The Role of Natural Gas as a Vehicle Transportation Fuel

by
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ABSTRACT:
This thesis analyzes pathways to directly use natural gas, as compressed natural gas (CNG) or liquefied natural gas (LNG), in the transportation sector. The thesis focuses on identifying opportunities to reduce market barriers in order to make the US natural gas vehicle market more efficient. We also identify vehicle market segments where NGV technology is mature and does not require sustained public subsidy to economically compete with comparable gasoline or diesel vehicles.

This thesis finds that natural gas can play a useful but modest role as a vehicle fuel in the US, predominantly as CNG in high-mileage, light-duty fleet vehicles and in heavy-duty, short-haul fleet vehicles. For light-duty applications, there is a need to address an existing market barrier in the US by reducing the incremental cost and improving the vehicle performance of CNG vehicles to levels found in Europe. This incremental cost reduction is critical to foster market penetration in high-mileage fleet vehicles and to create a potential opportunity for market penetration beyond high-mileage fleet vehicles to average-mileage individual drivers. Increased use of CNG in light duty vehicles would displace petroleum, reduce greenhouse gas emissions in the transportation sector, and hedge consumers from volatile world oil prices (if CNG is used in a bi-fuel - gasoline and CNG- vehicle). In the heavy-duty, short-haul sector, CNG provides an additional benefit of reduced nitrogen oxide emissions compared to diesel trucks.

With respect to long-haul LNG trucks, this thesis finds that while there is a large potential market for natural gas in the long-haul truck market, the present prospects for the use of LNG-powered long haul trucks appears quite limited. This is due to high incremental costs, unresolved operational issues, fueling infrastructure requirements, and reluctance of the trucking industry.

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Chapter 1: Introduction

1.1. Context

Currently, less than 0.1% of the vehicles in the United States operate on natural gas, accounting for less than 1% of US natural gas consumption (U.S. DOE, 2010a). Notwithstanding the current limited demand for natural gas in the transportation sector, natural gas as a transportation fuel is an area of significant interest and possible growth. Vocal advocates have focused on using natural gas as a transportation fuel as a centerpiece for a US national energy plan (Pickens Plan, 2010) and there is pending legislation in the U.S. Congress to extend and enhance subsidies for vehicles that operate on natural gas (United States House of Representatives, 2009).

There are potential benefits to the increased use of natural gas as a transportation fuel. Natural gas could serve as a substitute for gasoline or diesel fuels, thus reducing the U.S.'s dependence on imported oil. In addition, natural gas provides reduced greenhouse gas emissions compared to petroleum-based fuels (Bosch, 2006) and as such may provide an effective option for governments to meet reduced greenhouse gas emission goals in the transportation sector (e.g. California's Low Carbon Fuel Standard) (State of California, 2009). Finally, in heavy-duty applications, natural gas provides reduced nitrogen oxide emissions compared to the best currently available technology for diesel trucks (Hogo, 2009). Diesel trucks are beginning to deploy new technology to meet future, more stringent nitrogen oxide regulation (Cummins, 2009) and as a result natural gas trucks may provide a more cost effective means to meet future nitrogen oxide regulation.

In this thesis, I assume that the above potential benefits may justify discrete public subsidies for a finite period of time to develop a market for natural gas vehicles (e.g. infrastructure or vehicle subsidies for a limited period of time to start a market). In this thesis, I also assume that a permanent subsidy for natural gas vehicles serves to preferentially select natural gas vehicles as the technology winner over other alternative fuels and improved gasoline/diesel engine efficiency without respect for the economic market and is therefore not in society's best interest. This thesis seeks to identify the most promising opportunities to cost-effectively develop a market for natural gas vehicles by identifying:

- existing barriers that could be reduced to improve the efficiency of the natural gas vehicle market and
- natural gas vehicle market segments that could offer a self-sustaining market without the need for permanent public subsidy.

This information is used to develop an illustrative sizing of the future natural gas vehicle market.

1.2. Thesis roadmap

Chapter 2 characterizes the current market for natural gas vehicles, both globally and in the United States. This chapter illustrates that CNG-fueled vehicles are a currently available technology that have been adopted, with varying levels of market penetration, in many places in the world. In addition, the chapter shows that CNG vehicle market penetration in the United States lags behind Asia, South America, and Europe.

Chapter 3 provides a technology assessment of vehicles that operate on compressed natural gas (CNG) and liquefied natural gas (LNG). The chapter focuses on operational issues and pollutant emissions (greenhouse gases, nitrogen oxides, and particulate matter). Chapter 3 shows that CNG vehicle technology is mature and does not pose significant operational issues but that LNG technology remains fragile and has associated operational and greenhouse gas emission challenges. Until these challenges are cost-effectively addressed, the market for LNG as a transportation fuel appears quite limited. The chapter also shows that CNG vehicles provide a greenhouse gas and nitrogen oxide (for diesel displacing applications) emission benefits compared to gasoline/diesel vehicles.

Chapter 4 explores the factors that drive the market penetration of natural gas vehicles. This chapter begins by examining empirical work on the financial benefit (measured in payback period) to drivers who switched from a gasoline vehicle to a CNG vehicle in areas experiencing significant CNG vehicle market penetration. Chapter 4 then presents the State of Utah during the summer of 2008 as an existence proof that the financial benefit that influenced market penetration in other parts of the world also applies to the United States. Chapter 4 then presents CNG and LNG vehicle options available to American and European drivers. Vehicle options are analyzed to identify opportunities to reduce the incremental cost of natural gas powered vehicles. Past fuel price differences (between natural gas and gasoline) are used to identify market segments where natural gas vehicles could be attractive to consumers without public subsidy.

Chapter 5 presents an analysis of the current status of CNG and LNG infrastructure in the United States. The analysis identifies challenges with developing adequate infrastructure to support the market penetration of natural gas vehicles beyond centrally-fueled fleets and identifies appropriate finite subsidies to support the development of infrastructure (e.g. public subsidies for methane venting systems to facilitate fleet use of CNG vehicles) for centrally-fueled fleets.

Chapter 6 synthesizes the findings from chapters 3, 4, and 5 to develop an illustrative market sizing for the future natural gas vehicle market. The chapter assesses the impact of the time required for vehicle fleet turnover and recently enacted low-carbon fuel standards on market penetration.

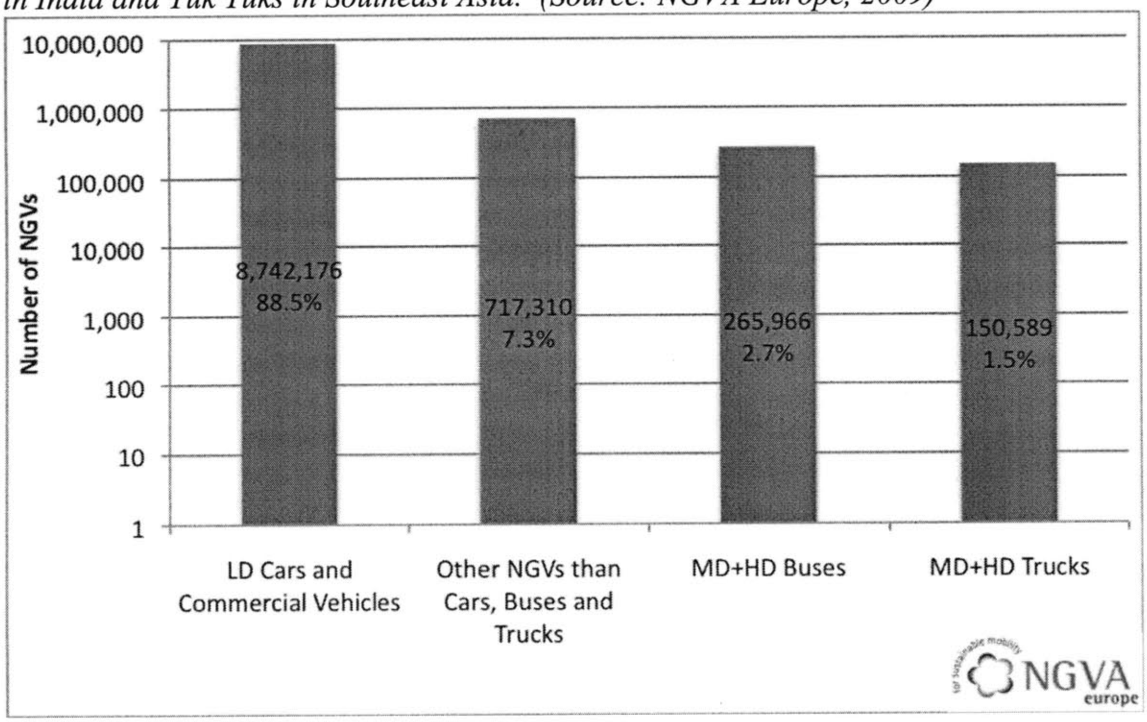
CHAPTER 2: CURRENT GLOBAL NGV MARKET

The Natural Gas Vehicle (NGV) market consists of vehicles that are fueled by compressed natural gas (CNG) and liquefied natural gas (LNG). This chapter characterizes the NGV market globally and in the United States.

2.1 WORLD NGV MARKET

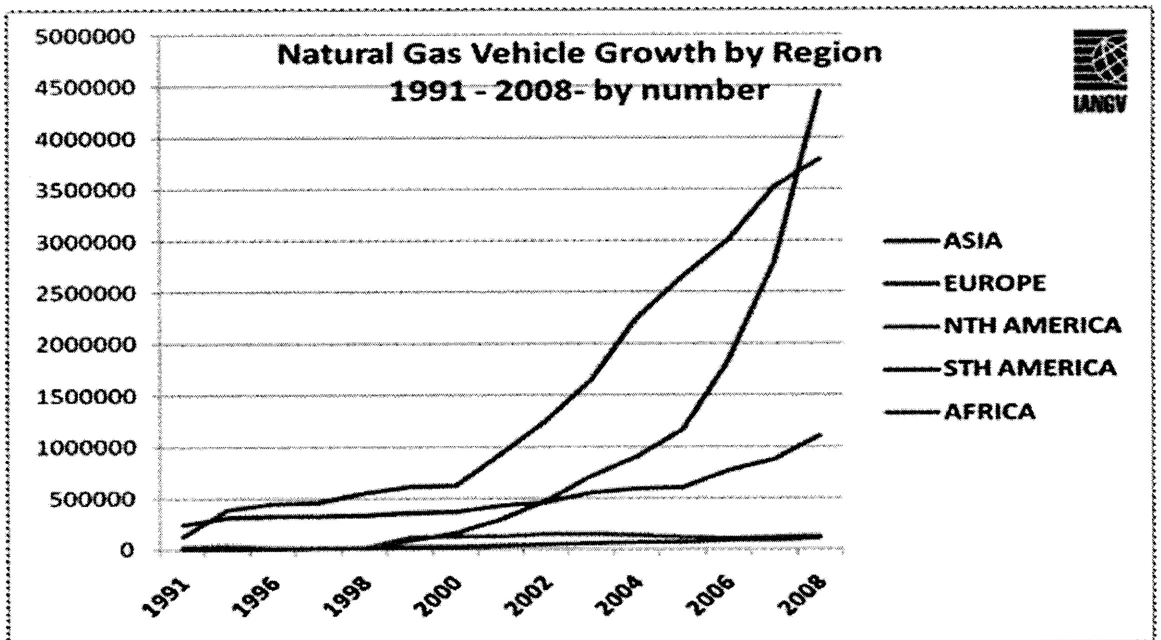
There are approximately 10 million NGVs on the road worldwide (IANGV, 2009). However, this is a small fraction, on the order of one percent, of the 860 million vehicles on the road worldwide. The majority of the world's NGVs are light-duty, bi-fuel CNG vehicles with the ability to operate on CNG or gasoline. Figure 2.1 provides a breakdown of the world NGV market by vehicle type (NGVA Europe, 2009).

Figure 2.1: Breakdown of the world NGV market by vehicle type. *Note: the category "Other NGVs than Cars, Buses, and Trucks" refers to three-wheeled vehicles including auto- rickshaws in India and Tuk Tuks in Southeast Asia. (Source: NGVA Europe, 2009)*



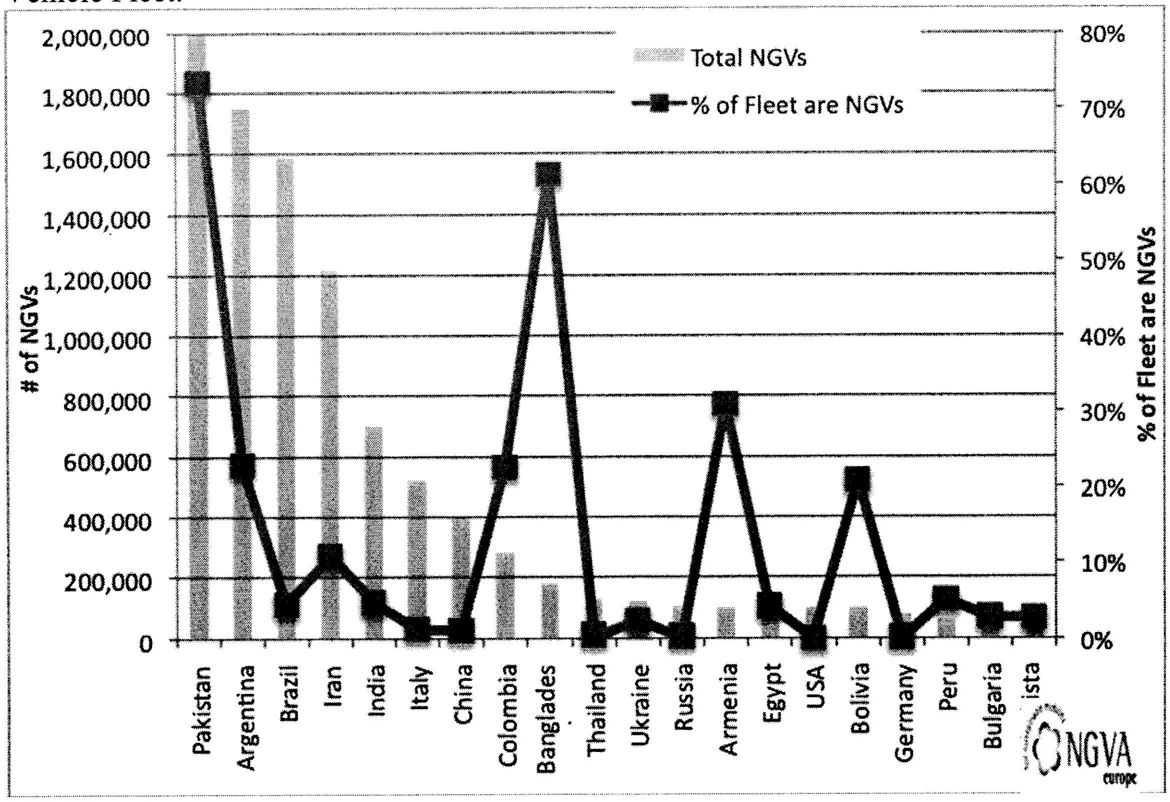
The largest NGV markets are found in select Asian (Pakistan and Iran) and South American (Argentina and Brazil) countries, the only two continents that have experienced exponential growth in NGVs in the last 10 years (IANGV, 2009). By contrast, Europe has experienced limited growth and North America has experienced essentially no growth in NGVs over this time period (IANGV, 2009). Figure 2.2 provides the growth of NGVs by world region.

Figure 2.2. Growth in the Number of NGVs by World Region (Source: IANGV, 2009)



In some countries, NGVs comprise a significant percentage of the nation's vehicle fleet. Figure 2.3 provides a count of NGVs by country and the associated percentage of the nation's vehicle fleet. Natural gas capable vehicles constitute 23% of the vehicles in Argentina and 73% in Pakistan (NGVA Europe, 2009). In chapter 4, I will address the factors that influence the market penetration of NGVs.

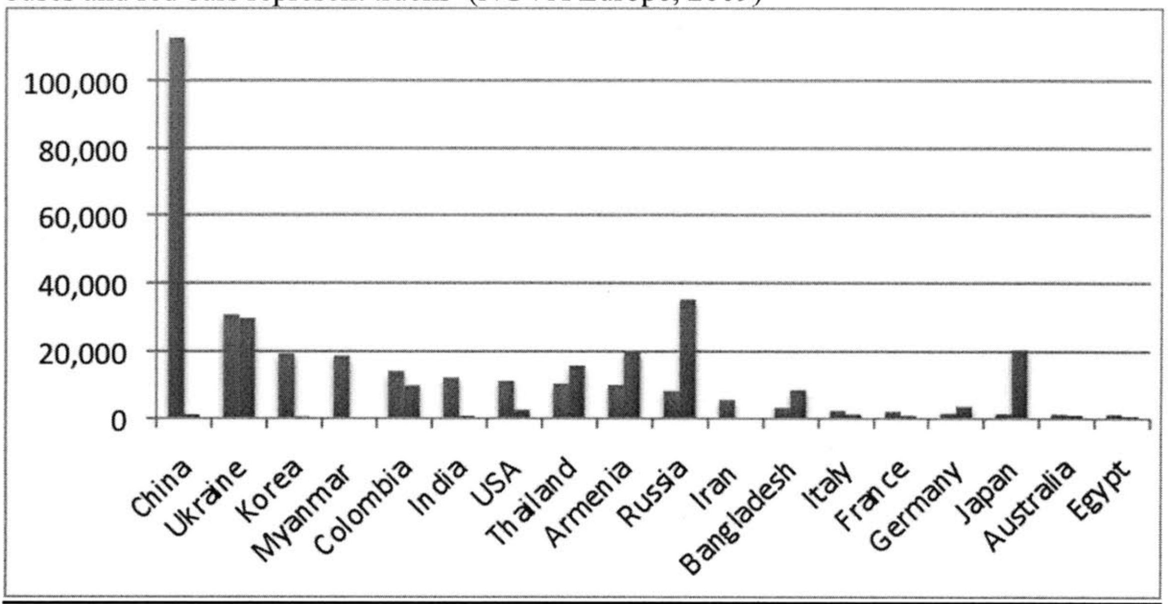
Figure 2.3: The Number of NGVs by Country and Associated Percentage of the Country's Vehicle Fleet.



Natural gas (both CNG and LNG) provides one of the few existing alternatives to diesel fuel. Diesel fuel currently powers the vast majority of the world's heavy-duty vehicles. Heavy-duty vehicles constitute less than five percent of the global NGV market. CNG is a diesel alternative for short-range applications (e.g. urban buses and delivery trucks). LNG, which requires only 1/3 of the storage volume of CNG, is a potential alternative for long-range applications (e.g. tractor trailers) (Bosch, 2006). LNG requires additional energy for cryogenic fuel storage and therefore has higher operational costs than CNG. In addition, the technology to effectively store LNG on the vehicle is still developing, while CNG fuel storage is a proven technology. Chapter 3 provides a technology assessment of CNG and LNG vehicles.

CNG powered transit buses is the largest market for natural gas as a heavy-duty transportation fuel. Currently, there are approximately 270,000 CNG transit buses in the world and 40% of these buses are found in China (NGVA Europe, 2009). Figure 2.4 provides a count of heavy-duty NGVs in the world by country.

Figure 2.4: Count of heavy-duty NGVs in the world by country. Blue bars represent CNG buses and red bars represent trucks (NGVA Europe, 2009)



2.2. United States NGV Market

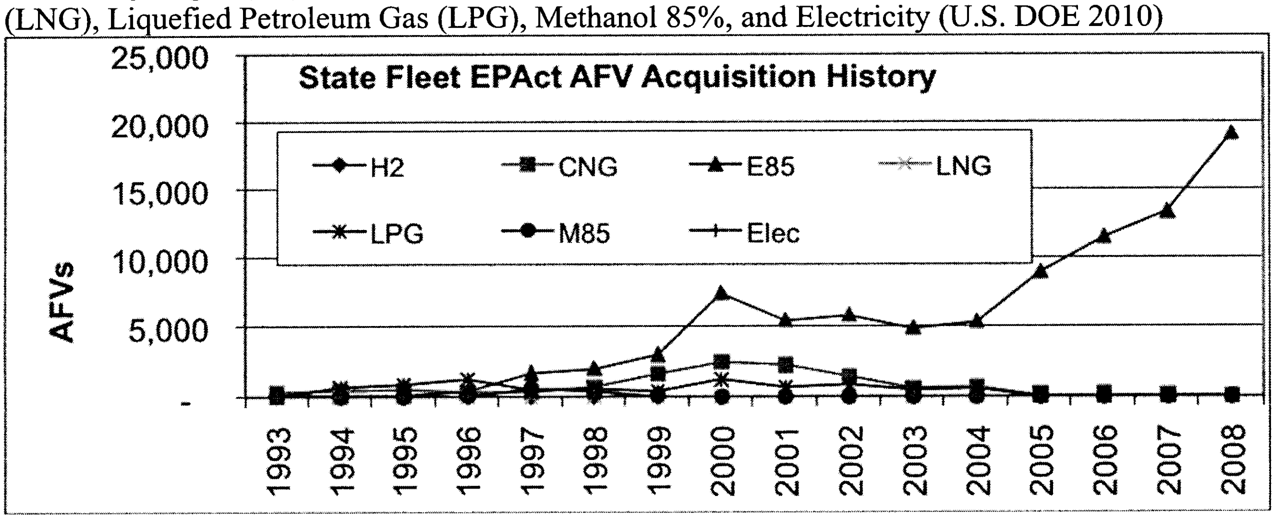
Table 2.1 provides the number of NGVs in the US by vehicle type. Currently, there are approximately 100,000 natural gas vehicles (NGVs) in the US (NGVA Europe, 2009). 85,000 of these vehicles are light-duty CNG vehicles that are predominantly dedicated CNG fleet vehicles and therefore are unable to operate on gasoline in addition to CNG. Currently, the purchaser of a dedicated natural gas vehicle is eligible for a U.S. federal income tax credit, but the purchaser of a bi-fuel CNG vehicle is not eligible for the tax credit (NGVA, 2009).

Table 2.1: The number of NGVs in the United States compared to total road vehicles in the US (NGVA Europe, 2009)

	All Road Vehicles (US)	NGVs (US)	% in US
Total Road Vehicles	241,212,763	100,000	0.04%
LD Cars and Commercial Vehicles	231,905,000	86,500	0.04%
MD+HD Buses	807,053	11,000	1.36%
MD+HD Trucks	8,500,710	2,500	0.03%

Many of these dedicated CNG vehicles were purchased for use by state government and alternative fuel provider fleets to comply with the Energy Policy Act (EPACT) of 1992 (U.S. DOE, 2010). Standard compliance with EPACT requires that 75% of the vehicle fleet is capable of operating on specified alternative fuels (U.S. DOE, 2010). Figure 2.5 provides state government fleets' acquisitions under EPACT (note: that additional CNG vehicle were purchased by alternative fuel providers under EPACT). From Figure 2.5, most alternative fueled vehicles acquired by state government fleets under EPACT were flex-fuel vehicles with the ability to operate on 85% ethanol and 15% gasoline.

Figure 2.5 Alternative Fuel Vehicles Acquired by State Fleets Under EPACT 1992. Fuels include Hydrogen (H2), Compressed Natural Gas (CNG), Ethanol 85%, Liquefied Natural Gas (LNG), Liquefied Petroleum Gas (LPG), Methanol 85%, and Electricity (U.S. DOE 2010)



There are 11,000 CNG buses in the US, approximately 8,000 of these CNG buses are transit buses, fueling 12% of the 66,000 total transit buses in the US (U.S. DOT, 2009). Table 2.1 has the urban transit fleets with the larger number of CNG buses.

Table 2.2: The 10 largest CNG transit bus fleets in the US (U.S. DOT, 2009)

Agency	Location	Total Transit Bus Fleet	CNG_fleet	%CNG
Los Angeles County Metropolitan Transportation Authority	Los Angeles-Long Beach-Santa Ana, CA	2,548	2,350	92.2%
MTA New York City Transit	New York-Newark, NY-NJ-CT	3,952	479	12.1%
Metropolitan Atlanta Rapid Transit Authority	Atlanta, GA	624	450	72.1%
Washington Metropolitan Area Transit Authority	Washington, DC-VA-MD	1,291	436	33.8%
Massachusetts Bay Transportation Authority	Boston, MA-NH-RI	1,049	360	34.3%
Metropolitan Suburban Bus Authority, dba: MTA Long Island Bus	New York-Newark, NY-NJ-CT	331	328	99.1%
MTA Bus Company	New York-Newark, NY-NJ-CT	1,344	301	22.4%
Sacramento Regional Transit District	Sacramento, CA	253	250	98.8%
Foothill Transit	Los Angeles-Long Beach-Santa Ana, CA	314	232	73.9%
San Diego Metropolitan Transit System	San Diego, CA	243	198	81.5%

The remaining CNG buses are school buses. CNG school buses comprise a small percentage of the approximately 600,000 school buses in the US (Ullman et al., 2002).

Chapter 3: Technology Assessment of CNG and LNG Vehicles

3.1 Overview of CNG and LNG Fuels

CNG and LNG are both predominantly composed of methane (80-99%) with the remainder including higher weight hydrocarbons (Bosch, 2006). On vehicle, CNG is stored in a steel or carbon fiber tank at approximately 200 atmospheres (Bosch, 2006). CNG, at this pressure has approximately 25% of the energy density of gasoline, requiring a larger tank volume compared to gasoline and/or reduced vehicle range (Bosch, 2006). LNG consists of predominantly methane (CH_4) that has been purified and condensed to a liquid by cooling cryogenically to -260F (-162C) (U.S. DOE, 2004). On vehicle, LNG is stored in double-walled, vacuum-insulated pressure vessels to maintain cold temperatures. LNG has approximate 60% of the energy density of diesel fuel. LNG, which requires only 1/3 of the storage volume of CNG, is a potential alternative for long-range applications (e.g. tractor trailers) (Bosch, 2006). LNG requires additional energy for cryogenic fuel storage and therefore has higher operational costs than CNG.

3.2 .Operating Vehicles on Natural Gas

Light Duty Vehicles:

Most light-duty NGVs use CNG. On vehicle, CNG is stored in a steel or carbon fiber tank at 200 atm (~2,900 PSI). Since CNG has approximately 25% of the energy density of gasoline (30 KBTU/gallon for natural gas compared to approximately 120 KBTU/gallon for gasoline), the CNG fuel storage tank is typically larger than a gasoline fuel storage tank and provides reduced vehicle range compared to a gasoline tank. Many CNG vehicles are bi-fuel vehicles and are able to operate on CNG or gasoline. Bi-fuel vehicles increase the vehicle range of a CNG vehicle, allow CNG drivers to travel to areas without significant natural gas fueling infrastructure, and give the driver a substitute fuel when either gasoline or natural gas prices are high.

Figure 3.1 provides a depiction of a CNG and gasoline bi-fuel light duty vehicle. In the depiction, there are multiple CNG tanks, designed to maximize fuel storage volume without impinging on cargo or passenger space. There is also a gasoline fuel tank in the depiction. With a switch near the steering wheel, the driver can switch between CNG and gasoline.

When operating on CNG, CNG (at 200 atmospheres) is transported via high-pressure tubing to a pressure regulator near the engine that reduces the pressure of the gas. The gas under reduced pressure is then injected into the engine cylinder. Natural gas is combusted in the same spark-ignition engine that is used for gasoline, but an engine control module is used to optimize the timing of spark-ignited combustion for use with natural gas. Since natural gas is more knock resistant than gasoline, engines using natural gas could operate at a higher compression ratio, offering improved efficiency and horsepower compared to an engine operating with gasoline.

Figure 3.1: Depiction of a CNG and Gasoline Bi-Fuel Vehicle (Green Car Congress, 2004)

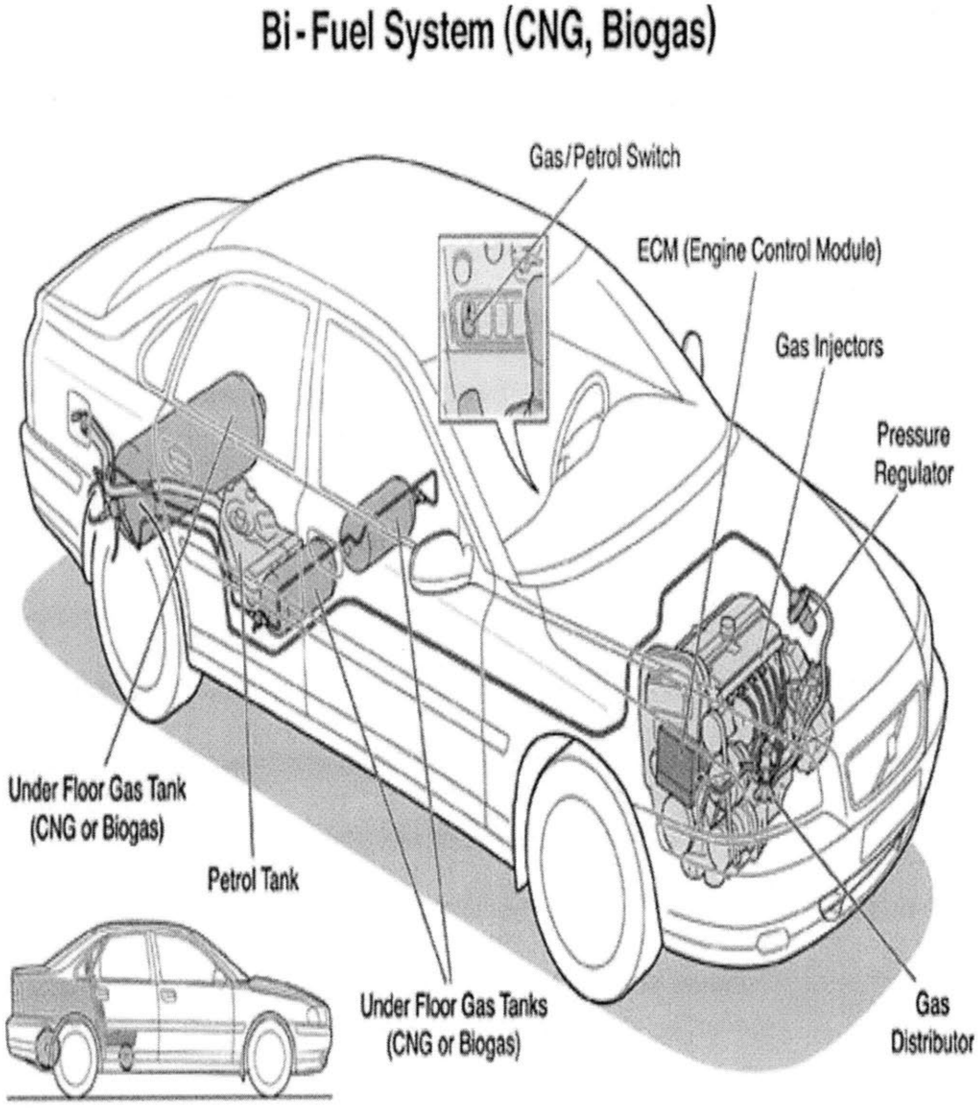


Figure 3Volvo S80

Heavy Duty Vehicles:

In the heavy-duty market there are two predominant engine designs to utilize natural gas. Cummins Westport (a joint venture between Cummins Inc. and Westport Inc. formed in 2001) produces standard examples of the two heavy-duty natural gas engine designs: the ISL-G and the

ISX-G engines (Cummins Westport, 2010). The ISL-G engine is an 8.9-liter spark-ignition engine that can operate on CNG or LNG. The ISL-G engine is used in transit buses, refuse trucks and in some tractor-trailers that require reduced hauling capacity (Cummins Westport, 2010). The ISX-G engine is a compression ignition engine that injects a small quantity of pilot diesel fuel (approximately 6% by volume) into the engine cylinder to give the engine diesel-like compression while using natural gas as the predominant fuel (Cummins Westport, 2010). Specifications of the ISL-G and ISX-G are provided in Table 3.1. The ISX-G (also known as the Westport HPDI engine) provides greater horsepower and torque, but has greater nitrogen oxide (NO_x) and particulate matter (PM) emissions.

Table 3.1: Specifications of the ISL-G[1] and ISX-G[2] Heavy Duty Natural Gas Engines

	ISL-G	**ISX-G**
Power	250–320 hp	450 hp
Torque	895–1,356 N•m	1,650 lb-ft (2,236 Nm)
Displacment	8.9 L	15 L
NOx emissions	0.2 gm/bhp-hr	0.6 g/bhp-hr
PM emissions	0.01 gm/bhp-hr	0.03 g/bhp-hr
Fuel Type	CNG or LNG	LNG with 6% Diesel Fuel

1. Cummins Westport, 2010
2. Green Car Congress, 2004a

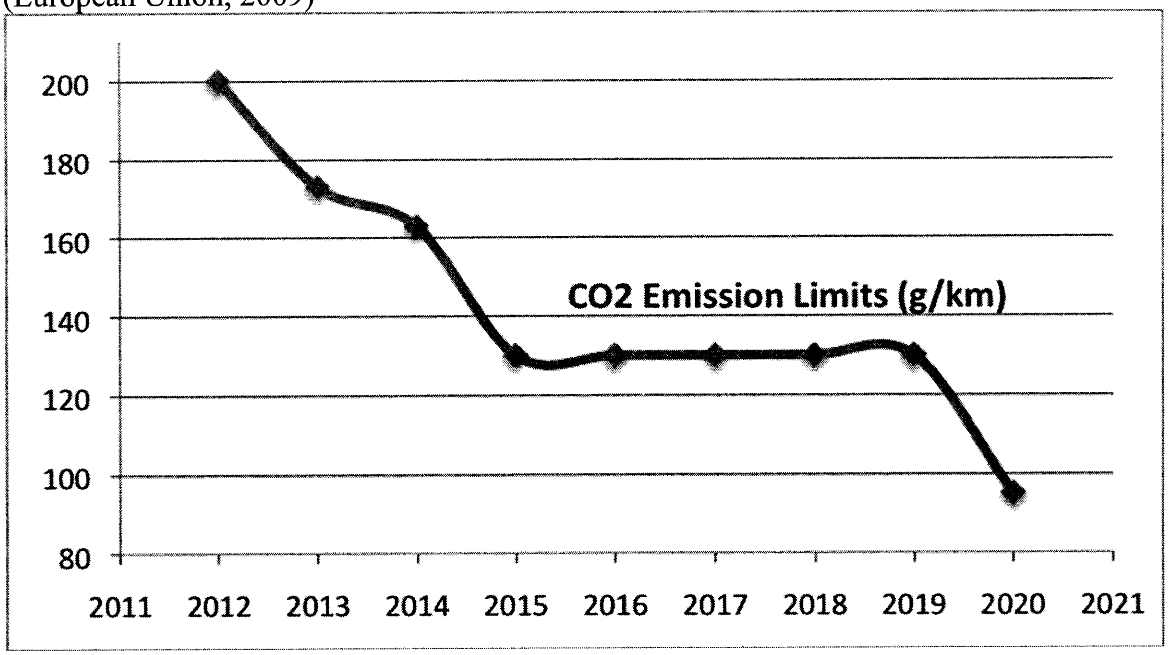
3.3. Greenhouse gases emissions from NGV fuel storage and use

Natural gas combusted in spark-ignition engines, in an engine that has not been optimized to operate on natural gas, reduces greenhouse gas emissions (GHGs) by approximately 25% compared to gasoline (due to methane's lower carbon to hydrogen ratio (1:4) compared to gasoline (1:2.3)) (Bosch, 2006). In addition, use of an increased compression ratio and a highly downsized and turbocharged engine could significantly improve the performance and efficiency of spark-ignition natural gas engines. These improvements could be obtained at an affordable cost and would improve the appeal of CNG vehicles to consumers and further reduce GHG emissions compared to gasoline or diesel powered vehicles.

The reduced greenhouse gas emissions from CNG vehicles could help American and European governments meet newly enacted low carbon fuel standards (e.g. California Low Carbon Fuel Standard or EU Regulation No 443/2009) (State of California, 2010 and European Union, 2009). For example, the California low carbon fuel standard requires a 10% decrease in greenhouse gas emissions from fuels sold in 2020. Corn-based ethanol may be assigned approximately the same greenhouse gas rating as gasoline (due to indirect land use), leaving natural gas and improved petroleum refining efficiency as the only existing methods to meet the requirement.

Figure 3.2 provides the CO_2 emission limits for vehicles in Europe based on the European low-carbon fuel standard (European Union, 2009). For reference, the CNG-powered Volkswagen Passat TSI Eco-Fuel emits 119g of CO_2/km where the comparably equipped gasoline powered Volkswagon Passat TSI 160 emits 172g CO_2/km (VW, 2009). Base on the European standard, illustrated in Figure 3.2, the CNG-powered Passat meets the European low-carbon standard until 2020, while the gasoline-powered Passat fails to meet the low-carbon standard after 2013.

Figure 3.2 Carbon Dioxide Emission Limits based on the European Low Carbon Fuel Standard (European Union, 2009)



Methane is itself a strong greenhouse gas and venting of methane during natural gas production, distribution, liquefaction, or storage can significantly contribute to lifecycle GHG emissions. Venting of methane is not an issue during storage on a CNG vehicle but is a potential issue for LNG vehicles. On vehicle, LNG is stored cryogenically in a double-walled tank with a vacuum between the walls. As LNG warms, methane boils off of the liquid LNG surface creating additional pressure in the fuel tank. In theory, the double-walled tank with vacuum design is able to able to hold LNG without methane venting to the atmosphere for approximately 7 days (for a 70-gallon tank) (O'Brien and Siahpush, 1998). Over this 7-day period, the "LNG tank pressure increases from approximately 80 pounds per square inch (psi) to 240 psi at which time a venting pressure relief-valve opens" (O'Brien and Siahpush, 1998). Manufacturing issues, a collision, or extended use could reduce the ability of the tank to store LNG cryogenically. If the integrity of the vacuum is compromised the tank is less effective at storing LNG cryogenically, resulting in increased boil-off and methane venting into the atmosphere.

Previous LNG truck demonstration projects have documented issues with the vacuum tank design (U.S. DOE, 2004), that resulted in lower non-venting retention times, associated increased methane venting, and reduced usable LNG fuel in the tank. In the demonstration project, this resulted in trucks unexpectedly running out of fuel (U.S. DOE, 2004). In addition, the LNG storage tank is a significantly component of the incremental cost for a LNG truck over a diesel truck (O'Brien and Siahpush, 1998). Improving the robustness of the double-walled vacuum tank design and lowering the tank's cost is necessary to allow LNG trucks to compete with diesel trucks on price and performance.

Analysis of the life-cycle greenhouse gas benefit of LNG trucks concludes that LNG produces 9-14% less GHGs over its lifecycle compared to diesel if LNG conversion processes are 90% efficient (Areconi et al., 2010). If efficiency drops to 80%, LNG provides no GHG benefit compared to diesel (Areconi et al., 2010).

In addition, methane boil-off creates operational challenges for truckers. Methane boil-off can reduce the amount of useable fuel in the tank, reducing a truck's range, and adversely effects driver's flexibility (e.g. creating a need to use the fuel in relatively short time and difficulty with roadside assistance) in a highly competitive industry. There is currently strong reluctance in the trucking industry to use LNG in long-haul trucks (ATA, 2009). This reluctance is based on concerns about the operational reliability of the LNG fuel storage tank, in addition to a lack of fueling infrastructure with price competition, and the current high incremental cost relative to a diesel long-haul trucks.

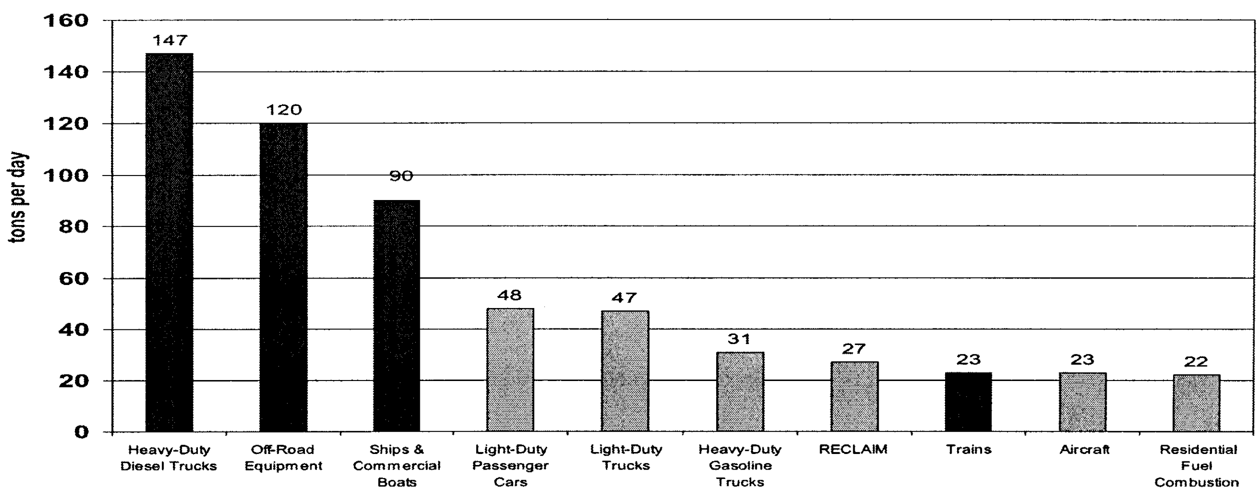
3.4 Nitrogen Oxide and Particulate Matter Emissions

The Clean Air Act requires the U.S. Environmental Protection Agency (EPA) to set national ambient air quality standards for five criteria pollutants, including two pollutants that have been historically associated with diesel emissions from heavy duty vehicles: nitrogen oxides (NO_x) and particulate matter (PM). Gasoline-powered light-duty vehicles readily meet NO_x and PM pollutant regulations and therefore switching from gasoline to natural gas in vehicles using a spark-ignition engine provides essentially no benefit to meet existing EPA regulation.

Nitrogen Oxides (NOx)

Diesel-fueled heavy-duty trucks are a significant source of NO_x. For example, diesel trucks are the leading source of NO_x in California's South Coast Air Quality Management district (SCAQMD) that includes the Ports of Long Beach and Los Angeles, a region that is non-compliant with federal air quality standards (Hogo, 2009). Figure 3.3 provides a list of major sources of NO_x in SCAQMD, with red columns indicating the source is associated with the Ports.

Figure 3.3: NOx Sources in SCAQMD, Red Columns are Associated with Port Activities (Hogo, 2009)



In 2010, the U.S. EPA NO_x standards are set to become significantly more stringent than the existing 2007 standards. As of September 2009, no diesel trucks have been certified to meet the 2010 NO_x standards using the standard after-treatment technology used to meet the 2007 standards (Hogo, 2009). Multiple natural gas trucks using spark ignition engines have met the 2010 NO_x standard using a three-way catalyst. The three-way catalyst is a proven and widely deployed technology for natural gas trucks. Figure 3.4 provides an overview of historic EPA NO_x standards and Figure 3.5 provides the NOx certification testing data for engines evaluated through September 2009.

Figure 3.4: EPA NOx and PM regulations have become more stringent over time. 2010 NOx standards will require diesel to employ new technology (Hogo, 2009)

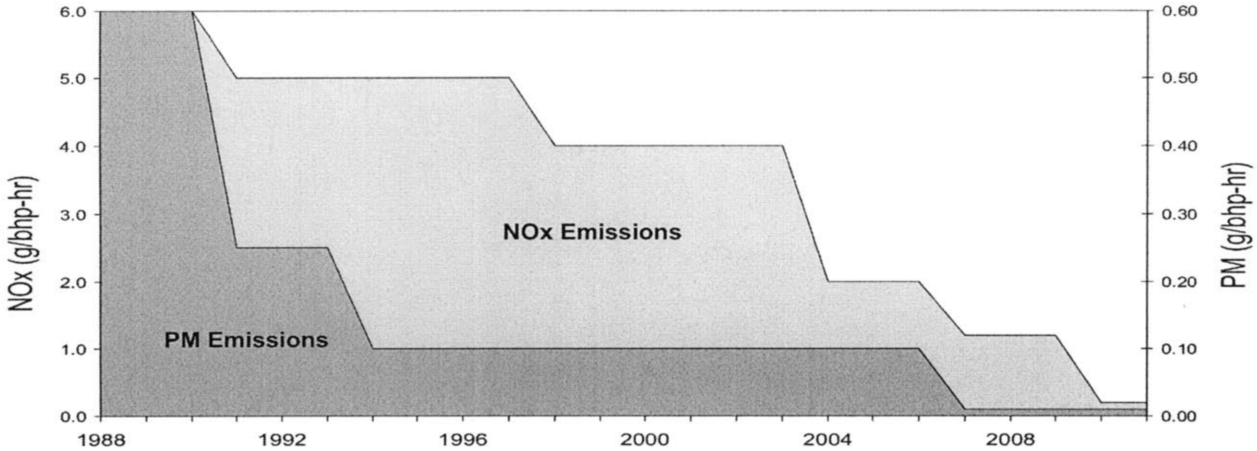
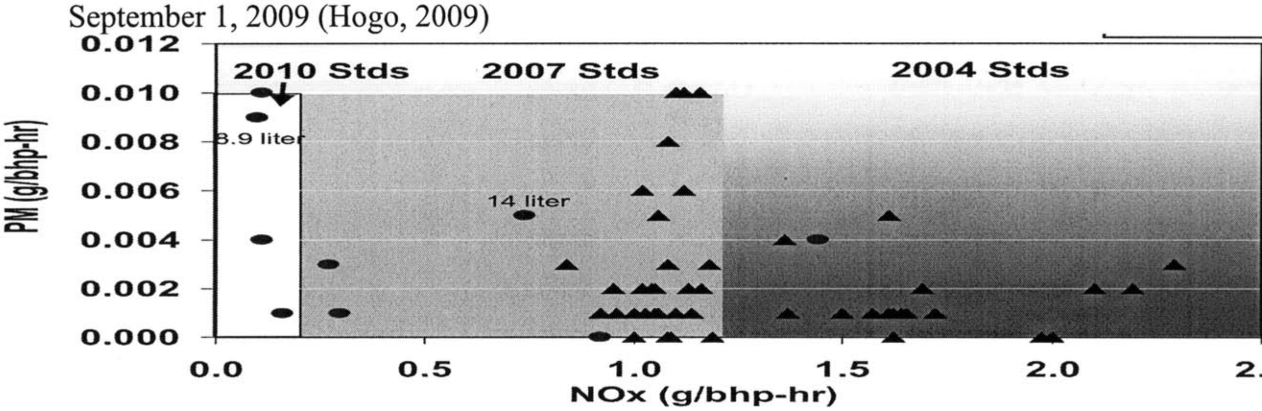
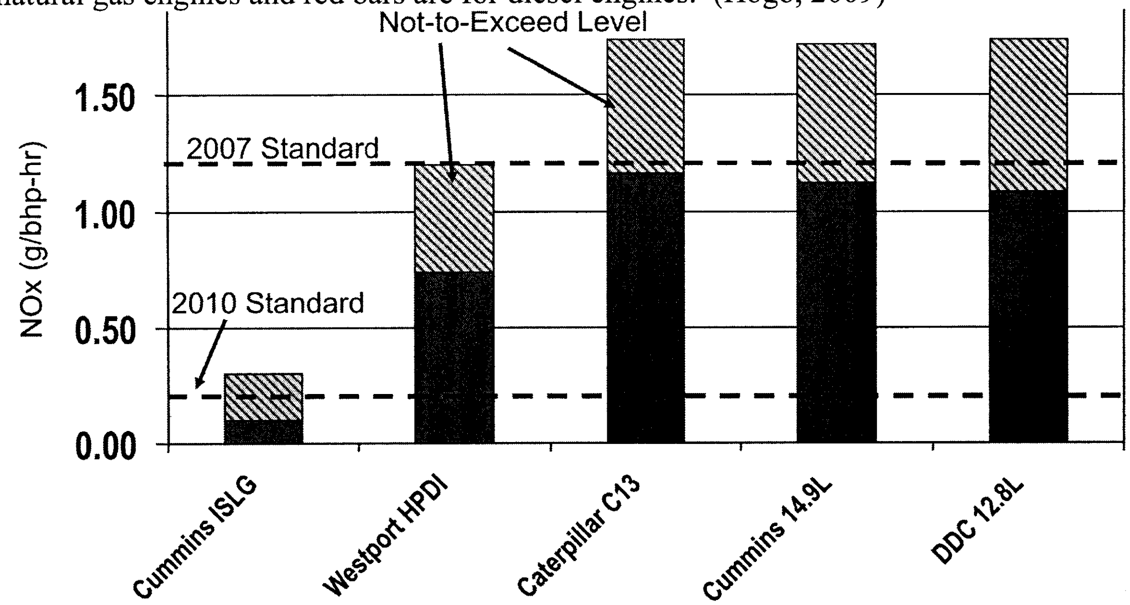


Figure 3.5: Certifications for Diesel (black triangles) and LNG (blue circles) Class 8 Trucks as of September 1, 2009. No diesel trucks have been certified to meet 2010 NO_x standards as of September 1, 2009 (Hogo, 2009)



In addition, although diesel trucks have been able to meet 2007 certification, measures of not-to exceed emission levels (maximum emissions expected based on operating conditions) are greater than 2007 standards (Figure 3.6). Natural Gas trucks not-to-exceed emission levels are below the 2007 standards. The specifics for the two natural gas engines are provided above in Table 3.1.

Figure 3.6: Not to Exceed NO_x Emissions Standards in 2007 and 2010. Green bars are for natural gas engines and red bars are for diesel engines. (Hogo, 2009)



Cummins, a diesel engine technology leader, has explicitly stated that after-treatment technology that is currently not used in the US (but used in Europe) will be required to meet 2010 NO_x standards (Cummins, 2009). The after-treatment cited by Cummins is Selective Catalytic Reduction (SCR). SCR uses a "chemical reactant that converts to ammonia in the exhaust stream and reacts with NO_x over a catalyst to form harmless nitrogen gas and water" (Cummins, 2009). The reactant is formed from solid urea, and SCR requires periodic urea refilling. Cummins cites several challenges associated with SCR. These challenges include being "affordable both in initial price and operational cost" and being "reliable and durable to control emissions in all environmental conditions over the life of the product" (Cummins, 2009). SCR is a new technology for the American trucking industry. SCR requires a national infrastructure of urea to allow truck drivers to regularly refill onboard urea tanks. This national infrastructure is not currently available. An additional key challenge with the SCR system is monitoring compliance. An empty urea tank does not affect truck performance but renders the

NO_x after-treatment system ineffective. Tractor-trailers are not currently required to have on-board diagnostic (OBD) systems to assess the performance of the SCR system over the life of the engine (California will require trucks to have OBDs by 2013). Due to these challenges, there is significant uncertainty regarding the additional cost of 2010 NO_x-compliant diesel trucks.

In addition, it could well be that NO_x limits will continue to become more stringent. There is significant uncertainty as to how diesels will be able to meet future regulation. CNG and LNG options may provide a more cost-effective option to meet future NO_x regulation.

<u>Particulate Matter (PM)</u>

Through improved engine operation and the use of diesel particulate filter (DPF) exhaust after-treatment technology, particulate matter (PM) emissions from diesel engines have significantly decreased over the last 10 years to levels that are similar to PM emissions from natural gas engines. Regardless of this decrease, diesel PM is listed as a toxic air contaminant under the California Toxic Air Contaminants Program while PM from natural gas is not listed (Kado et al, 2005). Few peer-reviewed studies have characterized the emissions of particulate matter (PM) and other toxic compounds from heavy-duty vehicles using natural gas (Kado et al, 2005). Recent work from CARB showed that "emissions from CNG fueled vehicles contain a complex mixture of toxic compounds, many of which are known or probable human carcinogens as seen in diesel exhaust" (Kado et al, 2005). Previous work does not calculate the unit risk from natural gas exhaust, but simply provides emission data for future epidemiological analyses that could provide a "quantitative risk assessment for cancer" (Kado et al, 2005). An analysis of the health effects of PM from natural gas as a transportation fuel requires additional work.

Therefore, there is currently uncertainty if natural gas PM provides a reduced health risk compared to diesel PM.

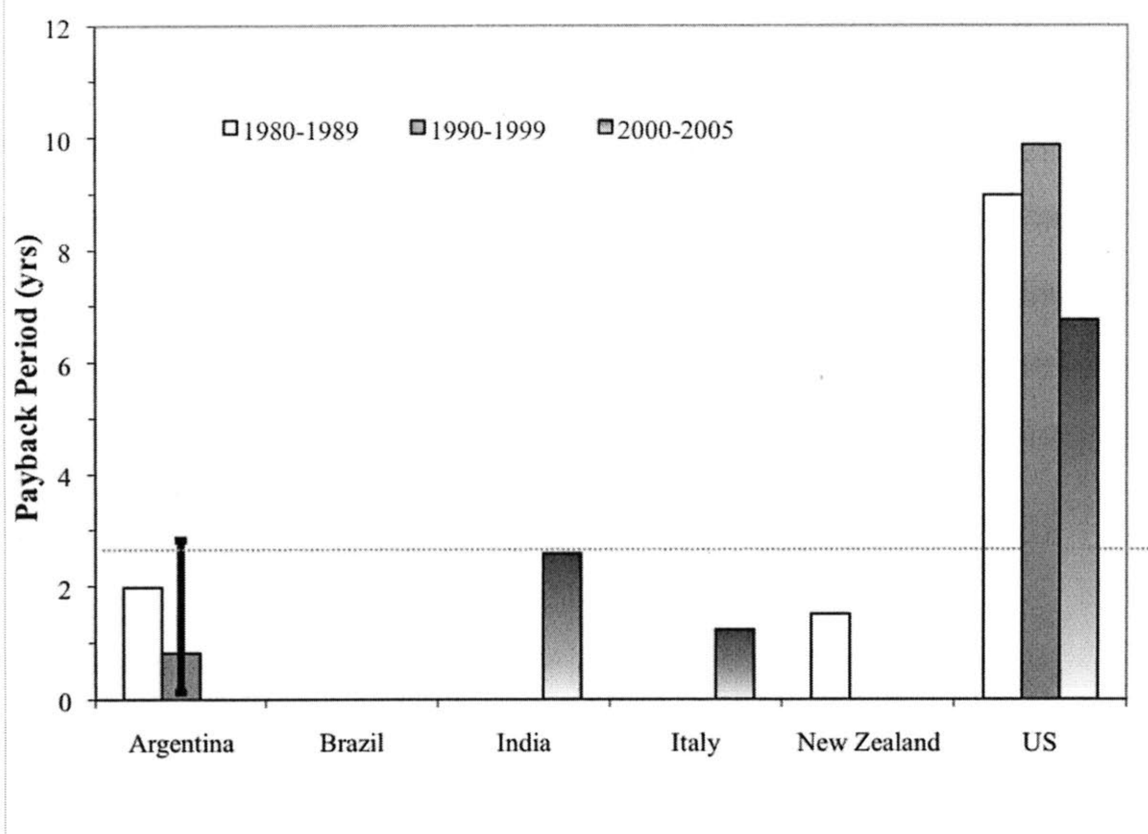
Chapter 4: Factors that Drive NGV Market Penetration

4.1 Influence of payback period on NGV market penetration

Empirical work (presented in Figure 4.1) observed that during periods of strong CNG vehicle market penetration, consumers in Argentina, Brazil, India, Italy, and New Zealand were able to payback the incremental cost of their CNG vehicles in less than three years (Yeh, 2007). The payback period is the time required in fuel savings, with less expensive natural gas compared to gasoline or diesel, to recoup the additional capital cost of a natural gas vehicle. The United States, with substantially longer payback periods and extremely limited light-duty CNG vehicle market penetration, is included for reference.

In South American and Asian countries that have experienced exponential growth in light duty CNG vehicles, two factors are responsible: a very low incremental cost of CNG or bi-fuel vehicles and a large fuel price spread between natural gas and gasoline. For example, in Pakistan, consumers are offered the opportunity to add CNG capability to a gasoline-powered car at dealerships (considered an after-market conversion) for approximately $800 (Suhail Ahmad, Pers. Comm.). These aftermarket CNG fuel systems may not be compliant with U.S. or European safety standards. In addition, the Pakistani government heavily subsidizes natural gas (Diesel Fuel News, 2002) creating a significant fuel-price spread with inexpensive natural gas (relative to the price of gasoline on an energy equivalent basis). The combination of a low incremental capital cost for a CNG vehicle and a high fuel price spread for natural gas has resulted in 73% of cars in Pakistan with the ability to operate on CNG (NGVA Europe, 2009). Similar anecdotal evidence exists for other countries in Asia and South America that have experienced an exponential growth in CNG fueled vehicles.

Figure 4.1: Empirical work showing that during times of strong market penetration (Yeh, 2007)



4.2. Utah Case Study

Although the United States has not experienced sustained market penetration of light-duty NGVs, there have been periods of time in spatially limited areas in the US with CNG light-duty market penetration. Figure 4.2 provides a snapshot of a story from the New York Times on August 29, 2008 (NYTIMES, 2008). The article describes a surge in demand for light-duty CNG vehicles in Utah. I have highlighted insightful portions of the article, including that the surge started when there was a fuel price spread of approximately $2.40 per gasoline gallon equivalent.

Figure 4.2: Snapshot of a New York Times article describing spatially limited NGV market penetration in the US (NYTIMES, 2008)

Surge in Natural Gas Has Utah Driving Cheaply

By CLIFFORD KRAUSS
Published: August 29, 2008

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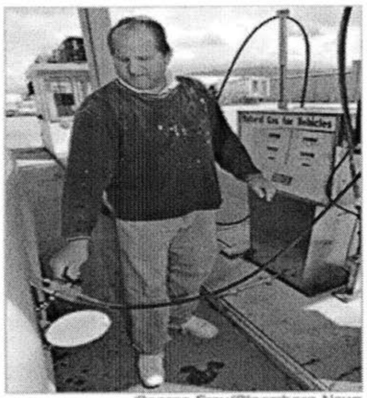
MY LIFE IN RUINS

SALT LAKE CITY — The best deal on fuel in the country right now might be here in Utah, where people are waiting in lines to pay the equivalent of 87 cents a gallon. Demand is so strong at rush hour that fuel runs low, and some days people can pump only half a tank.



George Frey/Bloomberg News
Bret Oliphant stopping to fill up in Salt Lake City.

The Energy Challenge
A Foreign Oil Alternative
Articles in this series are

It is not gasoline they are buying for their cars, but natural gas.

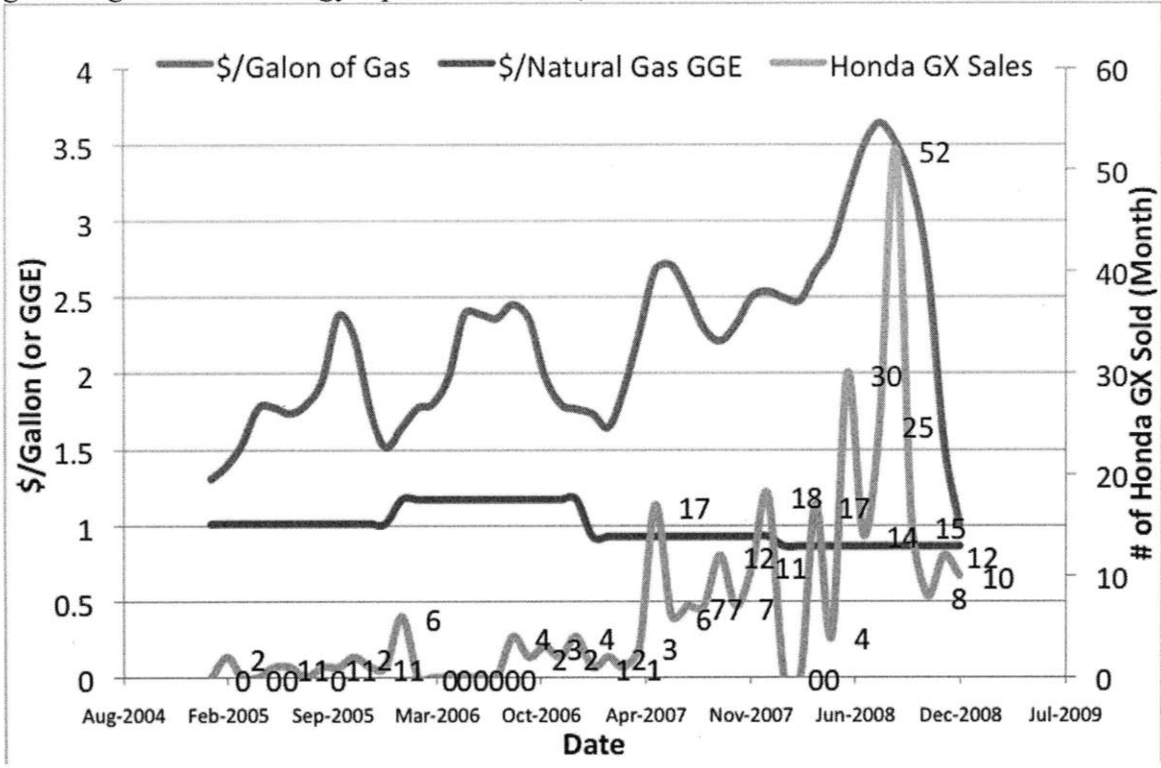
By an odd confluence of public policy and private initiative, Utah has become the first state in the country to experience broad consumer interest in the idea of running cars on clean natural gas.

Residents of the state are hunting the Internet and traveling the country to pick up used natural gas cars at auctions. They are spending thousands of dollars to transform their trucks and sport utility vehicles to run on compressed gas. Some fueling stations that sell it to the public are so busy they frequently run low on pressure, forcing drivers to return before dawn when demand is down.

It all began when unleaded gasoline rose above $3.25 a gallon last year, and has spiraled into a frenzy in the last

The Honda GX is the only OEM (Original Equipment Manufacturer) produced CNG vehicle available in the US. As an indicator of the relationship between an increased interest in CNG vehicles and the fuel prices spread (with less expensive natural gas compared to gasoline on a energy equivalent basis), Figure 4.3 shows the relationship between Honda GX sales with the fuel price spread between natural gas and gasoline at the fuel pump for drivers in Utah. Data on Honda GX vehicle sales is from the Utah State Tax Commission (State of Utah, 2008).

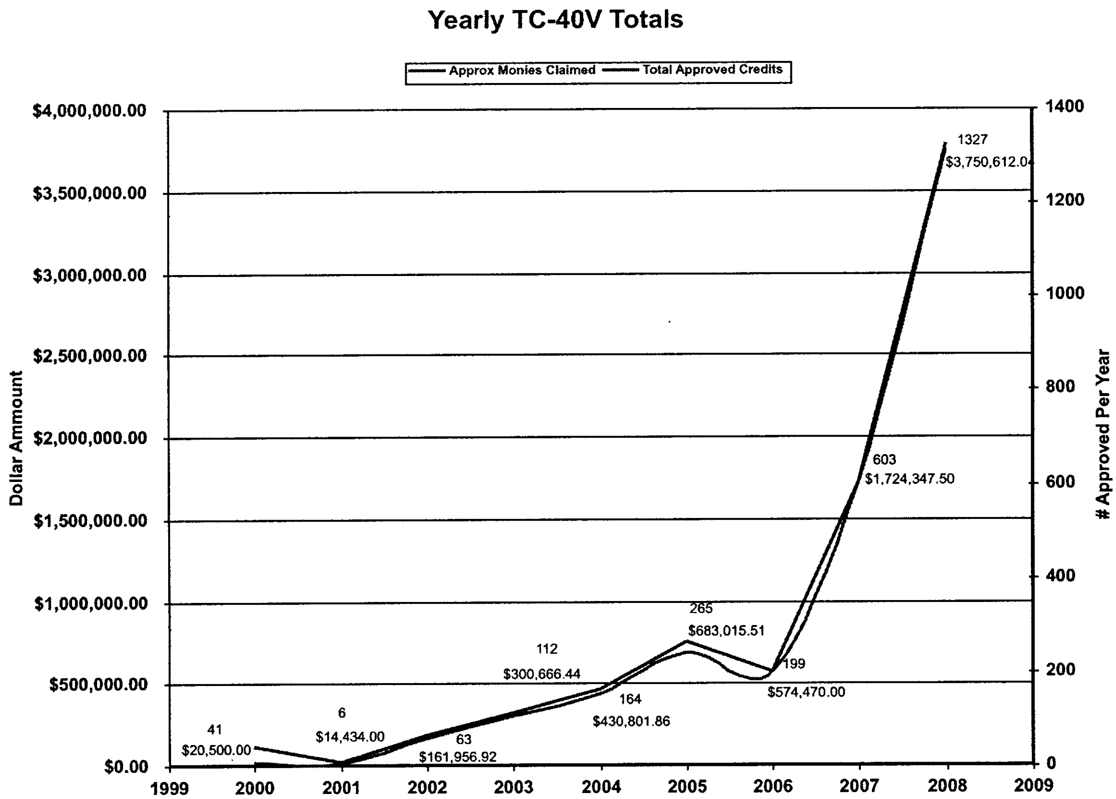
Figure 4.3: Relationship between the sales of CNG powered Honda GXs the price of natural gas and gasoline on energy equivalent basis (DOE EIA, 2009 and State of Utah, 2008)



Note - that although there appears to be a clear relationship between the fuel price spread and interest in the Honda GX - the number of Honda GXs sold during this time remains relatively small. This small number of Honda GXs is because there is a limited supply of the Honda GX, with Honda only producing about one thousand Honda GXs per year (Edmunds, 2006).

In addition, the State of Utah provides a tax credit for individuals who purchase a vehicle powered by natural gas from an OEM or have a their gasoline vehicle converted (considered an after-market conversion) to operate on natural gas. Figure 4.4 provides the number of tax credits granted by the State of Utah with time and shows a surge in the number of tax credits issued for OEM produced and after-market conversions to CNG vehicles during periods of high fuel price spreads. The Ford F-150 was the vehicle make with most number of after-market CNG conversions that received a tax credit from the State of Utah (Utah Department of Environmental Quality, 2009).

Figure 4.4: The number of tax credits for consumers who purchased an OEM produced NGV or had an aftermarket conversion of their gasoline vehicle to operate on natural gas (State of Utah, 2009) (Utah Department of Environmental Quality, 2009)



The State of Utah estimates that approximately 4,000 drivers who had after-market conversions to operate their vehicles on CNG in the summer of 2008 did not apply for the Utah state tax credit (Utah Department of Environmental Quality, 2009). The Utah state tax credit requires proof that the conversion meets the U.S. EPA standard for vehicle conversion. The State of Utah believes that some vehicle owners did not seek the State tax credit because they procured uncertified vehicle conversions that were less expensive than a certified conversion with the tax credit. This indicates that a significant number of the after-market CNG conversions in Utah were conducted outside of the standard US safety protocol. I will describe the US after-market certification process in Section 4.3.

4.3 Light Duty Vehicle Options Available to Consumer in the US and Europe

Consumers in the US currently have two options to purchase a light-duty CNG vehicle: the Honda GX and an aftermarket conversion. The Honda GX is approximately $7,000 more expensive than a comparably equipped gasoline-powered Honda Civic Sedan but with reduced truck space, horsepower, and travel range (see Figure 4.5) (Honda, 2009). The Honda GX is a dedicated NGV, meaning that the GX only operates on CNG and is not able to use gasoline, limiting GX drivers to regions with sufficient CNG fueling infrastructure. Bi–fuel operation has been a key feature in the worldwide growth of natural gas vehicles beyond fleet applications to individually owned vehicles. Currently, only dedicated NGVs receive US federal subsidies (NGVA, 2009)

Table 4.1: Comparison of the CNG powered 2009 Honda Civic GX and a comparably equipped gasoline powered Honda Civic (Honda, 2009)

	2009 Honda Civic GX NGV	**2009 Honda Civic Sedan**
Engine Displacement (cc)	1799	1799
Horsepower @ 6300 rpm	113	140
Torque (lb-ft @4300 rpm)	109	128
Compression Ratio	12.5:1	10.5:1
Cargo Volume (ft3)	6	12
Fuel (gallon)	8 GGE @ 3600 PSI	13.2
Fuel Economy (City/Highway/Combined)	24/36/28	25/36/29
Vehicle Range	224	382.8

The after-market conversion of a gasoline-powered vehicle to operate on CNG provides a second option for American consumers. From a technical perspective, the conversion of a gasoline vehicle to operate as a bi-fuel or dedicated CNG vehicle is fairly straightforward. A CNG vehicle uses the same engine as a gasoline-powered vehicle. The conversion consists of replacing the fuel storage system and including an electronic module to control engine operation. In the US, the after-market conversion of a vehicle must be certified by the U.S. Environmental Protection Agency (U.S. EPA) (or in California by the California Air Resources Board) under the Clean Air Act. The applicable section of the Clean Air Act regarding after-market vehicle conversion is Section 203(a)(3)(A) stating that it is prohibited:

"for any person to remove or render inoperative any device or element of design installed on or in a motor vehicle or motor vehicle engine in compliance with regulations under this title prior to its sale and delivery to the ultimate purchaser, or for any person knowingly to remove or render inoperative any such device or element of design after such sale and delivery to the ultimate purchaser." (42 U.S.C 7552(a)(3)(A)).

"The EPA generally interprets this to mean that any change to a vehicle's engine or fuel system that leads to higher pollutant emissions constitutes tampering under section 203" (Congressional Research Service, 2008).

The EPA has been certifying vehicle emissions since its inception in 1970. In 1974, the EPA addressed the after-market conversion issue by issuing Memorandum 1A that allowed small volume manufacturers (SVMs) to convert vehicles if they had a 'reasonable' basis to believe that the conversion would not increase emissions over the life of the vehicle (Congressional Research Service, 2008). In 1997, the EPA issued an addendum to Memoradum 1A, requiring that all future after-market conversions meet EPA or CARB certification (Congressional Research Service, 2008).

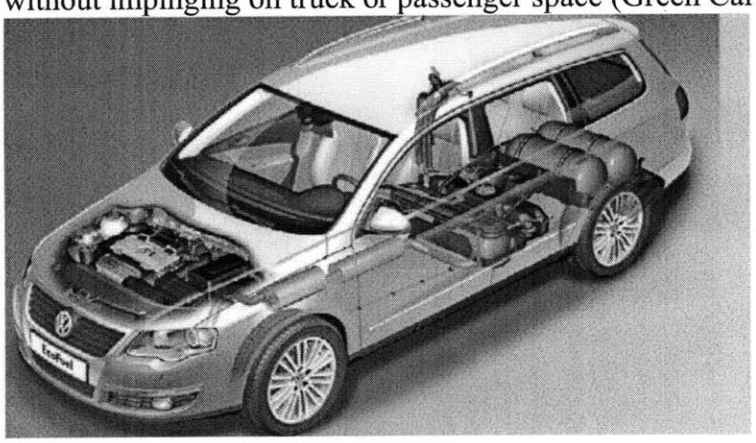
The EPA issues a certification for an aftermarket conversion process for a specific vehicle make and model (e.g. 2010 Ford Focus). In order to obtain the certification, the small volume manufacturer (SVM) that converts gasoline vehicles to operate on CNG provides the EPA with emissions data to show that their conversion technology does not increase the level of emissions over the lifetime of that specific vehicle make and model. In addition, the EPA may request a converted vehicle to verify the emissions data and ensure that the converted vehicle works well with the vehicle's on-board diagnostic (OBD) system. The EPA certification process is a time-intensive and expensive process for SVMs and may cost as much as $200,000 or more per vehicle make and model certification (Yborra, 2008). The SVMs amortize the cost of this certification process over a relatively small number of converted vehicles produced. This high price of certification for SVMs by engine family is likely to continue "unless the Clean Air Act is amended or the EPA makes changes to its enforcement of the Clean Air Act" (Congressional Research Service, 2008). A certified after-market conversion to operate a vehicle as a bi-fuel or dedicated CNG vehicle costs the consumer approximately an additional $10,000 compared to the price of gasoline-powered vehicle (Yborra, 2008). For example, if a gasoline powered 2010 Ford Focus costs $16,000, then the equivalent 2010 Ford Focus converted to also operate on CNG would cost $26,000.

The $7,000-$10,000 incremental cost for light-duty CNG vehicles in the US is substantially greater than the $3,500 incremental cost to the driver found with European OEM CNG vehicles (VW, 2009) and the $2,500 after-market conversions in Singapore that meet European safety standards (C.W. Melcher, 2009). The Volkswagen Passat TSI Eco-Fuel, a European OEM produced CNG and gasoline bi-fuel vehicle provides similar acceleration, range, and cargo volume compared to a comparably equipped Volkswagen gasoline-powered vehicle (see Table 4.2) with a significantly lower incremental cost compared to the Honda GX available in the US.

Table 4.2: The 2009 VW Passat TSI Eco-Fuel provides similar acceleration, range, and cargo volume compared to a gasoline-powered vehicle VW TSI 160 (VW, 2009)

VW Passat	TSI EcoFuel	TSI 160
Engine Displacement (cc)	1390	1798
Horsepower	150 at 5,550 rpm	160 at 5,000 rpm
Torque (lb-ft @4300 rpm)	162 at 1500-4500	184 at 1500
Acceleration (0-62 m/hr)	9.8	9.9
Top Speed m/hr	132	137
Cargo Volume (ft3)	17	17
Range (Total/NG/ Petrol) m	572/292/280	577/NA/577
CO2 emissions (g/km)	119	172

Figure 4.5 Depiction of the VW Passat TSI Eco-Fuel bi-fuel CNG and gasoline vehicle. Note that CNG fuel storage containers are stored on the vehicle's floorboard to maximize tank volume without impinging on truck or passenger space (Green Car Congress, 2004)



The German's Drivers Association (ADAC) named the VW Passat TSI Eco-Fuel the most environmentally friendly car in Europe in 2009, with the Toyota Prius awarded second place (NGV Global News, 2009). In addition, Volkswagen devoted significant effort to developing a marketing campaign for the Passat TSI Eco-Fuel. This ad campaign won an award at the 2009 Cannes Film Festival and is available here: **www.jazzcalculator.com** . In the ad campaign, a user selects two cities in Sweden for the Passat TSI Eco-Fuel to drive between. The site then creates a song list of jazz standards that cumulatively emit an equivalent amount of carbon dioxide (from the exhaling of the musicians on wind instruments) to the carbon dioxide emitted during the VW Passat TSI's trip. In the marketing campaign, VW assumes that the vehicle is operating on biomethane and estimates the greenhouse gas equivalent of operation is 20 grams of carbon dioxide/ km. This value is significantly higher than when the vehicle operates on CNG (estimated at 119g/km), with VW giving biomethane an emissions credit for trapping methane that would have been emitted to the atmosphere if not used as a fuel. European governments have not yet certified the emissions level of biomethane.

The $2,500 after-market conversions in Singapore that meet European safety standards cited above are produced by C.W. Melchers Company, a German company operating in Singapore. Sinapore's conversion standards are loosely based on the Australian standard, that requires CNG fuel storage cylinders to comply with ISO 11439 (C.W. Melchers, 2009). C.W. Melchers, being a German company uses the ECE R110 standard for their conversions (C.W. Melchers, 2009).

The International Organization of Standardization developed ISO 11439, entitled "Gas cylinders – high pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles", between 1987 and 2000 (Trudgeon, 2005). "The standard was not fully adopted by any country but provides a series of test for approval of NGV cylinders, guidance on cylinder design, and proper maintenance" (Trudgeon, 2005). In 2000, the United Nations, using ISO

11439 as a starting point, developed ECE R110 to provide "uniform provisions concerning the approval of specific components of motor vehicles using compressed natural gas (CNG) in their propulsion system" (Trudgeon, 2005). ECE R110 provides standards for all components of a CNG fueling system including the CNG cylinder. A revised version of ECE R110 was issued in 2001 and is used to regulate the aftermarket conversion of CNG vehicles in the European Union, Brazil, and Argentina (Trudgeon, 2005).

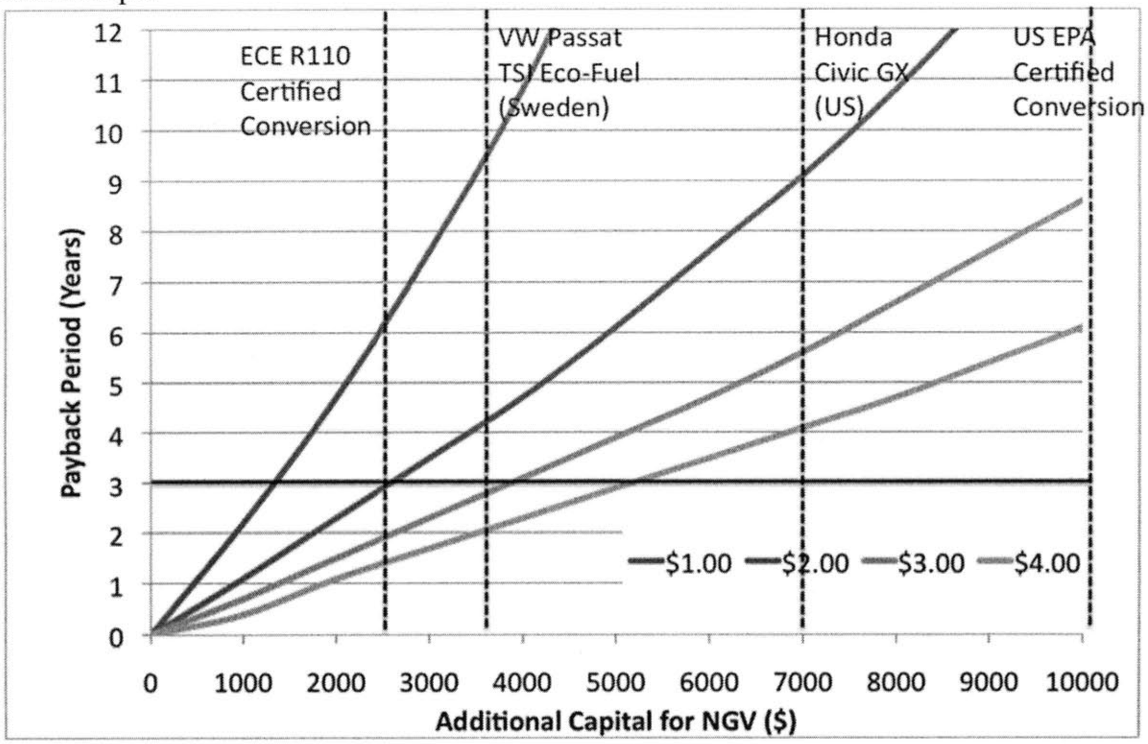
Argentina and Brazil, that have observed significant growth in CNG light duty bi-fuel vehicles in the last ten years, and Europe that has experienced some growth in CNG vehicles both use ECE R110 that certify parts to be used in a wide range of CNG vehicle conversions. The US after-market conversion process certifies specific conversion kits to be used on designated model year engine families (e.g. 2010 Ford Focus) and tests to ensure that the conversion does not adversely affect emissions levels over the lifetime of the vehicle. Conversions in the US cost approximately $10,000 where the ECE R110 compliant C.W. Melchers conversions cost approximately $2,500.

The CNG vehicle market in Brazil and Argentina is predominantly comprised of after-market conversions where the European market is predominantly comprised of OEM produced CNG-gasoline bi-fuel vehicles (Boisen, 2009). The role of after-market conversions, and ECE R110, has been more significant in South America compared to Europe. There is currently a small market for after-market conversions in the United States, and it is currently not clear if reducing the cost of a CNG after-market conversion by adopting the ECE R110 standards will dramatically impact the market penetration of CNG vehicles. Consumers in the United States, like European consumers may have a strong preference for vehicles produced from OEMs and may be, on average, reluctant to purchase after-market conversions from small volume manufacturers.

Figure 4.6 illustrates the impact of the incremental cost of light duty CNG vehicles on the time required for drivers to payback the incremental cost with lower cost natural gas as a fuel. In the figure, the number of years required to payback the incremental cost of the four light-duty CNG vehicles described in this chapter is on the Y-axis. On the X-axis is the incremental cost of each vehicle. The four diagonal lines represent the fuel price spread between natural gas and gasoline. For example, the $1.00 line represents natural gas that is $1.00 less expensive per gallon of gasoline equivalent compared to a gallon of gasoline, saving the driver of a natural gas vehicle $1.00 for each gallon of gasoline equivalent used. Figure 4.6 assumes an average driver who drives 12,000 miles per year and has a car with a fuel efficiency of 30 miles per gallon. The analysis assumes a five percent discount rate.

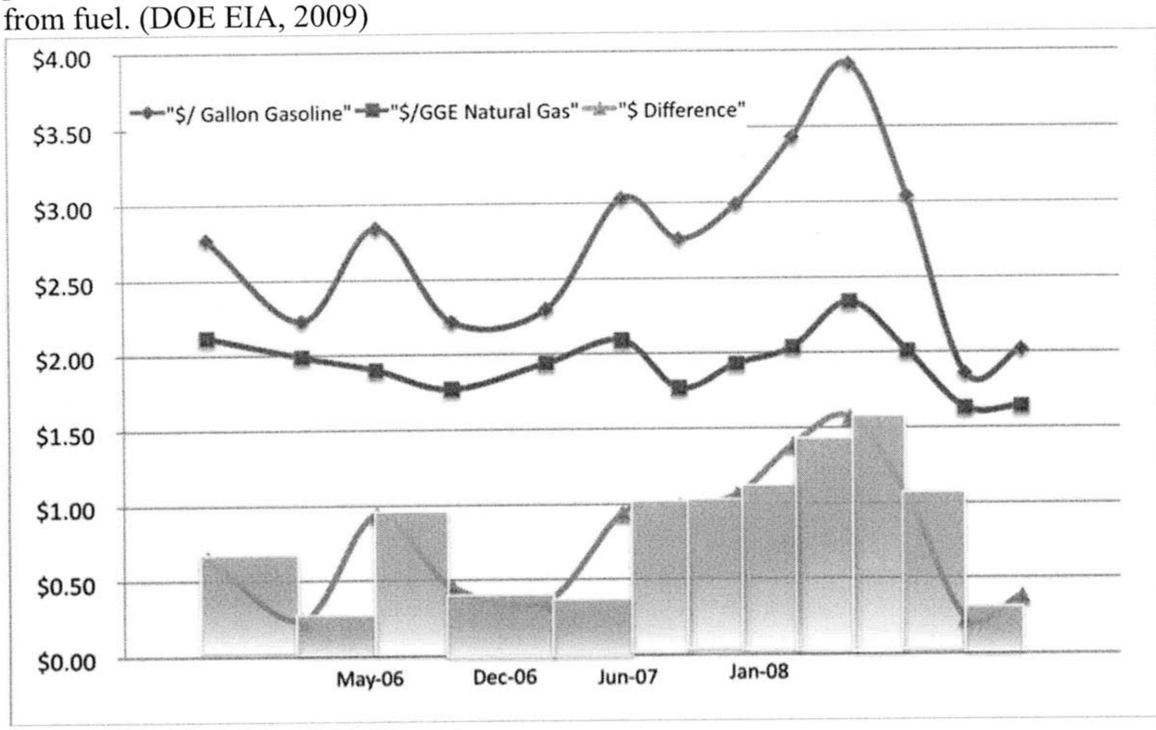
In Figure 4.6, I have highlighted the three-year payback period that previous empirical work has associated with periods of strong CNG vehicle market penetration (Yeh, 2007). The European OEM and aftermarket conversion provide significantly shorter payback periods compared to the OEM and aftermarket conversion options in the US. The European aftermarket conversion and OEM produced CNG vehicle requires a $2.00 to $3.00 fuel price spread to payback the incremental cost of the vehicle in less than three years. The American options require a fuel price spread of greater than $4.00 per gallon of gasoline equivalent.

Figure 4.6: The payback period for an average driver (12,000 miles/year and 30 miles/gallon, 5% discount rate) to recoup the increment cost of light-duty CNG vehicles available in the US and Europe.



Over the last 5 years, natural gas in the US has been consistently less expensive than gasoline at the fuel pump on an energy equivalent basis. The fuel price advantage for natural gas at the fuel pump compared to the price of gasoline (fuel price spread) has fluctuated between $.50/Gasoline Gallon Equivalent (GGE) to $1.50/GGE (during the summer of 2008), with geographically limited extreme fuel price spread spikes to $2.50/GGE (e.g. Utah in the summer of 2008) (DOE EIA, 2009, NYTIMES, 2008). A figure depicting the national average price of gasoline and natural gas at the pump is provided in figure 4.7. In addition, please see Appendix 1 that provides a relationship between the wellhead price of natural gas with the price of CNG as a transportation fuel.

Figure 4.7: National average price of gasoline (blue) and natural gas (red) per gasoline gallon equivalent. The bottom green line provides the difference between the gasoline and natural gas prices. The difference line is numerically integrated (grey boxes) to estimate the total savings from fuel. (DOE EIA, 2009)



From the numerical integration in Figure 4.7, the fuel savings from the use of natural gas instead of gasoline, on average in the US, over the last 3.5 years is $1,350 or $370/year. The fuel saving in the 6- month period from April 2008 to October 2008 (during the most recent period of high fuel price spread) is $360 or $720/year. Fuel savings calculations assume a driver that drives 12,000 miles/year with a fuel efficiency of 25 miles per gallon.

The higher incremental costs found in the US have severely lengthened the payback period for CNG light-duty vehicles. Table 4.3 illustrates the impact of this higher incremental capital cost for average mileage drivers, represented by 12,000 miles per year use, and high-mileage drivers (e.g. taxis) represented by 35,000 miles per year use.

Table 4.3: The number of years required to payback the NGV incremental cost based on a fuel price spread from less expensive natural gas compared to gasoline (on GGE basis) for low and high mileage drivers (assumes 30 miles per gallon and a 5% discount factor)

		12,000 mile per year		*35,000 miles per year*	
Fuel Price Spread	**Incremental Cost**	**\$3,000**	**\$7,000**	**\$3,000**	**\$7,000**
	\$ 0.50	>60	>60	**6**	>60
	\$ 1.50	**5.8**	36.1	**1.9**	**4.5**
	\$ 2.50	**3.3**	**8.7**	**1.1**	**2.6**

Payback periods of 3 years and less, which previous empirical work has associated with strong CNG vehicle market penetration, are highlighted in yellow. Payback periods that are greater than 4 years but less than the life of a vehicle, which may attract some consumer interest, are highlighted in gray.

Under the higher incremental cost found in the US (represented as \$7,000 in Table1), there will only be an attractive payback period for the case of high mileage drivers with a very high fuel price spread (with respect to historical fuel price spreads) of around \$2.50/GGE and limited interest during times of high fuel price spreads (\$1.50/GGE). In the case of the lower incremental cost CNG vehicles (\$3,000), representative of the incremental cost for an OEM vehicle and aftermarket conversion that meet European safety standards, high mileage vehicle owners will have a very attractive payback period during high fuel price spreads and a reasonable payback period during low fuel price spreads. Reducing the incremental cost of CNG vehicles could create a compelling proposition for high-mileage, light-duty drivers or fleet owners to purchase CNG vehicles.

In the case of the lower incremental cost CNG vehicles, average mileage drivers will have an attractive payback period during periods of high fuel price spread. Reducing the cost of a light-duty CNG vehicle in the US is critical to solidifying the CNG vehicle market for high-mileage light-duty drivers and extending the potential market for CNG vehicles to a subset of average-mileage drivers. In addition, lowering the cost of CNG vehicles in the US would reduce the level of public funds necessary during a period of finite public subsidy to start a market for CNG vehicles. Finally, extending these federal subsidies to bi-fuel vehicles will allow CNG to serve as a hedge to consumers with bi-fuel vehicles during periods of high gasoline prices and allow early adopters to effectively use CNG vehicles in areas with limited fueling infrastructure (see infrastructure section below).

From this analysis, I would recommend that the US government encourage opportunities to reduce the incremental cost of OEM produced and after-market converted CNG vehicles. In particular, the US should review and streamline current aftermarket vehicle conversion certification policy. In addition, US public subsidies designed to start a market for CNG vehicles should include bi-fuel CNG and gasoline vehicles in addition to dedicated CNG vehicles.

4.4. Heavy-Duty Vehicle Options Available to Consumer in the US

In heavy-duty applications, when natural gas is used to displace diesel fuel, in addition to reduced greenhouse gases, natural gas provides reduced nitrogen oxide emissions. The US is a leader in the heavy-duty NGV technology, both in more established CNG technology and in nascent LNG applications.

In order to characterize the heavy duty NGV market, I provide vehicle options available in three heavy-duty vehicle market categories: tractor-trailers, transit buses, and delivery trucks.

Tractor Trailers:

Natural gas powered tractor-trailers in the US predominantly use the Cummins Westport ISL-G and ISX-G engines that are characterized in Table 3.1. Most tractor-trailers in the US are used for long-haul applications and therefore use LNG, which has a higher energy density compared to CNG. Approximately 10% of class 8 trucks (that includes tractor trailers) are centrally refueled (Bromberg and Cohn, 2009) and therefore are limited range vehicles that could potentially use CNG. A number of truck manufacturers utilize the ISL-G and ISX-G engines in tractor-trailers designs. Figure 4.8 provides an example of each engine in Peterbilt trucks. Both of these trucks are options for truck drivers in the Port of Long Beach's Clean Truck Program.

The Port's Clean Truck Program is the current largest market for LNG tractor-trailers in the US. The Port's Clean Truck Program is a critical part of the Port's "Clean Air Action Plan" developed by the Ports, along with staff from the U.S. EPA, California Air Resource Board, and California's SCAQMD (South Coast Air Quality Management District) to address the Port's pollutant emissions. Under the Clean Truck Program, old, polluting trucks are being progressively banned from Ports terminals on the following schedule:

- October 1, 2008: All pre-1989 trucks have been banned.
- January 1, 2010: 1989-1993 trucks will be banned from port terminals along with unretrofitted 1994-2003 trucks.
- January 1, 2012: All trucks that do not meet the 2007 federal clean truck emission standard will be banned from port terminals.

The Port is providing grants to truck drivers to purchase new trucks. The port is funding these grants by applying a $35 fee to cargo owners for every twenty-foot equivalent unit (TEU) container that enters the port (Port of Long Beach, 2008). Truck owners will receive a $67,000 grant toward the purchase a new, compliant clean diesel truck or $105,000 toward the purchase of a LNG truck (Port of Long Beach, 2008).

Figure 4.8: The Natural Gas Tractor Trailers Using the ISL-G and ISX-G Engines. *Note: the Costs and Subsidized Loan Values are from the Port of Long Beach's Clean Truck Program.*

Peterbilt 384 ISL-G LNG	Day Cab	Cummins-Westport ISL-G 320 HP		**Subsidized Lease:** $311/month for first 2 years; $529/month for next 5 years Cost: $139,050* Your Cost:$39,204 Or **Subsidized Loan:** Subsidy: $105,000
Peterbilt 386 ISX-G LNG	Day Cab	Westport ISX-G 400 HP		**Subsidized Lease:** $720/month for first 2 years; $1,192/month for next 5 years Cost: $197,161* Your Cost:$88,800 Or **Subsidized Loan:** Subsidy: $105,000

Assuming that a diesel truck costs $100,000, the incremental cost of an LNG tractor-trailer ranges from $40,000 (using the ISL-G engine) to $100,000 (using the ISX-G engine).

Buses and Delivery Trucks

There are 11,000 CNG buses in the US, approximately 8,000 of the CNG buses are transit buses, fueling 12% of the 66,000 total transit buses in the US (U.S. DOT, 2009). The remaining CNG buses are school buses. CNG school buses comprise a small percentage of the approximately 600,000 school buses in the US (Ullman et al., 2002). CNG buses operate on spark-ignition engines with an engine displacement in the 8-liter range (e.g. Cummins Westport ISL-G engine in Table 3.1)

The incremental cost an urban transit bus is approximately $22,000 compared to a diesel transit bus (TIAX, 2005). The incremental cost of a CNG school bus is comparable to that of an urban transit bus with incremental cost estimates of $25,000 (Leonard et al. 2001).

Delivery trucks are considered medium duty trucks that operate on a spark ignition engine with a displacement on the range of 6 liters (e.g. Cummins B59G engines). CNG delivery trucks have an additional incremental cost of $15,000 to $18,000 more than diesel trucks (U.S. DOE 2001).

Payback Period of Heavy Duty Trucks

Segments of the heavy-duty natural gas vehicle market also provide attractive payback periods (see Table 4.4) under the recent low ($.50/GGE) and high ($1.50/GGE) fuel price spreads (see Figure 4.7).

Table 4.4: *Payback period (in years) required to recoup the incremental cost for select illustrative heavy-duty NGV market segments based on fuel savings from less expensive natural gas compared to gasoline (on GGE basis).*

		School or Transit Bus	***Single Unit, 2 axle, 6 tire truck***	***Tractor Trailer***
	Fuel	*CNG*	*CNG*	*LNG*
	Incremental Cost	*$25,000*[b,c]	*$18,000*[f]	*$70,000*[a]
	VMT/Year	*45,000*	*35,000*	*65,000*[e]
	MPG	*3*[c]	*5*	*5*[e]
Fuel Price Spread	*$0.50*	3.7 yrs	6 yrs	15.4 yrs
	$1.50	1.2 yrs	1.9 yrs	4 yrs
	$2.50	0.4 yrs	1 yrs	2.4 yrs

a) POLB, 2009 *b) Cohen et al, 2005* *c) TIAX, 2005*
d)vehicle miles traveled *e) U.S. DOT, 2007* *f) US DOE, 2001*

School or transit buses and delivery trucks (represented as single unit, 2-axle, 6-tire trucks in Table 2) provide an attractive payback period under low and high fuel price spreads where tractor-trailers require a high fuel price spread to provide an attractive payback period. In addition, tractor-trailers operate on LNG, which is currently a more fragile technology compared to mature CNG technology (see technology assessment on LNG tractor trailers in Chapter 3).

Chapter 5. Infrastructure

5.1 CNG and LNG Fueling Infrastructure

Currently in the U.S. there are 0.6% of the CNG refueling stations compared to gasoline refueling stations, Utah has the highest percentage of CNG refueling stations compared to gasoline stations in the U.S. at 6.8% (DOE, 2010). The sustained growth of non-fleet alternative fuel vehicles (AFV) requires AFV refueling stations to have 10 -20 % of the locations compared to gasoline stations (Nichols et. al, 2004).

CNG stations costs vary widely based on type of station (fast vs. slow fill) and the compression capacity of the station - with a rule of thumb of $800-$1,000 for each standard cubic meter (SCM) of natural gas compressed and delivered per minute (SCM/min) capacity (Eudy, 2002). 125 SCM of natural gas has approximately the same energy content as a gallon of gasoline equivalent (GGE). Therefore a fast-fill station that fills a car with a 10 GGE tank in 10 minutes requires capacity of 125 SCM/min and costs $125,000 (or $500,000 for a station with the capacity to fill 4 cars simultaneously).

An investment of $8.5 Billion (assuming $500,000/station) is required for CNG stations to have 15% of the locations compared to gasoline stations in the US. The investment to create an adequate network of CNG stations is significant and is complicated by a chicken and egg dilemma: CNG fueling stations are unlikely to be built in areas where there is a dearth of NGVs and conversely, individuals are unlikely to purchase NGVs in areas without adequate natural gas fueling infrastructure. The investment for the widespread deployment of CNG fueling stations for non-fleet applications is attractive only if natural gas is expected to be significantly less expensive than gasoline for an extended period of time. A high fuel price spread (e.g. natural gas is $1.50 to $2.50 less expensive per GGE) with a $3,000 incremental vehicle cost is required for average mileage light-duty drivers to consider purchasing a CNG light-duty vehicle to develop sufficient demand for these CNG fueling stations. The promotion of bi-fuel CNG vehicles could allow drivers to purchase CNG vehicles even if they drive in areas without sufficient CNG refueling infrastructure (see above recommendation to extend federal subsidies for CNG vehicles to bi-fuels).

LNG stations are more expensive than CNG stations and cost approximately $1 million per station (not including the cost of an off-site liquefying facility) (AQMD, 2009). Current efforts to create strategic LNG fueling stations along trucking routes does not adequately support a competitive LNG fuel market, contributing to reluctance in the trucking industry to support the increased use of LNG (ATA, 2009).

5.2 Additional Infrastructure for CNG and LNG Vehicle Operation

Non-fleet users may refill their CNG vehicles using a residential compressed natural gas refueling station called the Phill, formerly made by Honda. The Phill costs approximately $5,000. A user with a Phill in an area without adequate CNG refueling stations must stay in the vicinity of their home, making long-distance trips difficult unless the vehicle has bi–fuel capability.

Large vehicle fleets that operate internal fueling infrastructure are likely segments for NGV market penetration. In addition to fueling infrastructure, fleet operators must make addition investments to use natural gas including upgrading enclosed areas (maintenance and parking facilities) with systems to detect and vent methane (Conference of Northeast Regional Fire Safety Officials, 2000). Methane detection and venting system upgrades cost approximately $100,000. Costs to upgrade maintenance and parking facilities could be substantially higher in fleet facilities with older infrastructure that must be brought up to standards (e.g. asbestos removed or Americans with Disabilities Act compliance) before new venting systems are installed (Eudy, 2002). An additional related infrastructure concern for some municipalities could be certifying that enclosed structures are adequately vented to temporarily house CNG vehicles (e.g. tunnels and public parking garages). In order to support the market penetration of CNG vehicles in fleet applications, the US government should explore opportunities to support fleet owners with fueling and facility infrastructure upgrades required to use natural gas.

Chapter 6. Market Penetration of NGVs

6.1 Illustrative Market Sizing of NGV Market Penetration

Due to the emergence of large, domestic natural gas reserves, the lack of a global natural gas market, and expected increase in world oil demand as nations emerge from recession, natural gas in the US may be less expensive, and potentially significantly less expensive, than gasoline in the near future. We also recognize that the future price of natural gas and gasoline is difficult to predict since both are volatile commodities with complex economic, technical and political factors influencing price. In light of future price uncertainty, a reasonable NGV policy is to identify and encourage the market penetration of technologically mature light and heavy duty CNG vehicles that offer a financial benefit to the driver under recent low fuel price spreads of \$.50/GGE (see Figure 4.7 for fuel price spreads over the last five years), thus minimizing the necessary level of public support to a finite period of time to develop a market. As outlined in the Chapter 4, these vehicles market segments include high-mileage light duty CNG fleet vehicles and heavy-duty CNG vehicles.

Table 6.1 provides an illustrative sizing of the potential market for NGVs in the US. Market segments in yellow are attractive to vehicle owners during low (\$.50/GGE) fuel price spreads. All market segments presented use CNG except 90% of class 8 trucks (represented as combination trucks in table 6.1), 50% of the bus market, and 20% of single unit trucks. Approximately ten percent of Class 8 trucks are centrally fueled (Bromberg, and Cohn, 2009) and therefore could operate on CNG. I assume that fifty percent of the bus market is comprised of urban transit buses and schools buses that could use CNG, while the remaining fifty percent are long-haul buses that would require LNG. In addition, I assume that 80% of single unit trucks are for urban or regional haul or delivery and could use CNG. As described previously, use of LNG (particularly in long-haul trucks), is much less established than the use of CNG and faces challenges of high incremental cost, more demanding infrastructure requirements, and operational issues related to cryogenic fuel storage along with the reluctance of the American Trucking Association (ATA, 2009). It is likely that substantial progress in resolving these issues will be needed before there is significant market penetration of LNG-powered long haul trucks.

Table 6.1*: Illustrative Market Sizing of Potential US NGV Market. Segments are converted into natural gas energy equivalents (Trillion Cubic Feet (TCF) of Natural Gas). Market segments in yellow provide attractive payback periods during low fuel price spreads and use mature CNG technology. Note: illustrative market sizing assumes light duty high mileage vehicles equals fleet vehicles. (US DOE 2010a)*

Light Duty	Cars Low Mileage	Cars High Mileage	Light Duty Trucks Low Mileage	Light Duty Trucks High Mileage
Number of Vehicles in the US	135,932,930		101,469,615	
Total TCF/YR Size of Market	7.9		7.4	
Fleet Size of Market	2.9% (0.2 TCF)		8.2% (0.6 TCF)	
Heavy Duty	Single Unit Truck- 2 axle, 6 tire	Combination Trucks	Bus	Urban Transit Bus
Number of Vehicles in the US	6,806,630	2,220,995	834,436	65,249
Total TCF/YR Size of Market	1.9	3.5	1	0.1
% of Market That Could Use CNG	80%	10%	50%	100%
Size of CNG Market (TCF CNG/YR)	1.5	0.4	0.5	0.1

6.2 Impact of Vehicle Fleet Turnover on NGV Market Penetration

In this illustrative market sizing, the total attractive market (in yellow in table 6.1) is approximately 3.3 TCF/year of natural gas. Due to infrastructure barriers, we assume that fleet vehicles are the most likely areas for early market penetration. Figure 6.1 provides an illustration of the relationship between the total share of a vehicle fleet that operates on CNG and the percent of new vehicle sales that that are CNG vehicles (assuming a vehicle fleet turnover period of 14 years). Due to the long time period required for vehicle fleet turnover and consumer acceptance of alternative fuel vehicles (AFVs), a significant amount of time is required to exploit this potential market.

Figure 6.1: Relationship between NGV Share of Total Vehicle Fleet and the % of New Vehicle Sales that are NGVs

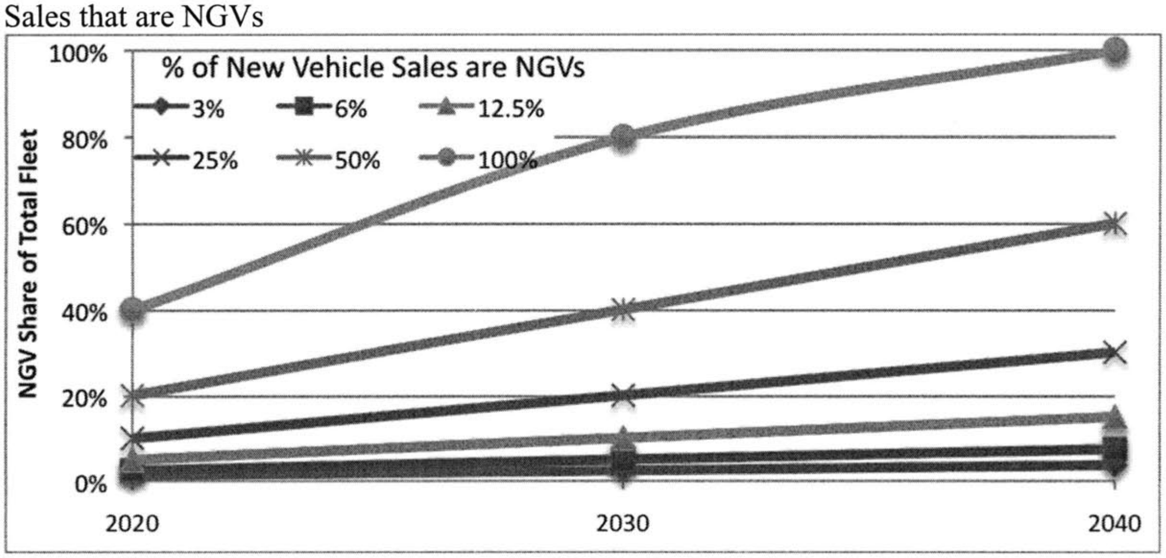


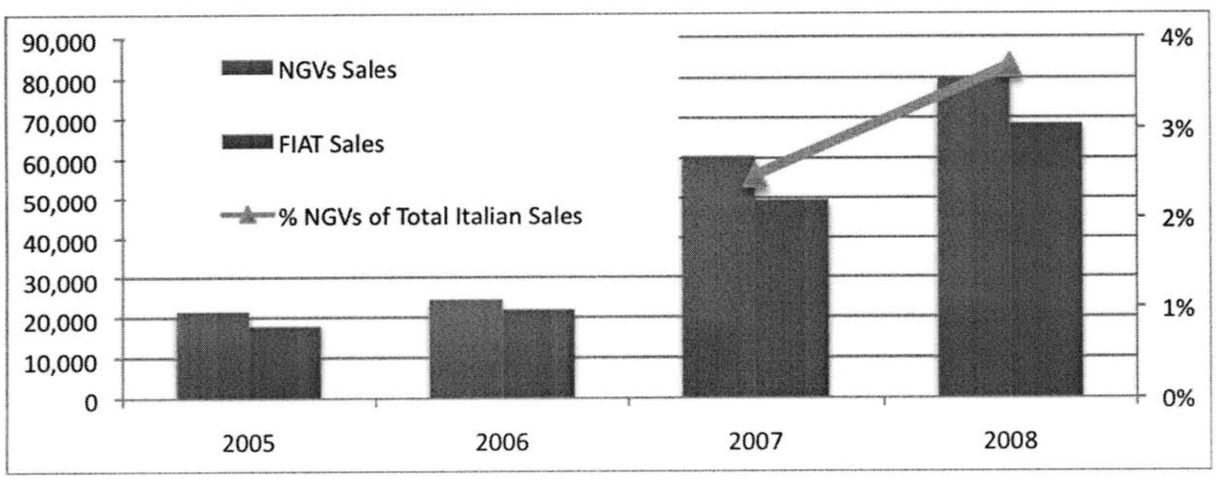
Table 6.2 provides an illustrative estimate of the size of the natural gas market for transportation over time for different percentages of new cars sales that are CNG vehicles based on a total market potential of 3.3 TCF and a 14-year vehicle fleet turnover.

Table 6.2: The size of the natural gas for transportation market in TCF of gas, assuming a total NGV market potential of 3.3 TCF described in Table 3, by decade based on the percentage of new vehicle sales that are CNG vehicles.

	Year		
% of New Vehicle Sales that Operate on Natural Gas	**2020**	**2030**	**2040**
6%	0.1 TCF	0.2 TCF	0.2 TCF
13%	0.2 TCF	0.3 TCF	0.5 TCF
25%	0.3 TCF	0.7 TCF	1.0 TCF
50%	0.7 TCF	1.3 TCF	2.0 TCF

For reference, in Italy, that has a strong tradition of using natural gas as a transportation fuel, less than 5% of new car sales operate on natural gas (see Figure 6.2) (FIAT, 2009). Based on this illustrative market sizing, the demand for natural gas as a transportation fuel is likely to be modest over the coming decades.

Figure 6.2: The Italian NGV Market (FIAT, 2010)



6.3 Impact of Low Fuel Standards on NGV Market Penetration:

Recently enacted state low carbon fuel standards (e.g. California) could provide additional motivation for the market penetration of natural gas vehicles. CNG vehicles emit approximately 25% less greenhouse gases compared to gasoline and diesel vehicles. For example, the California low carbon fuel standard requires a 10% decrease in greenhouse gas emissions from fuels sold in 2020. Corn-based ethanol may be assigned approximately the same greenhouse gas rating as gasoline (due to indirect land use), leaving natural gas and improved petroleum refining efficiency as the only existing methods to meet the requirement. As a rough estimate of the effect, if all of the decrease in GHGs were to come from the increased use of CNG vehicles, CNG vehicles would have to constitute 40% of the fuel use. As discussed above, the estimated economically attractive potential market for CNG vehicles is 3.3 TCF/YR out of a total transportation fuel consumption of approximately 22 TCF/YR (all transportation fuels converted into natural gas units) or around 15% of fuel use. Thus, the high-mileage light duty fleet and CNG heavy-duty markets would in principle serve to meet less than 40% of the low carbon fuel standard requirement. In order to meet the low carbon fuel standard with natural gas, additional CNG vehicle market penetration in non-high mileage light-duty applications is required. The above recommendation to lower the incremental cost and improve the performance of CNG light-duty vehicles to levels found in Europe and extend federal subsidies to bi-fuel CNG and gasoline vehicles may be critical to facilitate this larger market penetration.

If state low-carbon fuel standards allow for trading with the electric power sector to provide a low-carbon fuel for plug-in hybrid and fully electric vehicles, then low-carbon fuel standards may not significantly promote the market penetration of CNG vehicles. This is because the marginal abatement cost for removing GHG emissions from the transportation sector is significantly higher than the marginal abatement cost in the electric power sector (Holland et al, 2009). Appendix 2 provides a comparison of the efficiency of natural gas use and the marginal abatement cost of using natural gas in a CNG vehicle compared to using natural gas generated electricity in a plug-in hybrid electric vehicle.

There will also be additional motivation for the use of LNG in trucks - however, the greenhouse gas reduction benefit for LNG is approximately 10% (Areconi et al., 2010) rather than 25% for CNG. In addition, LNG is a fragile technology that requires additional technological development prior to significant market penetration.

Chapter 7: Summary and Conclusions

Vehicles fueled on compressed natural gas are a readily available technology that has been adopted at scale in a number of countries throughout the world. The market penetration of CNG-fueled vehicles in the United State is significantly lower than the market penetration in South America and Asia (that have experienced exponential growth in CNG vehicle market penetration) and Europe (that has experienced a moderate growth in CNG vehicles). CNG vehicles emit approximately 25% less CO_2 during combustion compared to gasoline. In heavy-duty applications, CNG vehicles have lower nitrogen oxide emissions than diesel and may provide a cost effective alternative to meet future, more stringent nitrogen oxide emissions regulation.

A financial benefit to the driver, measured in a short payback period for the higher incremental cost of CNG vehicles based on lower priced natural gas compared to gasoline, has been the prime driver for CNG vehicle market penetration in select countries. There is an opportunity to reduce the incremental cost of CNG vehicles in the US (currently $7,000-$10,000 compared to $2,500 to $3,500 in Europe) and improve the performance of US CNG vehicles to levels found in Europe. The current US aftermarket certification process can be streamlined to reduce the price of conversions from approximately $10,000 to $2,500 per vehicle. This reduction of incremental cost would create a very attractive payback period for CNG vehicles for high-mileage fleet owners and could extend market penetration beyond high-mileage fleet vehicles to average mileage individual drivers.

Heavy-duty CNG vehicles (e.g. transit buses, urban delivery trucks) may also provide an attractive payback period for fleet owners. In total, the potential market for high-mileage fleet vehicles and heavy-duty vehicles that can operate on CNG is approximately 3.3 TCF of natural gas/year. Due to the long time period required for vehicle fleet turnover, it could take many decades for CNG vehicles to exploit a fraction of this potential market. Therefore, natural gas use as a transportation fuel, in the medium term, is expected to be modest. This use of natural gas in transportation is also beneficial, providing States with a readily available option to meet low carbon fuel standards and for urban fleets to reduce nitrogen oxide emissions.

With respect to long-haul LNG trucks, this thesis finds that while there is a large potential market for natural gas in the long-haul truck market, the present prospects for the use of LNG-powered long haul trucks appears quite limited. This is due to high incremental costs, unresolved operational issues, fueling infrastructure requirements, and reluctance of the trucking industry.

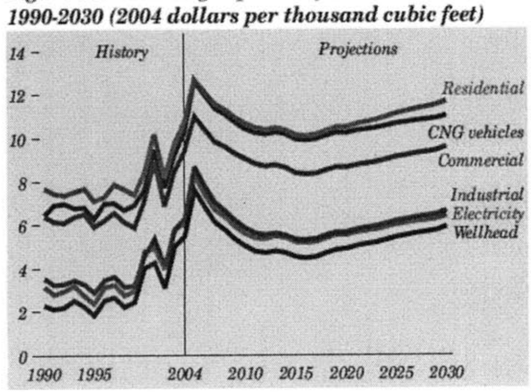
Appendix 1: Price of Natural Gas at the Wellhead and CNG as a Transportation Fuel Compared to the Price of Gasoline and Diesel

Between 2005 and 2008, the U.S. DOE's EIA's Annual Energy Outlook (AEO) reported the price of natural gas to different end use consumers including CNG as a transportation fuel. Note, in 2009 the AEO did not include this analysis. Figure A1-1 provides this analysis from AEO 2005 through 2008.

Figure A1-1. Natural Gas Prices for Different End Use Consumers from AEO 2005-2008 (DOE EIA 2005, DOE EIA 2006, DOE EIA 2007, DOE EIA 2008)

Delivered Natural Gas Prices Follow Trends in Wellhead Prices

Figure 76. Natural gas prices by end-use sector, 1990-2030 (2004 dollars per thousand cubic feet)



Delivered Prices Follow Projected Trends in Wellhead Prices

Figure 86. Natural gas prices by end-use sector, 1970-2025 (2003 dollars per thousand cubic feet)

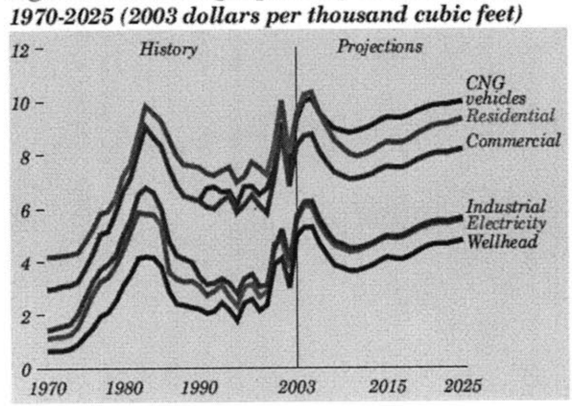
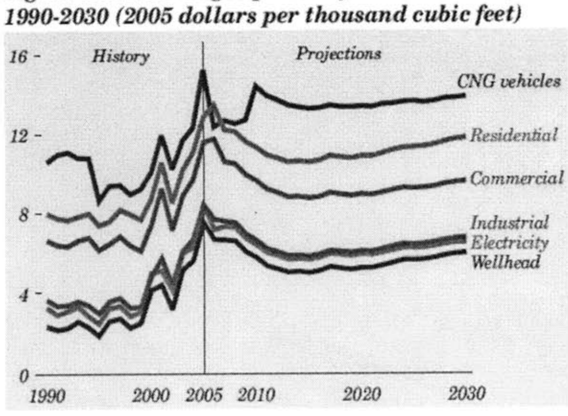
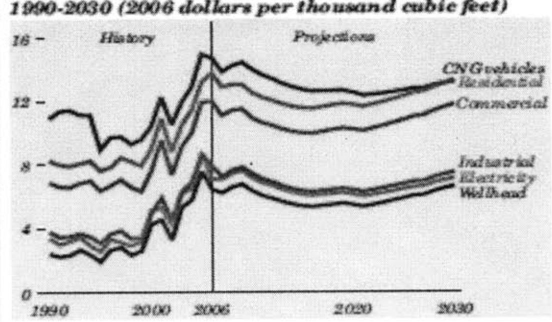


Figure 73. Natural gas prices by end-use sector, 1990-2030 (2005 dollars per thousand cubic feet)



Delivered Natural Gas Prices Follow Trends in Wellhead Prices

Figure 78. Natural gas prices by end-use sector, 1990-2030 (2006 dollars per thousand cubic feet)



The prices in Figure A1-1 include taxes, delivery, storage, and compression. In addition, all prices assume a vendor who must recover the capital and operating cost of the fueling infrastructure with the sale of CNG as a transportation fuel (TIAX, 2005).

From Figure A1-1, in AEO 2005 through 2008, the price of CNG as a transportation fuel has been consistently similar to the price of natural gas to residential consumers. Figure A1-2 provides the cost of natural gas per MMBTU (note: a MMBTU of natural gas is roughly equivalent to the energy content of 1000 ft^3 of natural gas). From Figure A1-2, the price of natural gas to residential consumers (and as CNG as a transportation fuel) is approximately two times greater than the wellhead price of natural gas.

Figure A1-2. Price of Natural Gas to End Use Consumers (DOE EIA, 2010)

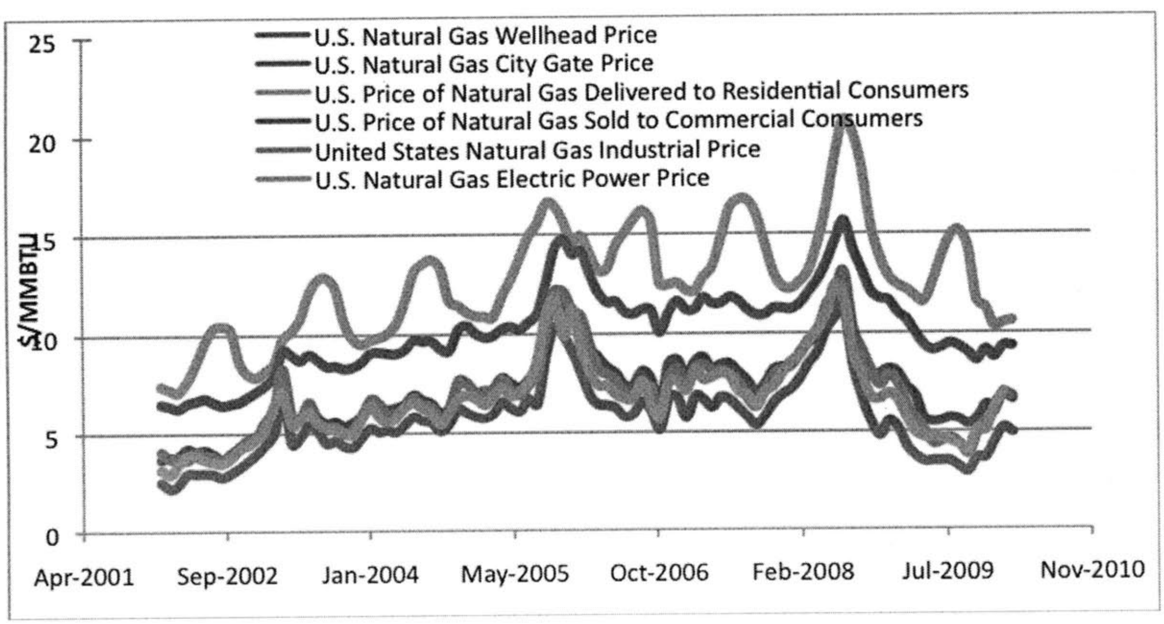


Figure A1-3 shows the relationship between the price of CNG as a transportation fuel (using residential fuel as a surrogate for price) compared to the price of gasoline on a gallon of gasoline equivalent unit.

Figure A1-3. Price of CNG (represented as NG residential price) vs. U.S. regulator gasoline price in Gallons of Gasoline Equivalent (2001-2009). US DOE EIA, 2009

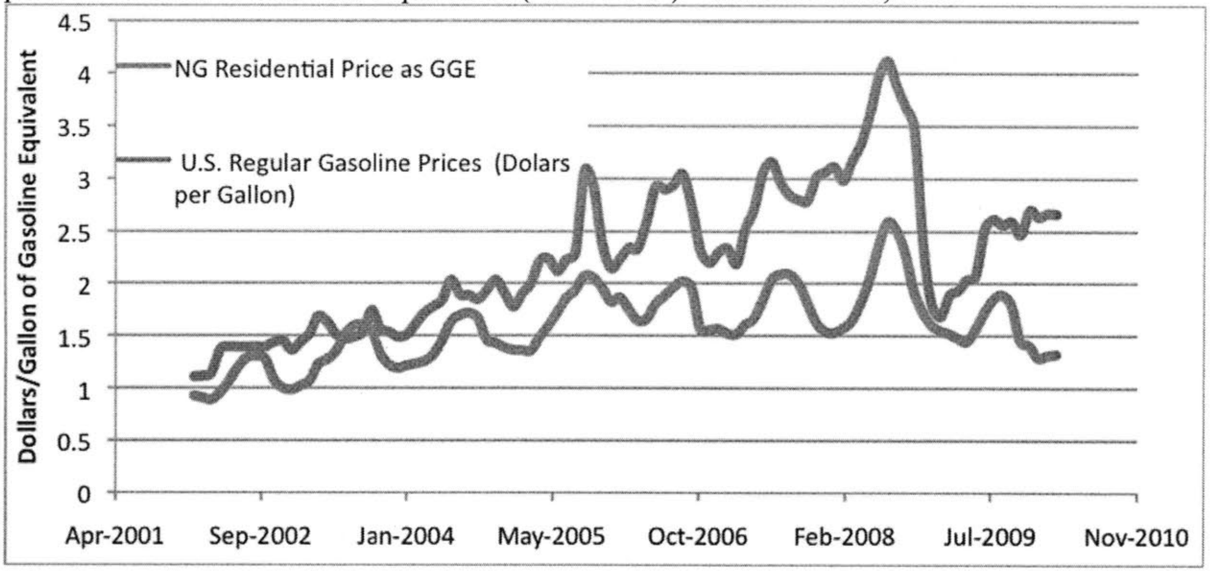


Figure A1-4. Histogram of Monthly Fuel Price Spread for Natural Gas on a Gallon of Gasoline Equivalent Basis

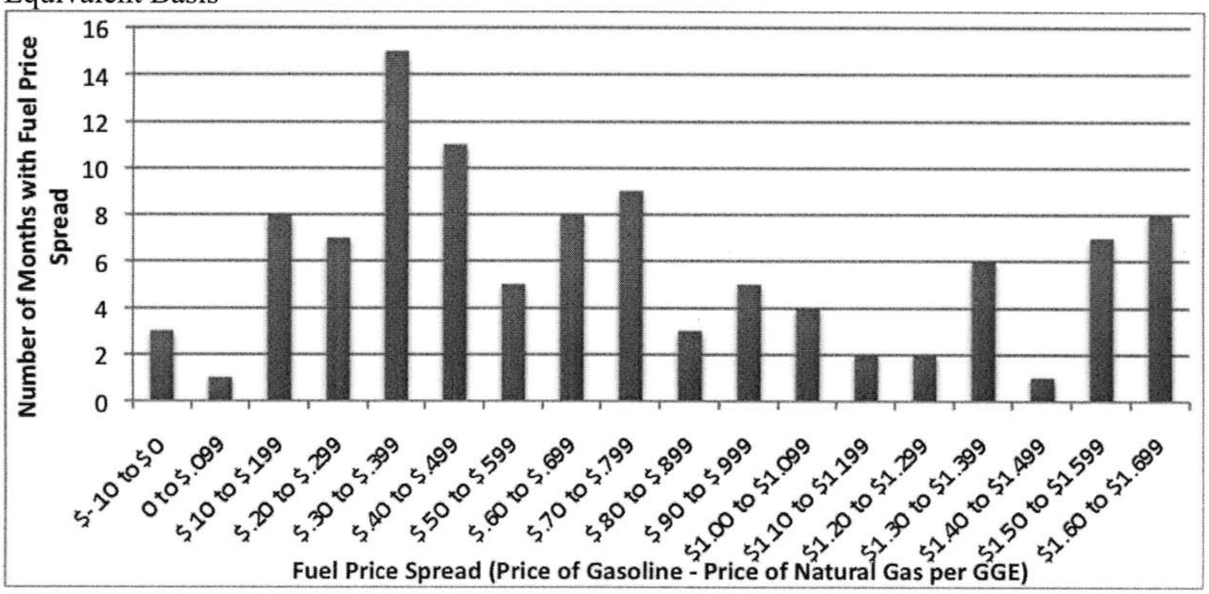


Figure A1-4 provides a histogram of monthly fuel price spreads between CNG as a transportation fuel and gasoline on an energy equivalent basis from 2001 to 2009. Over this time period, the price of CNG as a transportation fuel was less expensive than gasoline for all but three months. For 15 months, the price of CNG was at least $1.50 less expensive than gasoline on a gallon of gasoline equivalent basis. For the majority of time, the fuel price spread between natural gas and gasoline ranged from $.40 to $.60 per gallon of gasoline equivalent. Based on this information, throughout this thesis, I assume two fuel price scenarios – a low fuel price spread of $.50/GGE and a high fuel price spread of $1.50/GGE. The most recent fuel price spread included in the data was $1.30/GGE in February 2010 (with gasoline at $2.60/gallon and natural gas at $1.30 GGE).

Appendix 2: CNG vs. Natural Gas Produced Electricity as a Vehicle Fuel

Table A2-1 provides a comparison of CNG and natural gas produced electricity as a vehicle fuel using the most recent commodity prices from Appendix 1 (February 2010). In February 2010, the price of gasoline was $2.66/gallon, the price of CNG was $10.58/MMBTU, and the price of natural gas to electricity producers was $6.76/MMBTU.. The difference in price between CNG and natural gas to electricity producers is due to an increased need for transmission, distribution, and compression for CNG vehicle fuel compared to natural gas for electricity production.

However, the cost of electricity to the owner of an electrically powered vehicle is also increased because of transmission and distribution charges. These costs add around $.05/kWhr to the cost of around $ .06/Kwhr of electricity from the power plant (which includes capital depreciation and operating costs other than fuel). The cost of electricity to the vehicle owner from a natural gas powered plant is approximately $0.11/Kwhr. For a vehicle electricity use of 4000 kWhr/yr (corresponding to around 11 MMBTU of energy to the wheels which corresponds to around 55 MMBTU of fuel or around 400 gasoline equivalent gallons in an internal combustion engine vehicle at 20 % efficiency) , the electricity cost is around $ 440/yr. Table A2-1 also assumes the incremental cost of currently available CNG and PHEV vehicle technology (Honda GX CNG Vehicle with an incremental cost of $7,000 and the Chevy Volt PHEV with an incremental cost of $18,000). Table A2-1 also includes achievable lower incremental cost values (VW Passat TSI Eco-Fuel CNG vehicle with an incremental cost of $4,000 and a lower cost battery design that allows the PHEV vehicle to have an incremental cost of $10,000).

From Table A2-1, the PHEV has a higher incremental cost compared to the CNG vehicle due to the current high cost of battery technology. Table 1 shows that the yearly fuel cost of a PHEV (operating exclusively on electricity which in this case has a 40 mile range) is significantly lower than the fuel cost of a CNG vehicle. This is due to two reasons: 1) the feedstock natural gas to a electricity producer is less expensive than CNG at the pump and 2) natural gas is more efficiently used in a natural gas combined cycle plant (55% thermal efficiency) with transmission and distribution (90% efficiency) used in an electric engine (80% thermal efficiency) compared to CNG used in a spark-ignition internal combustion engine (20% thermal efficiency). This higher efficiency also results in lower CO_2 emission from a PHEV vehicle fueled by natural gas generated electricity (3 tons less CO_2 per year compared to a gasoline vehicle) compared to a CNG vehicle (1 ton less CO2 per year compared to a gasoline vehicle). But since the higher incremental cost of the PHEV, the marginal abatement cost for the PHEV is higher than the marginal abatement cost for the CNG vehicle. The CNG vehicle has a negative marginal abatement cost at current and future achievable incremental costs, while the PHEV has a significant marginal abatement cost at current incremental costs. Finally, both vehicles currently have payback periods that are significantly longer than the three-year payback that empirical work has determined is necessary for market penetration.

Table 1. *Illustrative Comparison of CNG Vehicles and Natural Gas Derived Electric Vehicles Vs. Gasoline Vehicles for an Average Driver (12,000 miles per year, 30 miles/GGE)*

	Gasoline	**CNG**	**Natural Gas Derived Electricity**
Range (% Compared to Gasoline)	1	0.25 [1]	0.1 [2]
Incremental Cost	N/A	\$4,000 to **\$7,000**[3]	\$10,000 to **18,000**[4]
Fuel Cost/Yr [5]	\$1,064	\$529	\$440
Fuel Cost Savings/Yr	N/A	\$535	\$624
Payback Time (Yrs)[6]		7.5 to 13	16 to 29
CO2 Reduction/Yr (tons)[7]		1	3 tons
CO2 Reduction/Vehicle Lifetime[8]		15 tons	45 tons
\$/ton of CO2 reduction[9]		\$-268 to **\$-68.3**	\$14 to **\$192** /ton
Fuel Infrastructure Change		Major	Modest Major

1. CNG has 25% of the energy content of gasoline (CNG 30K BTU/gallon vs. Gasoline ~120K BTU/gallon)
2. Electricity Vehicle Range is based on current 10kwH battery in Chevy Volt (~40 mile range)

3. \$7,000 CNG Vehicle represents current price of U.S. Honda GX and \$4,000 represents current price of European VW Passat TSI Eco-Fuel
4. Incremental Cost of natural gas electric vehicle based on projected cost of Chevy volt (\$18K) with assumption that the incremental cost can be reduced to \$10K within 5 years (Pearson and Turner, 2009).

5. Uses commodity prices from February 2010: gasoline (\$2.66/gallon), CNG at fuel pump (\$10.58/MMBTU), and electricity to wheels (\$17/MMBTU). Electricity values are calculated as follows. Natural Gas produced electricity costs approximately \$.06/kwh with a \$.05/kwh charge for transmission and distribution. For a vehicle electricity use of 4000 kWhr/yr (corresponding to around 11 MMBTU of energy to the wheels which corresponds to around 55 MMBTU of fuel or around 400 gasoline equivalent gallons in an internal combustion engine vehicle at 20 % efficiency), the electricity cost is around \$ 440/yr.

6. Payback period = Incremental Cost/Fuel Savings per year

7. Approximately 20 lbs of CO2 are emitted per gallon of gasoline *400 gallons per year = 8000 lbs/CO2 per (4 tons). Since natural gas has 25% less CO2 emissions than gasoline, there is a CO2 reduction of 1 ton per year. Natural gas combusted in a combined cycle natuarl gas plant has a high efficiency (55%) and after including transmission losses (10%) and electric vehicle engine efficiency (80%), the total efficience of using a electricity from a combined cycle natural gas plant is .55*.9.*8 = .4. This is twice as efficient as using CNG in a vehicle, therefore if CNG has .75 of the CO2 emissions of gasoline, then natural gas derived electricity has .75/2 or 38% of the gasoline CO2 emissions. 38% of 8 tons is 3 tons.

8. Assumes a vehicle lifetime of 15 years

9.Total Incremental Lifetime Cost of Vehicle/CO2 Reduction over Vehicle Lifetime. Where Total Incremental Cost of Vehicle is Total Incremental Cost of Vehicle - Fuel Price Savings Over Life of Vehicle.

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