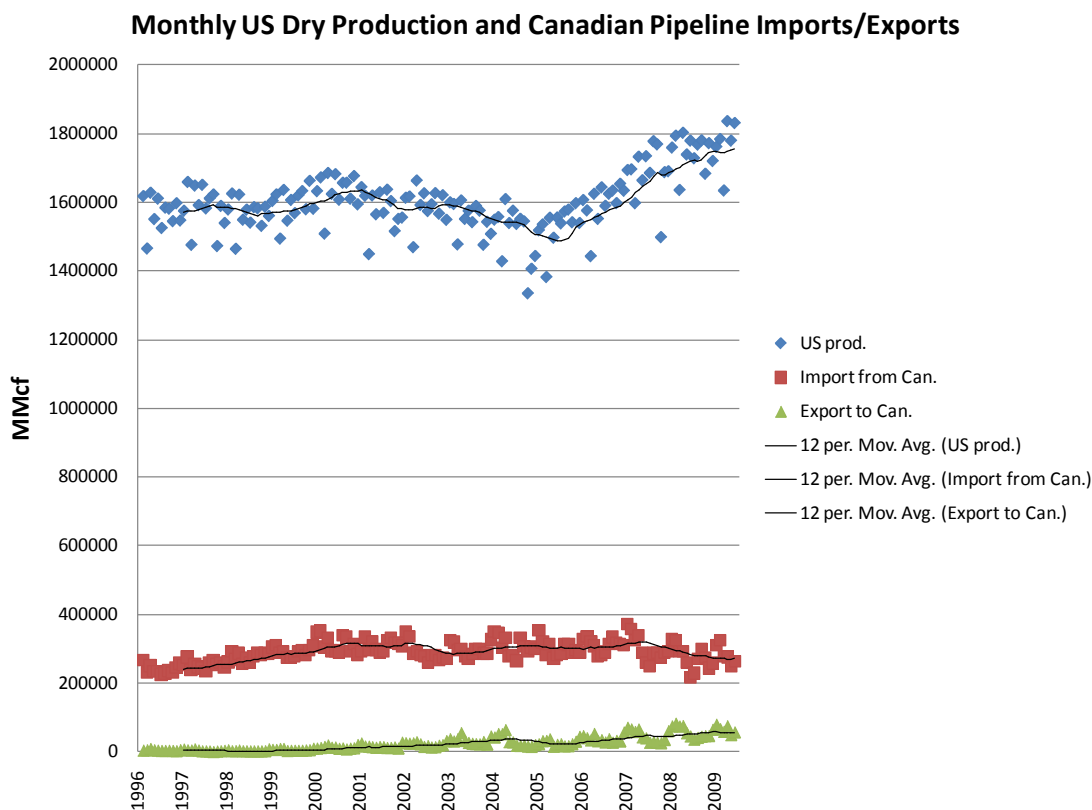


Figure 5.1. Current Trend in U.S. Natural Gas Production and Import/Export from Canada¹

To determine the infrastructure investments required to increase natural gas deliveries by a factor of 1.64, the analysis will draw heavily on a study performed by ICF International for the Interstate Natural Gas Association of America (INGAA) Foundation examining future infrastructure requirements. The report projects natural gas pipeline and storage infrastructure needs through 2030.² The report considers the combined Canadian and U.S. markets and examines a base case as well as low-growth and high-growth scenarios. The high-growth case amounts to a 34 percent increase in natural gas consumption and is based on growth in the use of natural-gas-fueled vehicles as well as use of natural gas in electrical generation to support plug-in hybrid vehicles. Although the growth in natural gas consumption in this case falls short of the 64 percent calculated above to displace imported oil, it is a useful benchmark to

¹ Data from EIA, production see <http://tonto.eia.doe.gov/dnav/ng/hist/n9070us2m.htm> , Canadian imports <http://tonto.eia.doe.gov/dnav/ng/hist/n9102cn2m.htm> , exports <http://tonto.eia.doe.gov/dnav/ng/hist/n9132cn2m.htm>

² “Natural Gas Pipeline and Storage Infrastructure Projections Through 2030” October 20, 2009, prepared by ICF International for INGAA Foundation Inc., Report available at www.ingaa.org .

examine infrastructure requirements to support a significant increase in gas consumption. Lacking a better methodology, the estimates from the report are then used in a linear extrapolation to estimate costs associated with the envisioned expansion of natural gas usage to displace petroleum-based vehicle fuels.

A table in the report comparing the base-case predictions for the U.S. gas market to a variety of other projections is reproduced below as Table 5.3¹. As can be seen, the estimates for U.S. consumption vary widely, ranging from a 7.6 percent decrease to a 30 percent increase.

Table 5.3. Comparison of U.S. Natural Gas Market Projections, 2008 to 2030 (Tcf per year). Reproduced from “Natural Gas Pipeline and Storage Infrastructure Projections Through 2030”²

	EIA 2008	Delta 2030 less 2008 (Tcf per year)							
		INGAA (U.S. Only) Base Case	EIA AEO 2009 Reference	IHSGI	EVA	DB	IER	SEER	Altos
U.S. Dry Gas Production	20.56	5.31	3.04	1.77	(2.07)	(1.86)	(6.80)	(0.12)	(2.86)
Net Pipeline Imports	2.67	(2.71)	(2.85)	(2.16)	(0.18)	(0.84)	(0.70)	(2.35)	(2.66)
LNG Imports	0.30	1.40	0.55	2.75	6.38	3.26	5.38	3.12	10.70
Total U.S. Consumption	23.18	3.96	0.33	2.69	6.23	0.63	(1.77)	1.00	6.86
Residential	4.87	0.20	0.01	0.52	0.56	1.19	0.73	0.05	(0.24)
Commercial	3.12	(0.02)	0.39	0.11	0.05	(0.77)	(0.62)	0.54	0.57
Industrial	6.62	0.61	(0.28)	0.70	1.98	(1.53)	(3.20)	0.00	0.99
Power Generation	6.66	2.93	0.03	1.09	3.28	1.93	(2.30)	0.32	5.54
Other	1.91	0.23	0.17	0.28	0.36	(0.18)	3.61	0.08	na

Source: EIA AEO Comparison of Natural Gas Projections

Note: INGAA forecast produced by ICF International (January 2009) - Excludes Canadian volumes in this table for comparison.

EIA AEO - Energy Information Administration Annual Energy Outlook 2009 - Updated Reference Case (April 2009)

IHSGI - IHS Global Insight Inc. (September 2008)

EVA - Energy Ventures Analysis, Inc. (January 2009)

DB - Deutsche Bank (September 2008)

IER - Institute of Energy Economics and the Rational Use of Energy - Stuttgart (November 2008)

SEER - Strategic Energy and Economic Research, Inc. (April 2008)

Altos - Altos World Trade Model - (October 2008)

A key conclusion from the INGAA report is that natural gas infrastructure costs will be primarily determined by significant shifts in natural gas production as current conventional resources are depleted and are displaced by unconventional (defined as requiring well stimulation or other technologies to produce) and to a lesser extent arctic resources. The portion of natural gas supply obtained from conventional resources is expected to decline from 71 percent currently, to about 43 percent for the base case and to 38 percent in the high gas growth case by 2030. The infrastructure costs associated with this shift in supply sources is more important than the assumptions related to growth in natural gas consumption for the cases examined. Infrastructure costs incurred will include well drilling, gathering pipelines, gas treatment facilities, and interregional transmission pipelines. Both the base case and high gas growth cases assume expenditures of ~\$50 billion for construction of pipelines to access gas from natural gas fields in northern Alaska and in the Mackenzie Delta in Northern Canada.³ Estimated costs from the INGAA report are summarized in Table 5.4 for the base and high gas growth cases.

¹ Note that this table applies only to US gas markets while the remainder of the INGAA report and the extrapolation that follows in this report is on the basis of the combined US-Canadian market.

² October 20, 2009, prepared by ICF International for INGAA Foundation Inc., Report available at www.ingaa.org.

³ These projects significantly affect the estimates of transmission pipeline costs. The Alaska project would consist of 2000 miles of 48-in. pipe connecting Prudhoe bay to Alberta. The Mackenzie Delta project would consist of 746 miles of 30-in. pipe from the Mackenzie Delta in the Canadian Northwest Territories to Northwest Alberta.

Table 5.4. INGAA Estimates of Natural Gas Capital Expenditures through 2030. Includes the United States and Canada (INGAA 2009)

	Base Case	High Growth Case
Annual Gas Consumption in 2030, Tcf	31.8	36.0
Percent Increase Relative to 2008	19%	34%
Capital Expenditures, \$Billions		
Transmission Pipeline Infrastructure	129.5	162.8
Regional Storage	3.4	5.2
Gathering Pipelines	11.5	18
Processing Facilities	13.2	21.7
LNG	1.8	1.8
Total	159.3	209.5

Based on data from Table 5.4, an increase of 13.2 percent¹ in relative gas consumption results in an additional capital expenditure of \$50.2 billion. In the current study, it is desired to assess the impact of increasing overall gas consumption by 64 percent to supply sufficient natural-gas-fueled vehicles to displace imported oil. Making a linear extrapolation to a 64 percent increase provides a rough estimate of additional capital expenditures of \$243 billion². Adding the additional expenditures to the base case expenditures provides a total capital expenditure of approximately \$402 billion through 2030. While the extent of the linear extrapolation of the cost introduces the potential for significant error, it is clear that the additional investment to provide the additional 64 percent capacity would be significant.

However, to the extent that the additional consumption of natural gas is driven by market forces, the investment in natural gas infrastructure would be paid for through the revenue stream obtained from sale of the additional natural gas. Hence, the main impediment to large-scale adoption of natural gas as a transportation fuel is more related to the economic competition provided by gasoline and diesel fuels than the infrastructure investments required to supply the additional natural gas. The exception to this is the investment in natural gas refueling stations that dispense natural gas to vehicles and LNG production facilities (if LNG adopted), which will initially not represent profitable investments because of the low numbers of natural gas vehicles on the road.

5.2 Refueling Station Infrastructure

Costs to add natural gas refueling stations will vary with the capacity and whether they deliver LNG or CNG (or both) fuel. Smaller CNG stations are less expensive than LNG stations, but both types of stations are more expensive than typical gasoline/diesel stations.

CNG stations can be designed as slow-fill, cascade-fast-fill, or buffered-fast-fill stations. A slow-fill station fills vehicles over several hours while they are parked. These stations are suitable for fleet vehicles that return daily to a common location. The slow-fill station is less expensive because it does not have CNG storage and, by spreading the fueling over several hours, can use a smaller compressor. The

¹ Calculated based on 2030 gas consumption in high growth case of 36.0 Tcf relative to base case of 31.8 Tcf

² This effectively assumes vehicle fuel consumption grows at the same rate as natural gas consumption through 2030. If instead it is assumed that no increase occurs in vehicle fuel consumption from 2008 levels the estimate is \$205 vs. \$243Billion.

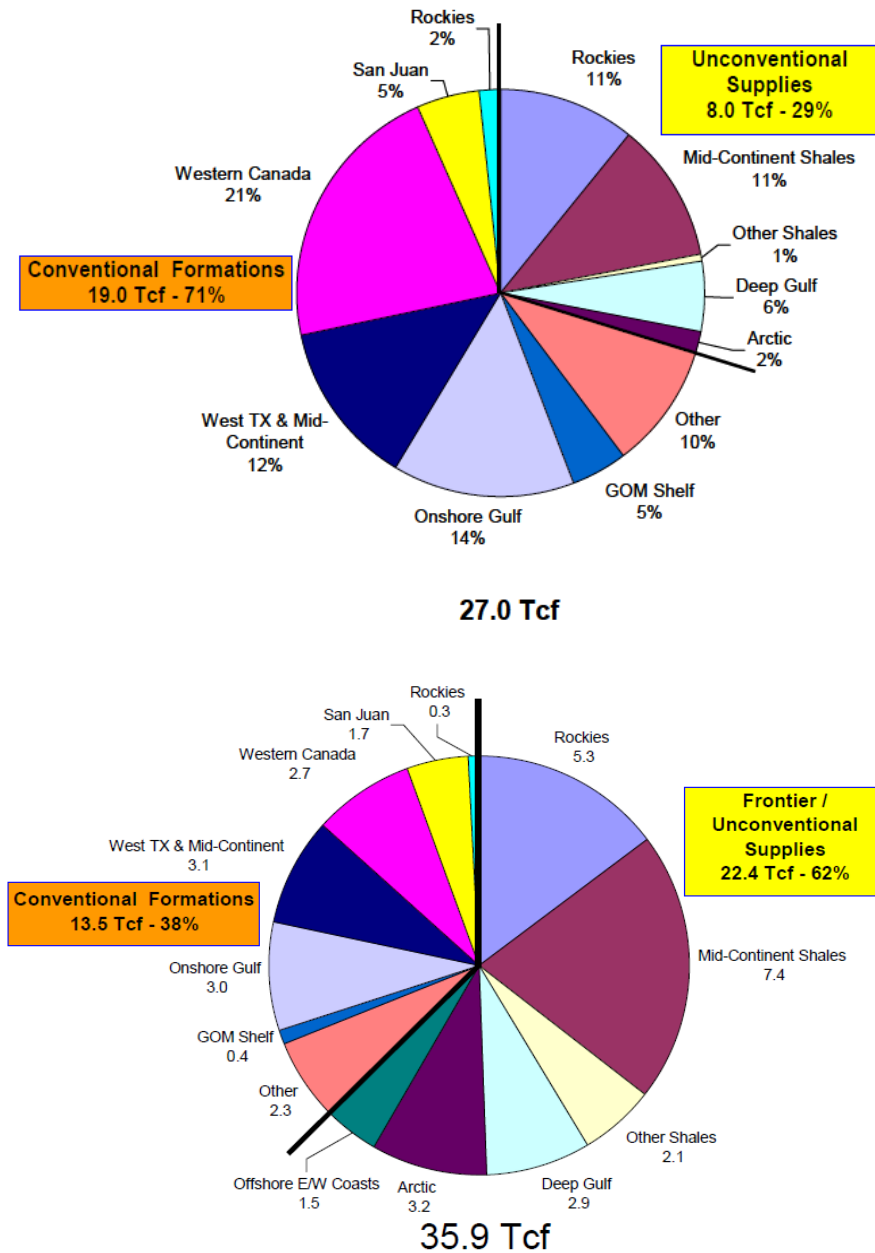


Figure 5.2. Distribution of North American Annual Gas Production Sources in 2008 (top) and Projected for 2030 (bottom) for the High Gas Growth Case. Figures reproduced from INGAA 2009. Does not include imported LNG¹.

¹ In addition to the increase in unconventional gas production, INGAA predicts a significant increase in annual LNG imports from 1 Bcfd to 5 Bcfd. Projected LNG capacity is projected to increase by 3.5 Bcfd to 20 Bcfd, indicating a utilization rate of only 25 percent. However, because most of the LNG infrastructure is constructed already and is utilized at very low levels, very little in the way of LNG infrastructure would be required to support the high growth case. LNG terminals are typically close to the point of consumption which minimizes the pipelines required to bring the gas to market.

cascade-fill station uses a compressor to fill high-pressure tanks that are then used to provide fast filling to a small number of vehicles or an occasional large vehicle with filling accomplished primarily with flow from the storage tank to the vehicle. The cascade-fill station adds the cost of high-pressure storage tanks but has the advantage of a fast-fill capability. However, if too many vehicles attempt to refuel in a given period, the fill rate reverts to a much lower rate associated with the compressor capacity. The buffered-fast-fill station uses a larger compressor, and fills vehicles primarily via flow from the compressor. The compressor continues to run between fills to pressurize the buffer tank. While slow-fill or cascade-fill designs may be suitable for fleet vehicles with predictable fueling schedules, commercial stations open to the public will need to have the fast-fill capability. An alternative fast-fill design for stations offering LNG is to pressurize the LNG and then vaporize the liquid to provide compressed gas from the LNG source.

The estimated costs for fast-fill refueling stations are shown in Table 5.5.

Table 5.5. Fast-Fill Natural Gas Refueling Station Costs¹

NG Refueling Station Type	Maximum Capacity	Maximum Capacity, gge Equivalent ²	Estimated Cost
CNG, small	<500 scfm	4.0 gge/min	\$400,000
CNG, medium	500-2000 scfm	4.0-15.8 gge/min	\$600,000
CNG, large	>2000 scfm	>15.8 gge/min	\$1,700,000
LNG, large	15,000 gallon storage	8,670 gge storage	\$1,700,000
CNG/LNG, large	>2000 scfm	>15.8 gge/min	\$2,000,000

The fuel costs here are consistent with an estimated range of \$1,000,000 to \$4,000,000 for LNG fueling stations mentioned in a U.S. Energy Information Administration analysis.³ This also is consistent with cost information from the Idaho National Laboratory, suggesting that just mechanical systems for an LNG station cost from \$350,000 to \$1,000,000, compared to \$50,000 to \$150,000 for a conventional station.⁴

Currently, not enough public natural gas refueling stations are available to eliminate the disincentive of a lack of fueling infrastructure for the vehicle purchaser. Neither are there enough natural-gas-fueled vehicles to make investment in refueling infrastructure profitable. Fleet vehicles can overcome this problem by making fueling for an entire fleet of vehicles and then purchasing a fueling station that is appropriately sized to serve the fleet, assuring the station capacity is well utilized. In many instances, the refueling station will be provided as part of a long-term agreement between the fleet owner and a supplier of CNG/LNG. AT&T's plans to deploy 8000 CNG-fueled vehicles will rely on Clean Energy Fuels to build, operate and supply the refueling stations needed.⁵ Similarly, the Los Angeles METRO Transit

¹ California Energy Commission Report #CEC-600-2010-001-CTD, July 2010, "2010-2011 Investment plan for the alternative and renewable fuel and vehicle technology program", Table 19: Natural Gas Infrastructure Costs.

Available online at <http://www.energy.ca.gov/publications/index.php>

² Converted at 126.7 scfm equivalent to 1 GGE

³ Report # DOE/EIA-0383(2010), release date May 11, 2010. U.S. Energy Information Administration www.eia.doe.gov/oiaf/aeo/natgas_fuel.html

⁴ <http://www.inl.gov/lng/projects/refuelingstation.shtml>

⁵ <http://fleetowner.com/green/archive/clean-energy-fueling-station-0402/>

Agency recently (reported June 28 2010¹) awarded a 10-year contract to Clean Energy for the upgrade, operation, and maintenance of CNG bus fueling facilities. The natural gas delivered by the stations is expected to be more than 9 million gallons diesel equivalent. Similarly, Clean Energy Fuels has contracted through 2015 to provide station monitoring and delivery of 3.5 million gallons of LNG annually to solid waste operator Republic Services.² Clean Energy serves fleet markets accounting for more than 17,800 vehicles at 196 locations.³ However, Clean Energy Fuels is not yet profitable.⁴

The next critical question with respect to infrastructure investment is the number of stations that must be installed before the lack of fueling infrastructure ceases to become a disincentive for use of natural-gas-fueled vehicles. Yeh (2007) examined the experience of several countries and assessed two criteria for determining whether enough refueling stations exist to enable a sustained natural gas vehicle market. One criterion is that the number of stations should be a minimum of 10 to 20 percent of the number of conventional stations. At this level, the lack of stations is no longer viewed as a major disincentive. As the market matures the number of stations will typically approach one station per 1000 natural-gas-fueled vehicles, which provides reasonable profitability for station owners.

The current number of refueling stations in the United States is not known precisely. A count by the National Petroleum News in 2005 arrived at a value of 168,987.⁵ Assuming this number is still approximately correct after 5 years, the capital investment in stations can be estimated to bring the total to 20 percent of conventional stations. The investment to supply adequate CNG/LNG fueling stations at \$2 million each would be:

$$(168,987 \text{ conventional stations}) \times (0.20) \times (\$2,000,000) = \$67.6 \text{ Billion}$$

This value includes only the CNG/LNG fueling stations required to reach a density such that the lack of fueling infrastructure is no longer viewed as a barrier to enabling a self-sustaining natural gas vehicle market. Ultimately, if the natural gas market grew to replace 56 percent of current petroleum use, it is reasonable to expect a proportional number of stations, which would suggest an investment on the order of:

$$(168,987 \text{ conventional stations}) \times (0.56) \times (\$2,000,000) = \$189.3 \text{ Billion}$$

These figures do not include the infrastructure associated with the liquefaction plants and LNG delivery trucks if an LNG fueling infrastructure were adopted (verses a CNG-only infrastructure).

¹ http://www.marketwatch.com/story/la-metro-transit-agency-awards-clean-energy-new-cng-station-upgrade-operation-maintenance-contract-to-help-support-americas-largest-clean-air-bus-fleet-2010-06-28?reflink=MW_news_stmp

² http://www.marketwatch.com/story/republic-services-contracts-with-clean-energy-to-supply-lng-fuel-to-republics-solid-waste-truck-fleets-that-serve-55-california-cities-2010-06-30?reflink=MW_news_stmp

³ <http://www.thedetroitbureau.com/2010/03/clean-energy-to-run-cng-fuel-stations-for-att/>

⁴ http://online.wsj.com/article/SB10001424052748704463504575301163956931040.html?mod=googlenews_wsj

⁵

<http://www.npnweb.com/ME2/dirmod.asp?sid=A79131211D8846B1A33169AF72F78511&nm=Market+Data&type=MultiPublishing&mod=PublishingTitles&mid=8F3A7027421841978F18BE895F87F791&tier=3&TierId=22B5C5F1434C4F2FBA24DBC8C8799E8D>

5.3 Capital Cost for LNG Production

The capital cost for a natural gas liquefaction plant will vary significantly depending on a number of factors such as its production scale (i.e., capacity) and location. Based on filings by Clean Energy in November 2008, the cost upon completion of the liquefaction plant at Boron, California, with a capacity of 160,000 gal/day, was expected to be \$75 million. Costs also are available for recent larger-scale liquefaction plants for a comparison. A Total-led LNG project in Yemen that began shipping LNG in 2009 has a capacity of 6.7 million tons per year and cost of \$4.5 billion. A recent natural gas liquefaction plant completed in Peru with a nominal capacity of 4.4 million tons per year required an investment of \$3.8 billion. Capital investments for LNG production capacity are summarized in Table 5.6.

Table 5.6. Capital Cost for LNG Production Capacity

Location	Year Operating	Capacity, Metric Tons/Year	Capacity Gallons, LNG/Year	Capacity, gge/Year	Capital Investment, \$	\$/Annual gge Capacity
Boron CA	2009	93328	5.84E+07	3.89E+07	7.50E+07	\$1.93
Yemen	2009	6.70E+06	4.19E+09	2.80E+09	4.50E+09	\$1.61
Peru	2010	4.40E+06	2.75E+09	1.84E+09	3.80E+09	\$2.07

Displacement of 56 percent of 2009 U.S. annual consumption of gasoline (8,986,000 bbl/day) and diesel fuel (2,861,000 bbl/day) would require a quantity of LNG equal to 105.1 billion GGE/year. Using the LNG plant in Boron, California, plant cost as a reference, this extrapolates to a total investment of $105.1 \text{ billion} \times 1.93 = \202.8 billion . Providing LNG production capacity equal to 20 percent of current consumption would require \$72.4 billion. Hence, the liquefaction plant capital cost appears to have a significant impact on the overall infrastructure cost of implementing a natural-gas-fueling infrastructure. These costs do not account for some quantity of imported LNG that may be trucked directly from receiving terminals and, therefore, would not require liquefaction.

5.4 Summary of Natural Gas Infrastructure Costs

The estimated infrastructure costs for implementing a natural gas refueling infrastructure are summarized in Table 5.7. Values are given both for a 20-percent penetration of the vehicle fuel market, which is estimated to be the point where availability of refueling infrastructure is no longer considered an obstacle, and for a 56-percent penetration that would displace a fraction of gasoline and diesel equal to the fraction of oil that is imported to the U.S.

Table 5.7. Summary of Natural Gas Infrastructure Costs

	20% Penetration	56% Penetration
Gas Production and Distribution	\$87 billion	\$243 billion
Liquefaction	\$72 billion	\$203 billion
Refueling Stations	\$68 billion	\$189 billion

There is a mature market for pipeline natural gas in the United States. As a result, the recovery of capital investments in infrastructure for production and delivery of natural gas to either refueling stations (for CNG only) or to liquefaction plants (for LNG/CNG) would be reflected in the natural gas price. However, investment in refueling stations and regional liquefaction facilities to support refueling stations is unlikely to occur on a large scale until enough vehicles are using natural gas to make the investments profitable.

6.0 Discussion

The key factor determining whether natural gas will be able to displace gasoline and diesel fuel will be the price differential between the fuels. The natural gas price must be sufficiently lower than the gasoline and diesel-fuel prices to compensate for undesirable factors associated with natural gas use, including higher capital cost for both the vehicles and the refueling infrastructure, reduced efficiency (depending on engine technology employed), reduced vehicle cargo space, increased vehicle weight, and reduced vehicle range between refueling. Because natural gas prices are much more variable among regions of the country than are gasoline and diesel-fuel prices, the introduction of natural-gas-fueled vehicles is expected to occur unevenly with greater penetration in regions where natural gas is less expensive.

Fleet vehicles offer the most attractive opportunity for displacement of vehicles fueled with gasoline and diesel fuel. There has been significant penetration of natural-gas-fueled vehicles into fleets of buses, refuse trucks, drayage trucks, and taxis. The factors that make fleet vehicles ideal candidates for natural gas include the large number of miles driven per year (which translates to greater potential fuel savings), operation over a limited range from a central facility, and the ability to refuel the vehicles at a single location by purchasing a private refueling station adequately sized to service the fleet. Because of the limited geographic range of operation, decisions to implement natural gas in fleet vehicles can be targeted at regions where the spread between natural gas and liquid fuel prices is greatest. In addition, concentrating the maintenance know-how and spare parts inventory for the natural-gas-fueled vehicles saves cost compared to adopting single vehicles.

Wide-spread adoption of natural-gas-fueled vehicles into the consumer passenger vehicle market faces several hurdles. First, the cost of the vehicles is higher than that for standard vehicles, and for those consumers willing to invest capital to save money on fuel costs, hybrid technology offers a better return on investment. Second, the lack of refueling infrastructure makes it difficult to operate a natural-gas-fueled vehicle in most parts of the country. The availability of home refueling devices could enable a consumer with home natural gas service to purchase a natural-gas-fueled vehicle for commuting purposes. However, these home refueling appliances are unlikely to have a large impact, because for a consumer driving a typical number of miles, the initial purchase and periodic maintenance costs of the compressor will greatly reduce or perhaps even reverse the price incentive for using natural gas. In addition, cars on the road that are refueled at home will not help create a profitable market for natural-gas-refueling stations because users who have invested in home refueling devices are unlikely to use public stations. Bi-fuel vehicles offer a potentially viable route for penetration of natural gas fuel into the fuel market for light-duty vehicles. Consumers who are concerned about the availability of a CNG refueling infrastructure may consider a bi-fuel vehicle if they have access to at least one CNG station. Unfortunately, tax credits that apply to natural-gas-fueled vehicles only apply to dedicated vehicles. Extending these credits to bi-fuel vehicles may be one way to improve the penetration into the consumer market. In the case of the natural-gas-fueled vehicle, the consumer makes a significant investment in order to be able to use a less expensive fuel. This is a qualitatively different situation than an E85 vehicle for which there is little additional cost involved in the vehicle purchase, and depending on fuel prices, the vehicle may be more expensive to operate on E85¹. In the case of natural gas, the consumer would have an incentive to refill with natural gas whenever possible because of the lower fuel cost.

¹ For example, see <http://www.edmunds.com/advice/alternativefuels/articles/120863/article.html>.

The use of natural gas in heavy Class-8 trucks hauling cargo cross country also faces a number of hurdles. Regional differences in price and availability of natural gas vehicle fuel are a particular problem. A company operating a truck is unlikely to control the refueling infrastructure, making the truck dependent on commercially viable public refueling stations. If operated on CNG, heavy trucks would suffer a severe reduction in vehicle range between refueling stops, making station availability even more critical. In addition, if using a spark-ignited engine, there would be sacrifices in available horsepower and engine efficiency. If using LNG in an HPDI engine, engine performance and vehicle range are improved to near diesel levels, but the lack of a fueling infrastructure is even more critical because there are currently more CNG stations than LNG stations. Even if LNG fueling stations became available, the fuel prices likely would be initially higher and more variable than CNG because of the long-distance transportation of LNG, which would continue until sales volumes justify the construction of natural gas liquefaction plants. An LNG refueling infrastructure will need to recover the capital investment in regional liquefaction plants, which is likely to put LNG at a price premium over CNG. It may be possible to alleviate the high capital requirement for building liquefaction capacity by incentivizing utility peak-shaving plants to provide vehicle fuel when their storage facilities are nearly full. However, this approach could lead to regional LNG fuel shortages when the plants operate for their intended purpose (i.e., generating electricity). In regions in which LNG receiving terminals are located, LNG may be supplied directly via truck transport.. However, this solution replaces foreign oil imports with foreign LNG imports, which is counter to one of the motivations for using of natural-gas-fueled vehicles.

Depending on the price at which LNG is available, a large combination truck has a shorter payback period than does a Honda Civic passenger vehicle. Table 6.1 highlights the comparison. In the table, combination truck cost is based on a Westport HPDI equipped truck. Truck fuel cost is based on CNG average prices, due to uncertainty about LNG prices. The miles driven and fuel mileage for the truck are based on average combination truck mileage from the 2002 Vehicle Inventory and Use Survey. Approximately 60% of combination trucks operate >75,000 miles/yr so there is a large subset of combination trucks for which the payback time for the differential investment would be even shorter.

Table 6.1. Comparison of Honda Civic GX to Combination Truck Cost Recovery

	Honda Civic GX	Combination Truck
Miles per year	15,000	65,290
Miles per gallon	29	5.1
GGE purchased/yr	517	12,839
Fuel savings per GGE or GDE	0.94	0.95
Fuel saving per year	\$486	\$12,197
Vehicle purchase cost premium	\$6,935	\$63,600
Tax credit incentive	\$4,000	\$28,800
Net cost premium	\$2,935	\$34,800
Years to recover cost	6.0	2.9

Using natural gas as vehicle fuel to the extent that it is equivalent to our imported fuel fraction (56 percent) results in a 64 percent increase in natural gas consumption. If this were to occur, it is unlikely that all of the reduction in fuel consumption would result in reduction in imports. Instead, the highest cost oil sources, which may be some mix of domestic and imported supplies, would be eliminated first. The increase in gas usage amounts to a 64-percent increase in natural gas consumption. While

natural gas is currently in abundant supply in the United States because of the availability of natural gas from shale deposits, a consumption increase of this magnitude would have the effect of increasing natural gas prices, which would reduce the cost differential. Because oil represents a more global market than does natural gas, the reduction in gasoline and diesel consumption would have less of an effect on market prices for liquid fuels.

It is estimated that about 20-percent penetration of the vehicular fuel market will be required before the lack of a refueling infrastructure is no longer seen by potential users as a barrier to adoption. The investment in natural gas infrastructure will be significant over the next 20 years regardless of whether natural-gas-fueled vehicles are adopted because of the shift from conventional to unconventional gas sources. It is estimated that the incremental investment in production and supply to reach this level is on the order of \$87 billion. However, the natural gas market is mature in that investments in infrastructure can be made based on gas prices and expected sales volumes needed to provide a given return on investment. As a result, public funding for the development and distribution infrastructure should not be required. Investment in refueling stations needed to reach a 20-percent penetration of the fuel market is estimated to be \$68 billion. Significant numbers of refueling stations likely will not be built until there are a sufficient number of vehicles on the road to make the stations profitable. In this case, incentives for investments in refueling stations may be needed. One possible way to bridge this gap may be to incentivize operators of fleets with natural-gas-fueled vehicles to provide more capacity than required for their fleets and to make their refueling stations accessible to the public. Initial subsidy of LNG prices may be needed if stations are made available over a wide area to facilitate use of LNG by heavy trucks. While sales volumes do not justify a regional liquefaction plant, LNG will be trucked over long distances from existing LNG plants. This may have the effect of making the fuel uneconomical to consumers of the fuel, which would prevent adoption.

The best approach to displacing liquid petroleum fuels may be to use natural gas to displace petroleum in both diesel and gasoline vehicles. The volume distribution of products produced from a barrel of crude oil includes 43 vol% gasoline and 25% distillate fuel oil.¹ About 97% of gasoline is used for on-road vehicles while about 65% of distillate fuel oil is used as diesel for on-road vehicles. As a result, about 42 vol% of a barrel of oil is used for on-road gasoline and 16 vol% is used for on-road diesel. Significant adoption of natural-gas-fueled vehicles offers the potential for reducing foreign oil imports. However, the economic relationships between supply and demand for gasoline, diesel, and other crude oil products are complex. For example, if natural-gas-fueled vehicles were to exclusively displace gasoline-fueled vehicles, this may result in excess gasoline supplies as petroleum is refined to produce diesel fuel. This would result in lower prices for gasoline, which would act to counter further adoption. This is discussed further in Appendix F.

Several key factors affect the decision of whether to purchase or convert a new vehicle to natural gas. These include:

- *Expectation of Price Advantage for CNG/LNG vs. Gasoline or Diesel Fuel.* The purchaser of a natural-gas-fueled vehicle will seek to recover the cost premium of the vehicle (or cost of conversion) through savings in fuel costs. The wider the price spread between natural gas and conventional vehicle fuels the more often natural-gas-fueled vehicles will be purchased.

¹ For additional information, refer to Appendix F.

- *Price Premium for Natural-Gas-Fueled Vehicles.* The purchaser of a natural-gas-fueled vehicle will attempt to recover the larger capital investment through fuel savings.
- *Refueling Convenience.* This includes the availability of refueling infrastructure and the relative convenience in terms of how often refueling is required and the distance driven to reach the refueling location.

Implementation will be most rapid for natural-gas-fueled vehicles in applications in which a large number of miles are driven per year in regions where natural gas prices are lowest. Fleet vehicles that are driven a large number of miles and that return to a common point for refueling or travel fixed routes over which refueling is available are the most likely to show penetration of natural gas vehicles.

Under current fuel price conditions, additions of natural-gas-fueled vehicles are likely to be limited to purchase or conversion of new vehicles because making an investment in a new vehicle provides a longer vehicle life over which the capital investment in the natural gas capability can be recovered. As a result, rapid implementation of natural-gas-fueled vehicles is limited by the rate at which the existing vehicle fleet is retired. In 2008, there were a total of 137,079,843 passenger cars registered in the United States.¹ In comparison, there were 6,806,000 new car sales and leases during 2008. This means new vehicles account for about 5 percent of the overall existing vehicular fleet. From 1990 to 2008, this rate of new car introduction to the fleet has steadily fallen from 7 percent to 5 percent while the average age of registered cars has increased from 6.5 to 9.4 years. Hence, if 20 percent of new cars were natural-gas-fueled vehicles, the rate of addition of natural gas vehicles to the fleet would be ~1 percent per year. Hence even if a significant fraction of new car sales are natural-gas-fueled vehicles, it would take many years to convert a significant fraction of the total fleet to natural gas.

Compared to cars with a median age of 9.4 years, trucks have a median age of 7.6 years, and age of transit buses ranges from 6.7 to 7.7 years depending on type. However, from 2005 to 2008, truck and bus sales fell by ~40 percent, bringing the rate of new vehicle addition to the fleet from 6.9 percent to only 3.9 percent. Hence, it is apparent that the overall economic conditions and rate of total truck and bus sales will contribute to the rate at which natural gas vehicle fuel could be widely adopted.

However, sharp increases in petroleum prices could greatly accelerate adoption by making it cost effective to retire gasoline-or diesel-fueled vehicles early to obtain the fuel cost savings. Given the recent rate of increase in domestic natural gas production, it seems unlikely in the near term that the ability to produce the required amount natural gas will be a limiting factor in the rate of adoption. However, the lack of fueling station availability in many areas could slow the adoption of natural-gas-fueled vehicles even if the fuel price differential is highly attractive. In this context, having a minimum level of refueling stations would better position the United States to respond to escalating oil prices through adoption of natural-gas-fueled vehicles. Factors that may aid in this are incentivizing operators of CNG-fueled fleet vehicles to provide public access to their refueling stations, incentivizing public refueling station construction, and encouraging bi-fuel vehicles, which can use natural gas when available but can still function on gasoline when necessary.

¹ http://www.bts.gov/publications/national_transportation_statistics/

7.0 Conclusions

The major incentive for adopting natural gas as a vehicle fuel is a price that is on the order of two-thirds more than that of gasoline on average and as low as one-third the price of gasoline in some areas of the country. As a result, adoption of natural gas as a vehicle fuel is expected to be uneven across the country with the greatest market penetration in areas where natural gas prices are low. The most efficient way to maximize use of natural-gas-fueled vehicles is to encourage use of both light- and heavy-duty vehicles that operate in regions where natural gas prices are low. Use of natural gas to fuel fleet vehicles that are driven a large number of miles per year offers the most attractive opportunity for natural-gas-fueled vehicles. Fleet vehicles typically return to a common depot one or more times per day, allowing a captive refueling capability to alleviate the lack of a public refueling infrastructure. For non-fleet vehicles, the lack of a public refueling infrastructure across most of the country is a major barrier to adoption of natural-gas-fueled vehicles. Incentives to encourage fleet operators to make their fueling infrastructure available to the public may be one way to begin the process of expanding the refueling infrastructure in place. Encouraging consumer bi-fuel vehicles may also help overcome consumer fears of an inadequate refueling infrastructure while at the same time providing more vehicles requiring CNG such that profitability of CNG refueling stations is improved.

7.1 Light-Duty Passenger Vehicles

Consumer natural-gas-fueled vehicles will be CNG-fueled since LNG is unsuitable as a fuel for these vehicles. Type-1 storage cylinders, which are the least expensive and most common tanks for consumer vehicles, result in a fuel system that is three times the volume and four to times the weight to provide equivalent fuel capacity. As a result, natural-gas-fueled vehicles will tend to have some combination of a shorter operating range and reduced cargo space relative to gasoline-fueled vehicles. Currently, the Honda Civic GX, which is offered as an OEM vehicle in the United States, sells at a price premium of \$6935 prior to application of tax credits. The cost of compliance with EPA regulations (intended to prevent vehicles converted to natural gas from having worse emissions than the conventionally fueled vehicles) results in natural gas conversions being very expensive and available for only a small number of vehicles.

For consumers concerned about saving money on gasoline, the availability of hybrid electric vehicles may provide a more attractive option for primarily city driving. As fuel prices increase, highly-efficient diesel vehicles, currently available in the European market, may become available in the U.S. market and may compete with natural-gas-fueled vehicles as well.

Consumers with natural gas service that are concerned about the availability of refueling infrastructure have the option of purchasing a home-based compressor. However, factoring in the purchase and maintenance costs and residential natural gas pricing, fuel from a home compressor is expected to be more expensive than CNG obtained from a public refueling station. In addition, the effective cost of the CNG will be less than gasoline only in regions with very low natural gas prices.

7.2 Heavy-Duty Vehicles

The time required for savings on fuel cost to recover the higher initial purchase cost for a natural-gas-fueled vehicle is much shorter for a heavy-duty vehicle than for a passenger vehicle. This is primarily due to the much higher miles driven per year and the relatively low mileage for the truck which translates to much larger quantities of fuel being purchased.

Heavy-duty vehicles hauling freight across long distances using natural gas as a fuel face a critical question of whether to operate on LNG or CNG. Operating on LNG increases the storage density of fuel on the truck relative to CNG but still requires 2.7 to 3.0 gallons of volume to store the equivalent of a gallon of diesel fuel. Use of LNG enables the use of an HPDI engine that provides power (up to 450 hp for the Cummings Westport GX engine) and efficiency closest to that offered by a diesel engine. However, the question of access to refueling infrastructure becomes more acute as there are many more CNG stations than LNG stations. Also, the adoption of an LNG-based fueling infrastructure introduces hazards that differ from CNG including the lack of an indicating odorant and the potential for spills to create denser than air ignitable vapor clouds and for boiling-liquid expanding vapor type explosions of delivery trucks or storage tanks that are involved in fires.

Operating on CNG currently limits the power to the 320 hp offered by Cummins-Westport ISL-G, which is a spark-ignited stoichiometric cooled-EGR engine and would be expected to provide slightly lower efficiency than a diesel engine. Using a stoichiometric engine has the advantage that a conventional three-way catalyst can be used to meet EPA's 2010 emission standards without the need for a particulate filter. However, compared to LNG storage, using a Type-3 cylinder to store CNG requires about 50 percent more space on the vehicle. In addition, a Type-3 cylinder is more difficult to fit into the vehicle because a long narrow cylinder provides a lighter tank than a shorter, larger-diameter cylinder.

The dual-fuel engine, in which natural gas is mixed at low pressure with incoming air of the diesel engine, offers the potential for a truck that could operate on a combination of natural gas and diesel fuel when natural gas is available and then revert to pure diesel fuel when natural gas is not available. The fuel storage issues potentially could be worse because natural gas tanks would be included along with a full-sized diesel fuel tank. Existing dual-fuel engines suffer from low engine efficiency, particularly at low engine loading. There are no EPA 2010 compliant dual-fuel engines currently available, but engines are under development so this type of engine may become an option in the future.

7.3 Natural Gas Infrastructure Costs

Based on an assumption of 20-percent penetration of the vehicle fuel market, it is estimated that incremental expenditures on production and distribution infrastructure would be ~\$87 billion. These costs would be incorporated into the price of delivered natural gas and would not require incentives to occur. However, investments in fueling stations and liquefaction capacity may not occur without added incentives because refueling stations will not be profitable until sufficient vehicles are on the road. If LNG/CNG infrastructures were adopted, the cost for fueling stations would be approximately \$68 billion with an additional \$72 billion for regional liquefaction plants. Costs for CNG stations would avoid the liquefaction costs.

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Appendix A

Diesel Passenger Vehicles and Pickup Trucks Available in the United States

Appendix A

Diesel Passenger Vehicles and Pickup Trucks Available in the United States

The use of diesel engines in cars offers an option for reducing fuel consumption relative to spark-ignited, gasoline-fueled cars. Diesel-powered cars would compete with natural-gas-powered cars for consumers who are particularly motivated by savings in fuel costs. At present, relatively few passenger cars are offered in the United States with diesel engines, and all the offerings are from European manufacturers. This is likely due to a combination of fuel prices in Europe creating a greater emphasis on fuel efficiency coupled with stricter diesel emission standards in the United States. The diesel options currently available include:

- Audi
 - A3, 2.0 L TDI 140 hp
 - Q7, 3.0 L TDI 225 hp
- BMW, 3.0 L, dual turbo, HPDI, with particulate filter and SCR offering 265 hp
 - 335d sedan
 - X5 xdrive 35d
- Mercedes, 3.0 L, 6 cylinder 210 hp, with Bluetec urea-based SCR
 - ML350 sport utility
 - GL350 sport utility
 - R350 crossover
- Volkswagen
 - Golf, 4 cylinder, 2.0 L
 - Jetta, 4cylinder, 2.0 L
 - Touareg, 6cylinder, 3.0 L.

In some cases, a nearly equivalent model is offered in both diesel and gasoline models, making a rough mileage comparison possible. Table A.1 provides a comparison for the vehicles identified above.

From the data in Table A.1, the diesel-powered vehicles offered in the United States provide a mileage boost of 25 percent in the city and 30 percent on the highway relative to the gasoline powered version. It should be noted that in most cases the gasoline engine selected to power a given model has a higher horsepower rating than the diesel engine selected. This may be influenced by the torque ratings of the diesel engines, but might also reflect a desire to highlight fuel efficiency to a buyer that is considering a diesel to improve fuel economy. Most of the gasoline variants of the diesel vehicles require premium fuel, with the exceptions being the Volkswagen Golf and Jetta. The increase in fuel efficiency between the nonpremium-gasoline-fueled vehicles and their diesel-fueled versions is greater (+30 percent city and +40 percent highway) than the group as a whole.

Table A.1. Mileage Comparison for Diesel-Powered vs Gasoline-Powered Passenger Cars

	Diesel Version			Gasoline Version		
	Engine	City/Hwy mpg	Engine	City/Hwy mpg	“P”Premium “R” Regular Fuel?	Notes
Audi A3	2.0L, 140hp	30/42	2.0L, 140hp	21/30	P	Not determined
Audi Q7	3.0L, 225hp	17/25	3.6L, 280hp	14/16	P	Urea SCR
BMW 335d	3.0L, 265hp	23/36	3.0L, 300hp	17/26	P	dual turbo, HPDI, with particulate filter and SCR Gas model 335i
BMW X5 xdrive 35d	3.0L, 265hp	19/26	3.0L, 260hp	15/21	P	dual turbo, HPDI, with particulate filter and SCR Gas model X5 xDrive30i
Mercedes ML350	3.0L, 210hp	18/25	3.5L, 272hp	16/21	P	Bluetec urea SCR
Mercedes R350	3.0L, 210hp	18/24	3.5L, 272hp	14/19	P	Blutec urea SCR
Mercedes GL350	3.0L, 210hp	17/23	3.5L, 272hp	16/22	P	Blutec urea SCR
VW Golf	2.0L, 140hp	30/42	2.5L, 170hp	23/30	R	NO _x storage catalyst
VW Jetta	2.0L, 140hp	30/42	2.5L, 170hp	23/30	R	NO _x storage catalyst
VW Touareg	3.0L, 222hp	18/25	3.6L, 276hp	14/19	P	Urea SCR

The diesel vehicles come with a price premium. Car prices are difficult to pin down because of incentives, differing trim lines, etc. However, based on “starting at” prices from the Volkswagen website, the price premium for the Jetta is approximately \$5100 (\$22,830 vs \$17,735) and about \$3500 for the Toureg (\$44,350 vs \$40,850).

Even higher mileage cars might be made available with sufficient economic incentives either through fuel prices or credits. For example, the Volkswagen Polo Blue Motion, currently sold in Europe, has a 1.2 L turbocharged diesel with start/stop technology and regenerative braking and gets a combined 71 miles per gallon on the European cycle.¹ The price (in U.S. dollars) in the United Kingdom starts at approximately \$22,364.² Similarly a Golf Blue Motion with a 1.6-L TDI engine is available in Europe that achieves 62 mpg³.

Most engines are using SCR with urea to meet emission standards. The Jetta meets emission standards with a nitrogen oxide storage catalyst without additional fluid addition.

¹ http://www.caranddriver.com/reviews/car/09q4/2010_volkswagen_polo_bluemotion_diesel-quick_spin

² Based on a February 18, 2010, article at <http://www.carsuk.net/vw-polo-bluemotion-2010-launched/> value of £14,445 converted to U.S. dollars using the exchange rate as of February 18, 2010.

³ http://www.greencarreports.com/blog/1036712_the-62-mpg-2010-volkswagen-golf-tdi-we-wont-get-in-the-u-s

A.1 Diesel Pickup Trucks

In addition to the diesel passenger cars listed in Table A.1, pickup trucks also are available with diesel engines. The Ford F250/F350/F550 series is available with a 6.7-L, eight-cylinder Turbodiesel engine. The GM Silverado/Sierra pickups in the 2500HD/3500HD series are available with a 6.6-L, eight-cylinder Duramax diesel engine. The Dodge Ram pickups in the 2500/3500/4500/5500 series are available with a 6.7-L Cummins Turbodiesel engine. As was the case in the cars, the diesel engine pickups would be expected to provide greater fuel efficiency than like trucks equipped with gasoline engines and also would be more expensive. The diesel engines provide higher torque ratings, which are valued for towing capability, but lower maximum horsepower than the gasoline engines offered. For example, figures for the engines available in the 2011 Ford pickup trucks are:

- 6.7 L, eight cylinders, Turbodiesel, 300 hp max, 660 ft-lb@1600rpm
- 6.2 L, eight cylinders, gasoline, 385 hp max, 362 ft-lb@4750rpm
- 6.8 L, 10 cylinders, gasoline, 362 hp max, 457 ft-lb@3250rpm.

All three manufacturers use a urea-based SCR technology for controlling nitrogen oxide emissions. For purposes of this report, pickup trucks are not included in the light-duty vehicle category.

Appendix B

Liquefaction of Natural Gas

Appendix B

Liquefaction of Natural Gas

Prior to liquefaction the natural gas must be treated to remove water, natural gas liquids (C_2+ hydrocarbons), carbon dioxide, hydrogen sulfide, and other impurities that may interfere with the liquefaction process. The natural gas is then compressed prior to feeding to the liquefaction process. The use of high feed pressures to the liquefaction process reduces the total energy consumption up to a pressure of about 70 bara (1015 psia) (Schmidt et al. 2010). Although each design is unique, two liquefaction process modeling studies make a feed pressure assumption of 5000 kPa (725 psia) (Yoon et al. 2009, Cao et al. 2006), suggesting that this value is representative. The natural gas is then liquefied by cooling it to approximately -162°C so it is a liquid at atmospheric pressure. Current LNG facilities can be divided between peak-shaving plants and base-load plants. Peak-shaving plants are located near the point of gas distribution. They liquefy pipeline natural gas and place the LNG in storage during periods of low gas consumption. During periods of high gas consumption, the gas is re-vaporized and fed to the pipeline to meet peak demand. Peak-shaving plants tend to be smaller and use simpler, less efficient liquefaction cycles (typically nitrogen recycle or single mixed refrigerant [SMR]). Base-load plants on the other hand are located near the natural gas source. They liquefy the natural gas from the well and provide it for transport to market in liquid form. Base-load plants tend to be larger and use more complicated and more efficient liquefaction cycles. Figure B.1 provides a summary of technologies offered by Air Products Inc. for natural gas liquefaction showing the range over which each technology is typically applied.

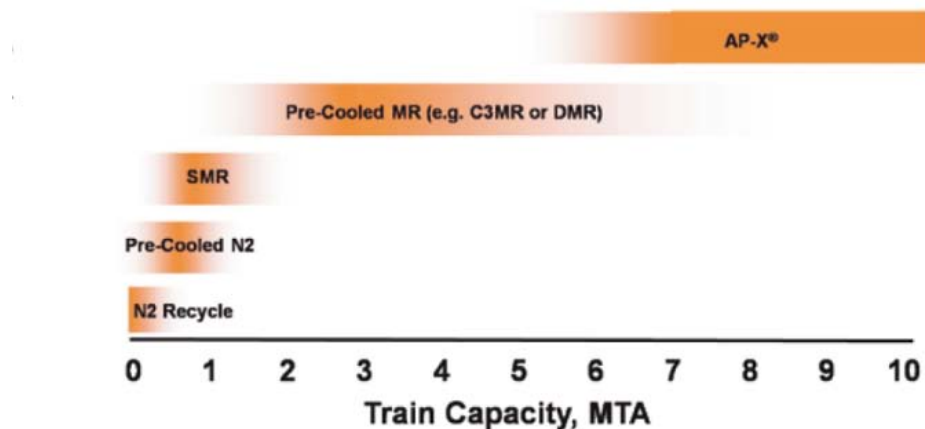


Figure B.1. Natural Gas Liquefaction Technologies. Horizontal axis is million metric tons per annum (MTA). Taken from Bronfenbrenner et al. (2009).

The specific power of a liquefaction process is defined as the shaft work input to the refrigeration compressors divided by the production rate of LNG. The technologies available along with the relative specific power required for liquefaction are summarized below:

Table B.1. Relative Specific Power and Description of Available Liquefaction Technologies. Taken from Schmidt et al. (2010) and Bronfenbrenner et al. (2009).

Liquefaction Technology	Relative Specific Power	Description
Nitrogen Recycle (Gas Expansion)	1.33	Nitrogen gas is compressed, cooled to near ambient temperature, then cooled by the nitrogen leaving the cold section and then expanded and used to cool and liquefy the natural gas.
Pre-Cooled Nitrogen Recycle	1.25	A second refrigerant cycle, typically using propane, is used to pre-cool the gas prior to the liquefaction step.
Single Mixed Refrigerant	1.25	
Pure Component Cascade ¹	1.1	Multiple refrigeration cycles using single component refrigerants are used to control the temperatures at which heat is removed.
Pre-cooled Mixed Refrigerant	1.0	Approach used in most base load LNG facilities. A mixed refrigerant is used to closely control the temperature at which the refrigerant is vaporized in the heat exchanger resulting in an improvement in efficiency. Variants include C3MR in which the pre-cooling is accomplished using propane and DMR in which the pre-cooling step is accomplished using a mixed refrigerant.
AP-X	1.0	A variant of the pre-cooled mixed refrigerant cycle in which the product is sub-cooled in a separate nitrogen gas expansion cycle. This approach increases equipment throughput, reduces capital cost per unit capacity and is used in very large capacity facilities.

In smaller plants, power to the refrigeration cycle compressors is likely to be provided by electric motors. Larger plants typically use industrial gas turbines requiring heat rates in the range of 7300 to 8600 BTU LHV/hp². A reasonable specific power for a dual-mixed refrigerant system is 280 kWh/ton.³ Based on these figures, it can be estimated that the effective loss of natural gas due to consumption in the compressor turbines is equal to 5.8 to 6.8 percent of the total natural gas flow.⁴ Hence, simpler nitrogen recycle-type plants use up to an equivalent of about 9 percent of the natural gas due to lower efficiency (although depending on electrical costs the economic effect may be greater than 9 percent). Note that this value does not include energy costs associated with compression and purification of the natural gas prior to feeding to the liquefaction process.

¹ It is unclear from the source whether the pure component cascade efficiency is applicable to the “optimized cascade” technology offered by Conoco Phillips. The optimized cascade uses propane, ethylene, and methane pure components.

² Schmidt et al. 2010. Paper PS3-1

³ Taken from case study 1b in Schmidt et al. 2010, paper PS3-1. 2.03 MTA plant.

⁴ Alternatively, the site <http://www.natgas.info/html/liquefiednaturalgaschain.html> estimates 8 to 10 percent consumption of the gas due to refrigeration.

Appendix C

Foreign Availability of Natural Gas Vehicles

Appendix C

Foreign Availability of Natural Gas Vehicles

Table C.1 provides a listing of natural-gas-fueled vehicles available around the world as tabulated by CNGnow. Additional information on the vehicles is available on their website.¹

Table C.1. Listing of Natural Gas Vehicles Available Worldwide

Model	Availability	Fuel Configuration
OPEL Astra Caravan CNG	Czech Republic, Bi-fuel	Bi-fuel (CNG/Gasoline)
Opel Combo CNG	Germany and Spain	CNG
Opel, Safira CNG	Germany and Spain	CNG
Ford C-Max CNG	Germany	Bi-fuel (CNG/Gasoline)
Ford Focus CNG	Germany	Bi-fuel(CNG/Gasoline)
Ford Ikon Flair CNG	India	Bi-fuel (CNG/Gasoline)
Chevrolet Optra Magnum CNG	Singapore	CNG
Mercedes Benz B170 NGT Blue Efficiency	Europe	Bifuel (CNG/gasoline)
Mercedes E200 NGT	Austria, Germany, Italy, Sweden, Switzerland	Bifuel CNG/Gasoline
VW Golf Variant	Czech Republic	Bi-fuel (CNG/gasoline)
VW Pasat Ecofuel (a)	Europe	CNG
VW Touran EcoFuel	Germany	CNG
Honda Civic GX	US	CNG
Hyundai Accent	India	Bi-fuel(CNG/gasoline)
Hyundai CNG i-blue	Non-production	CNG
Mitsubishi Lancer CNG	India	CNG
Citroen Berlingo	France, Germany	Bi-fuel, (CNG/gasoline)
Citroen Elysee	China	Bi-fuel, (CNG/gasoline)
Fiat Doblo 16V	Czech Republic, Germany, Italy, Spain	Bi-fuel, (CNG/gasoline)
Fiat Multipla Natural Power	Germany, Spain, Italy	Bi-fuel, (CNG/gasoline)
Fiat Panda Natural Power	Germany, Spain, Italy	Bi-fuel, (CNG/gasoline)
Fiat Punto Natural Power	Germany, Italy	Bi-fuel, (CNG/gasoline)
Fiat Siena 1.4 Tetrafuel	Brazil	CNG or Bi-fuel (LNG/Diesel)
Geely CK 1.3 L CNG	China	CNG
Lifan 520	China, Peru	Bifuel (CNG/gasoline) or Dual Fuel (LNG/Diesel)
Renault Kangoo	Germany	Bi-fuel
Skoda Octavia CNG	Germany, Spain	Bi-fuel
(a) Different source - www.volkswagenag.com/tsi_engine/envcommendation_tsi.pdf		

¹ <http://www.cngnow.com/EN-US/Vehicles/AroundTheWorld/Pages/GlobalGallery.aspx>

Appendix D

LNG Related Accidents Involving Explosions or Fires

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LNG Related Accidents Involving Explosions or Fires

This appendix provides a brief listing of known LNG related accidents involving fires or explosions. Spills that did not include ignition of the LNG are not included. Except where noted, the list is primarily taken directly from a webpage provided by the California Energy Commission¹ without adding quotes. Footnotes are provided where information is drawn from other sources.

LNG Related Explosions and Fires

October 1944, Cleveland, Ohio. An LNG tank failed and spilled its contents. The vapor cloud drifted into a mixed use area and entered the storm sewer system. The vapors ignited, and the resulting explosion and fire destroyed 70 homes and two factories in an approximately 1-mi² area. A total of 128 people were killed. The failure of the tank was attributed a low-nickel content alloy that became brittle when exposed to LNG. A more thorough discussion of this disaster is provided here.²

1964 and 1965. While loading LNG in Arzew, Algeria, lightning struck the forward vent riser of the transport ship Methane Progress and ignited vapor that was being routinely vented through the ship venting system. A similar event happened early in 1965 while the vessel was at sea shortly after leaving Arzew. In both cases, the flame was quickly extinguished by purging with nitrogen through a connection to the riser.

1969, Portland, Oregon. An explosion occurred in an LNG tank under construction. No LNG had ever been introduced into the tank. The cause of the accident was attributed to the accidental removal of “blinds” from natural gas pipelines that were connected to the tank. This led to the flow of natural gas into the tank while it was being constructed.

1972, Montreal East, Quebec, Canada. A back flow of natural gas from the compressor to the nitrogen line occurred during defrosting operations at an LNG liquefaction and peak-shaving plant. The valves on the nitrogen line were not closed after completing the operation. This caused over-pressurization of the compressor, and the natural gas entered the control room (where operators were allowed to smoke) through the nitrogen header. An explosion occurred when an operator tried to light a cigarette.

1973, Staten Island, New York. While repairing the interior of an empty storage tank, a fire started. The resulting increase in pressure inside the tank was so rapid that the concrete dome on the tank initially lifted and then collapsed into the tank, killing the 37 construction workers who were inside.

October 1979, Lusby, Maryland. LNG leaked through a pump electrical penetration seal. The LNG vaporized and passed through 200 feet of electrical conduit to an area where flammable gases were not expected. Arcing from the contacts of a circuit breaker ignited the gas, causing an explosion that killed one worker, severely injured another worker, and heavily damaged the building.

¹ Accessed 6/23/2010. <http://www.energy.ca.gov/lng/safety.html>

² [http://www.ircrisk.com/blognet/post/2010/03/29/LNG-Explosion-Levels-One-Square-Mile-\(Cleveland-1944\).aspx](http://www.ircrisk.com/blognet/post/2010/03/29/LNG-Explosion-Levels-One-Square-Mile-(Cleveland-1944).aspx)

April 1983, Bontang, Indonesia. A rupture in an LNG plant occurred as a result of over-pressurization of the heat exchanger caused by a closed valve in a blowdown line. The exchanger was designed to operate at 25.5 psig. When the gas pressure reached 500 psig, the exchanger failed, and the explosion occurred.

August 1987, Nevada Test Site, Mercury, Nevada. An accidental ignition of an LNG vapor cloud occurred at the U.S. Department of Energy Test Site during large-scale tests involving spills of LNG. The cloud accidentally ignited. Damaged polyurethane pipe insulation was propelled outside the fence.

August 2003, Bintulu, Malaysia. A major fire in Train 7 at PETRONAS' 23 million tons per annum LNG complex caused extensive damage but no injuries or deaths. The event was caused by a failure in a heat exchanger tube that allowed methane to leak into a hot turbine exhaust duct.¹

June 2004, Trinidad, Tobago. Workers were evacuated after a gas turbine at Atlantic LNG's Train 3 facility exploded.

January 2004, Skikda, Algeria. A steam boiler that was part of an LNG liquefaction production plant exploded, triggering a second, larger vapor-cloud explosion and fire that took 8 hours to extinguish. The explosions and fire destroyed a portion of the LNG plant and caused death, injury, and material damage outside the plant's boundaries. The accident killed 27 people and injured 56.² The fire destroyed three LNG trains but three additional LNG trains and LNG storage tanks were not damaged.

2004, Ghislenghien Belgium. A pipeline explosion killed 23 people. While some sources list this as an LNG event, it appears to have been a conventional natural gas pipeline event.

March 2005, District Heights, Maryland. A Washington Gas company-sponsored study released in July 2005 pointed to subtle molecular differences in the imported LNG the utility began using in August 2003 as the cause of a house explosion.

2005, Nigeria. A 28-in. underground pipeline exploded in Nigeria, and the resulting fire engulfed an estimated 27-km² area. Various sources conflict on the nature of the pipeline but it was most likely a CNG line feeding an LNG facility that was involved.³

¹ Ismail, N.H. and Stuart, T.R. (2005). "The Train 7 Fire at PETRONAS' LNG Complex, Bintulu, Malaysia" *LNG Journal*, July/August 2005. <http://www.laohamutuk.org/Oil/LNG/Refs/038IsmailPetronasFire.pdf>

² <http://www.ferc.gov/industries/lng/safety/safety-record.asp>

³ <http://portland.indymedia.org/en/2005/08/323888.shtml>

Appendix E

Conversion Factors for Equivalent Fuel Energy Content

Appendix E

Conversion Factors for Equivalent Fuel Energy Content

In various places in the report, it was necessary to convert between fuels on an energy equivalent basis. Because the use of the fuels in this case is to obtain useful mechanical work in an engine, all fuels are compared based on the LHV which is a measure of the energy released in combustion with water formed during combustion remaining in the gas phase. The LHV of actual samples of natural gas, gasoline, and diesel fuel vary slightly depending on the chemical composition. As a result, there are a number of slightly varying values available from various sources. LNG is nearly pure methane so it does not show variability with chemical composition. However, the liquid density is sensitive to the temperature such that various values can be reported depending on the assumed temperature of the LNG.

Typical LHV fuel values for gasoline (114,200 BTU/gal) and diesel fuel (130,000 BTU/gal) were obtained from the Chevron website¹. The energy value for natural gas was estimated using the average HHV of natural gas delivered to end-use sectors as reported by the Energy Information Administration for 2008 (1029 BTU/ft³)² and then converting to an LHV energy (927.2 BTU/ft³) assuming a ratio of LHV:HHV equivalent to that for methane. For LNG, a value of 75,000 BTU/gal was used. Comparing to data from the National Institute of Standards and Technology³ for pure methane, this corresponds to a pressure of 19 psia and a saturation temperature of -158°C. When considering gas obtained from vaporization of LNG, the gas was assumed to have a LHV of 802.34 kJ/mol, which implies an energy content of 1009.9 BTU/ft³ at 1 atm and 60°F. The energy values assumed and the derived conversion factors are summarized in Table E.1.

Table E.1. Assumed Energy Values for Fuels

Fuel	LHV Energy Value	Units
Gasoline	114200	BTU/gal
Diesel	130000	BTU/gal
CNG	927.2	BTU/ft ³ , (60°F, 1 atm)
LNG	75000	BTU/gal (19 psia sat)
Vaporized LNG	1009.9	BTU/ft ³ , (60°F, 1 atm)

From the energy values, the following LHV energy equivalencies can be determined:

- 1 gallon gasoline = 0.88 gallons diesel
- 1 gallon gasoline = 123.17 ft³ natural gas (60°F, 1 atm)
- 1 gallon gasoline = 1.52 gallons LNG
- 1 gallon diesel = 1.73 gallons LNG.

¹ http://www.chevron.com/products/prodserve/fuels/diesel_products.aspx

² <http://www.eia.doe.gov/emeu/aer/txt/ptb1304.html>, reference condition 60°F, 1 atm

³ Available at <http://webbook.nist.gov/chemistry/fluid/>

Appendix F

Impact of Natural-Gas-Fueled Vehicles on Crude Oil Imports

Appendix F

Impact of Natural-Gas-Fueled Vehicles on Crude Oil Imports

One of the objectives cited for replacing gasoline or diesel fuel with natural gas for vehicles is a reduction in oil imports. In 2008, 56 percent of U.S. oil was imported. Determining the extent of natural-gas-fueled vehicle adoption required to offset this amount of oil requires an understanding of the distribution and use of the products from a barrel of crude oil. Figure F.1 provides a breakdown of the products obtained from refining crude oil.

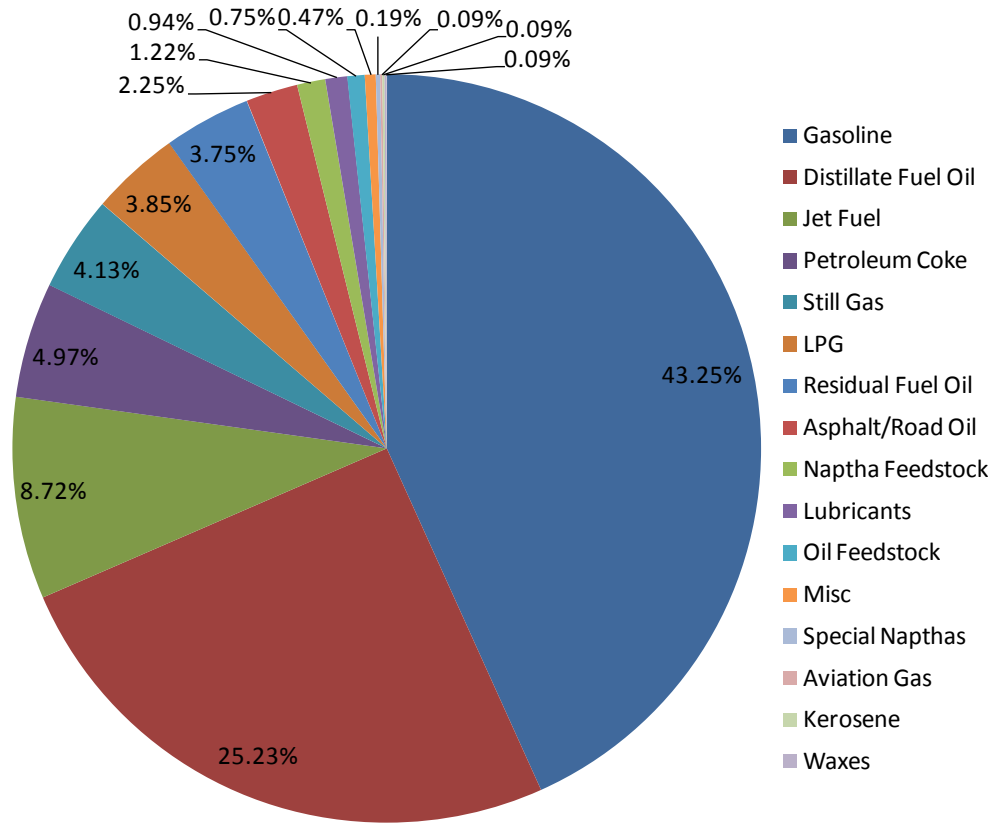


Figure F.1. Distribution of Refinery Products from Crude Oil in 2009¹

Distillate fuel oil is a category that includes diesel for both on and off-road use as well as heating oil. Note that gasoline and diesel only account for 68 percent of the products made from crude oil. When considering the impact of using natural gas for on-road cars and trucks, it must also be considered what fraction of the fuel is actually used for that purpose. Figure F.2 shows the distribution of consumption for distillate oil. About 64.7 percent of distillate fuel oil is used for on-road vehicles.² Hence the fraction of

¹ Data from EIA, volumes normalized, total volume swells 6.5% during refining. Data available at http://www.eia.gov/dnav/pet/pet_pnp_pct_dc_nus_pct_a.htm

² This is consistent with EIA refinery yield data showing No.2 Ultra-Low Sulfur fuel accounts for 70% of total No.1 and No.2 distillate fuel production. See http://tonto.eia.doe.gov/dnav/pet/pet_pnp_pct_dc_nus_pct_m.htm

a barrel of crude oil that is allocated to on-road diesel vehicles is approximately $0.2523 \times 0.6471 = 0.1633$. Hence, completely eliminating consumption of diesel fuel in on-road vehicles would eliminate the need for ~16 percent of the products made from a barrel of crude oil. This might be improved somewhat if off-road uses were pursued at the same time. For example, converting oil heating systems (7.88 percent “Residential” in Figure F.2) to natural gas or converting trains to natural gas (4.59 percent “Railroad” in Figure F.2) would provide additional savings of distillate fuel oil. Railroads may be an application for which natural gas can effectively be applied. Limitations on weight and volume for fuel storage, which are problematic for trucks, are reduced if fuel can be delivered from a tank car (or several) located behind the locomotive. In this configuration, the train could have significant range such that the fueling infrastructure required would be relatively few stations spaced a great distance apart.

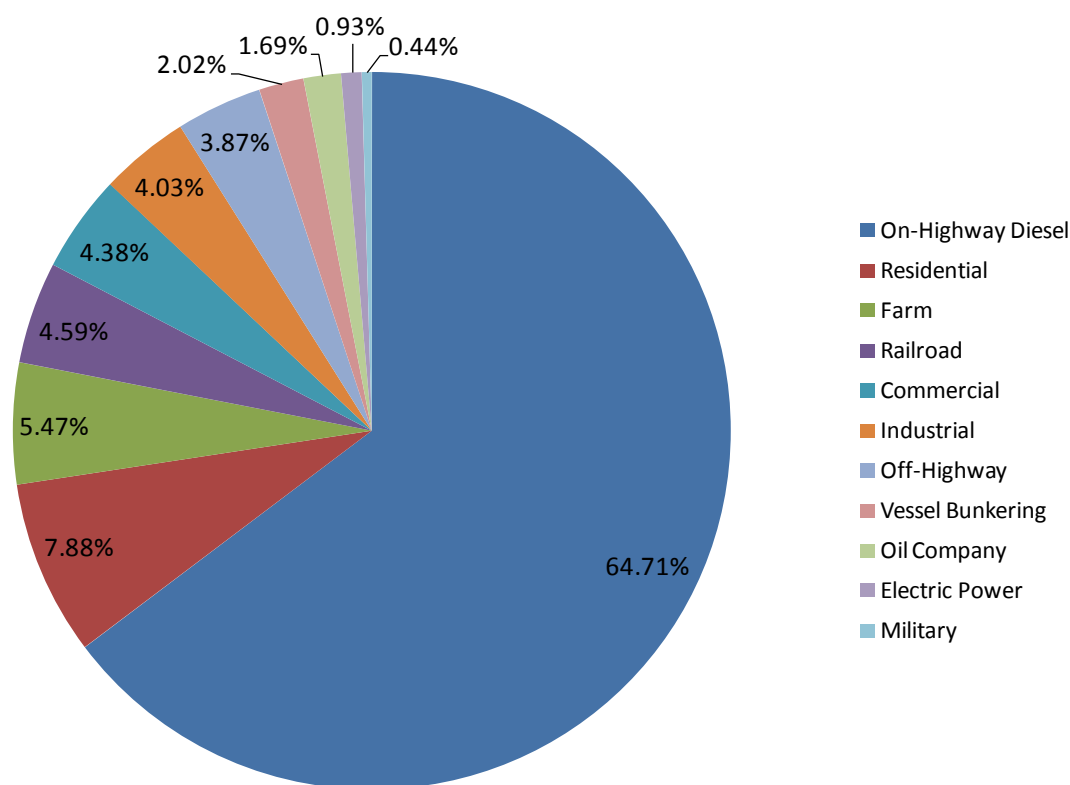


Figure F.2. Distillate Fuel Oil Consumption In 2008¹.

In the case of gasoline, a much greater fraction of the gasoline produced is used for on-road use. The Federal Highway Administration estimates that only about 2.77 percent of gasoline is used for off-road use.² Hence, if it were assumed that all gasoline vehicles were converted to natural gas, this would impact the market for $0.4325 \times 0.9723 = 0.4205$ or about 42 percent of the products from a barrel of oil.

At this point several conclusions can be drawn. First, the maximum potential impact on foreign oil imports is greater for converting gasoline vehicles to natural gas than for diesel fuel. Second, if natural gas is used only in on-road diesel-powered trucks, the impact on overall oil consumption will be limited

¹ Data from EIA, available at:

http://www.eia.doe.gov/oil_gas/petroleum/data_publications/fuel_oil_and_kerosene_sales/foks.html

² Data from the Federal Highway Transportation Administration, 2008, Table mf21. Available at

<http://www.fhwa.dot.gov/policyinformation/statistics/2008/mf21.cfm>

to ~16 percent, which is far short of the 56 percent required to displace oil imports¹. Similarly, if used only to displace gasoline use in on-road engines, the impact is limited to 42 percent, which also is short of the desired goal of 56-percent reduction. A nearly complete replacement of both on-road diesel and gasoline vehicles with natural gas vehicles would be required to eliminate oil imports.

However, gasoline and diesel-fuel consumption are affected by price, and there is some degree of interchangeability between them. For example, if a large portion of diesel-powered trucks were converted to natural gas, consumption of diesel fuel would decrease. Crude oil would still be refined to provide gasoline and other products, which would result in an excess of distillate oil causing its price to decrease. This would have several effects including a decrease in conversions of trucks to natural gas (due to low diesel prices), potential exports of diesel fuel to countries where prices are higher, and an increase in decisions by consumers to select oil heating systems and/or diesel-powered vehicles in response to the low diesel fuel price.

Similarly, if a large portion of gasoline vehicles were converted to natural gas, oil would need to be refined to provide diesel and other products resulting in excess gasoline causing its price to drop. The lower price may then result in reduced conversions to natural gas, exports of gasoline to countries with higher prices, and a greater preference for gasoline-fueled vehicles over diesel-fueled vehicles.

In addition, prices for products derived from crude oil other than gasoline and diesel will contribute to economic decisions that determine the amount of crude oil to import and refine.

Ultimately, successful introduction of natural-gas-fueled vehicles will depend on a consistent price signal that provides an economic advantage for adoption of natural gas as vehicle fuel. Adoption can best be achieved by pursuing natural-gas-fueled vehicles for the most economically attractive opportunities for displacement of both gasoline and diesel fuel.

¹ Alternatively this just below the target of displacing 1/3 of imports described in the “Pickens Plan”



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