

# Economic Implications of Natural Gas Vehicle Technology in U.S. Private Automobile Transportation

by

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B.S. Electrical Engineering  
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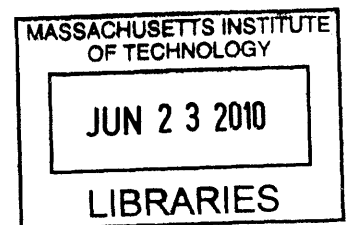
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## **Abstract**

Transportation represents almost 28 percent of the United States' energy demand. Approximately 95 percent of U.S. transportation utilizes petroleum, the majority of which is imported. With significant domestic conventional gas resources, optimistic projections of unconventional natural gas resources, and the growing international liquefied natural gas (LNG) market, gas prices are expected to remain lower than oil. While natural gas currently provides approximately 24 percent of the United States' energy consumption, there has been no significant growth in the natural gas vehicle market in the past fifteen years. Natural gas has comparative environmental advantages to gasoline and diesel, with lower CO<sub>2</sub> emissions per mega joule of fuel consumption. A natural gas powered vehicle fleet could reduce the country's fuel costs, dependence on imported fuel, and greenhouse gas emissions. To fully comprehend the future role of natural gas vehicles in the United States, all the major technological and market forces affecting the successful deployment of this vehicle technology must be analyzed interdependently under market and energy policy-regulated scenarios.

I investigate the potential role of natural gas in transportation using a computable general equilibrium (CGE) model of the global economy that is resolved for the US and other major countries and regions. To do so, I add a dedicated compressed natural gas (CNG) vehicle option to the Emissions Prediction and Policy Analysis (EPPA) Model as an option to the conventional internal combustion engine (ICE) vehicle. The model projects changing prices of fuel and other goods over time, given specification of resource availabilities. With the CNG vehicle specification I am able to evaluate the effect of the CNG option on transportation emissions, oil imports, natural gas use, and other economic indicators. I consider different policy scenarios for the future, including the adoption of a targeted emissions cap policy to see how that affects the competitiveness of CNG vehicles.

Several conclusions about the potential role of nature gas vehicles in the United States are drawn from this analysis. First, NG vehicles will reduce household transportation emissions in proportion to their share of the vehicle fleet. Second, stringent emissions policies will stimulate the penetration of natural gas vehicles, but high vehicle costs and infrastructure may hinder their deployment. There is a correlation between increased NG vehicle use and the reduction of oil imports. In the long term, development of cleaner alternative fuels with similar infrastructure to gasoline may hamper CNG vehicle growth.

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Teasel: Thanks for your help with everything. I've learned a lot. Yuma.

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# 1. INTRODUCTION

Private automobile use in the United States (U.S.) contributes to local pollution problems, greenhouse gas emissions, which play a role in climate change, and makes the country dependent on imported oil from unstable regions of the world. With a growing populace and the resulting increase of vehicle miles traveled, solutions for rising emissions and oil consumption associated with gasoline vehicles are becoming more urgent. This thesis focuses on the natural gas vehicle's potential to curb foreign oil consumption and related emissions in private household transportation. Natural gas vehicles (NG vehicles) utilize natural gas as a fuel replacement for refined oil. With its low carbon intensity and domestic availability, can natural gas offer a viable alternative or supplement to gasoline as a vehicle fuel?

While natural gas is available as liquefied natural gas (LNG) and compressed natural gas (CNG), this thesis will center on CNG vehicles, since most light-duty vehicles do not utilize LNG. CNG vehicles are available as dedicated (running on CNG only) or bi-fuel (running on CNG and gasoline). Despite the advantages of natural gas vehicles, this technology has not significantly penetrated the U.S. vehicle market. I will use the Emissions Prediction and Policy Analysis (EPPA) model to examine cost and policy scenarios that affect the penetration of NG vehicles in order to identify why and how this technology is adopted. I will also assess the resulting effects of NG vehicles on fuel consumption and greenhouse gas emissions.

With vast energy demand for transportation, concerns of energy security and greenhouse gas emissions, a solution to U.S. dependence on foreign gasoline needs to be found. Natural gas vehicles have been explored as a cleaner, less expensive alternative to

the U.S.'s reliance on oil for its transportation needs (Bandivadekar et al., 2008). The research presented in this thesis demonstrates that NG vehicles may only provide a suitable alternative to gasoline vehicles if the barriers that have so far limited their penetration can be overcome.

### ***1.1. Transportation in the U.S.***

Transportation accounts for a third of the nation's total energy consumption. The transportation sector is also responsible for 33 percent of carbon dioxide emissions in the U.S., which is primarily caused by fossil fuel combustion (EPA, 2009). According to the Environmental Protection Agency, the use of fossil fuel combustion was also responsible for 26 percent of methane (CH<sub>4</sub>) emissions and 67 percent of nitrous oxide (N<sub>2</sub>O) emissions in the transportation sector during 2008 (EPA, 2009). Most vehicle greenhouse gas emissions come from passenger vehicles and light duty trucks, which accounted for as much as 61 percent of transportation greenhouse gas (GHG) emissions in 2007, in part due to the petroleum combustion in these gasoline-fueled light duty vehicles (EIA, 2009).

The U.S. is the largest oil importer in the world, importing a significant amount from the Organization of the Petroleum Exporting Countries (OPEC). The use of an alternative domestic vehicle fuel would reduce the nation's foreign oil dependence. Most OPEC members are subject to geopolitical instability and often exercise oligopolistic market control. A combination of these circumstances may have contributed to a global oil crisis in the 1970s and most recently to price spikes in 2007 (Schafer, 2009).

Significant reduction in U.S. oil consumption will most likely come from the transportation sector (NPC, 2007). The solutions proffered to the transportation sector's

energy issues include improving fuel economy, reducing vehicle miles traveled (VMT) or switching to alternative fuels (Greene et al, 2003).

Until as recently as 2005, there had been a gradual decline in fuel economy (EPA, 2009(b)). Fuel economies for passenger cars and light trucks peaked at 29 miles per gallon (mpg) and 21 mpg in 1988 respectively. The lower CAFE standards for light trucks led to a surge in their popularity and a resulting lowered average of 24 mpg for vehicles sold by 2002 (Greene et al, 2003). By 2008, however, with the spike in oil prices, U.S. consumers responded with increased purchases of foreign cars with superior fuel economy. The lack of improvement in energy efficiency in U.S. automotive manufacturers' standards, combined with the spike in oil prices in 2008, and an economic recession may have contributed to the near collapse of the U.S. automotive industry. Furthermore, the United States' population growth also ensures that VMT will increase at an annual rate of 2 percent into the next decade. A 60 percent increase in VMT from 2005 to 2030 is projected, which implies that the reduction of miles traveled may not be the total solution for reducing energy usage in the transportation sector (DOT, 2008).

A possible solution to the transportation sector's emissions and oil consumption problems therefore lies in the development of an alternate transportation fuel, which pollutes less and is domestically sourced. An alternative energy source for passenger vehicles and light duty trucks has the potential to greatly reduce the United States' carbon emissions while simultaneously reducing the nation's reliance on foreign oil. There has been some recent success in emissions mitigation from transportation due to the introduction of ethanol (EIA, 2009).

This thesis focuses on natural gas vehicles because they have the potential to mitigate private transportation emissions and curb national dependence on foreign oil. A natural gas vehicle utilizes gas in conjunction with, or as a complete replacement for, gasoline in commonplace internal combustion engines (ICEs). The advantages of natural gas are great in comparison to the carbon intensity of standard gasoline-powered vehicles and lack of domestic oil availability. However, the lack of a robust NG vehicle refueling infrastructure and the unavailability of NG vehicles have proven problematic for the advancement of this technology. There is a limited range of NG vehicle models, with the most recently available model being the Honda Civic GX. Most vehicular innovation in recent years has focused on other technologies such as biodiesel, ethanol and electric hybrids.

### ***1.2. The Natural Gas Vehicle Option***

The implementation of natural gas vehicles is a possible solution to national energy concerns regarding energy security and the reduction of pollution from transportation. Despite being extremely price-volatile, natural gas is usually cheaper than other transportation fuels. According to the Environmental Protection Agency (EPA), compressed natural gas (CNG) vehicles can curtail greenhouse gas emissions by almost 29 percent. The CNG vehicle industry is also rewarded by fuel and infrastructural incentives from the Energy Policy Act. What combination of policy and vehicle pricing will facilitate a sustainable and competitive CNG vehicle industry? How will the proliferation of CNG vehicles affect emissions and fuel consumption?

Before further investment or support for natural gas vehicle technology is made, it is important to assess the resulting effects of the introduction of this technology. In order to

make this assessment, I will analyze several scenarios with varying vehicle costs and fuel availability under reference and emissions-restricted policy scenarios. These scenarios will provide market penetration and fuel consumption data that will prove useful for assessing the impact of natural gas vehicles.

This thesis builds on past natural gas vehicle work and methodology, which is reviewed in Chapter 1. While there are some general natural gas transportation models, there has not been a substantive analysis of natural gas vehicle promulgation under varying conditions of cost, resource availability and emissions policy. Chapter 2 of the thesis examines in more detail the attributes of the natural gas vehicle and compares them to other vehicle technologies. I will examine the domestic and global NG vehicle market, as well as assess the safety and policy issues that must be resolved to successfully advance NG vehicles. I will also gauge the availability of conventional and unconventional gas resources.

Chapter 3 explains the modeling system used to make my assessment. The EPPA modeling system components are explained, with a focus on the household transportation sector. The NG vehicle branch is added as a substitute for gasoline vehicles with estimates of annual vehicle expenditures.

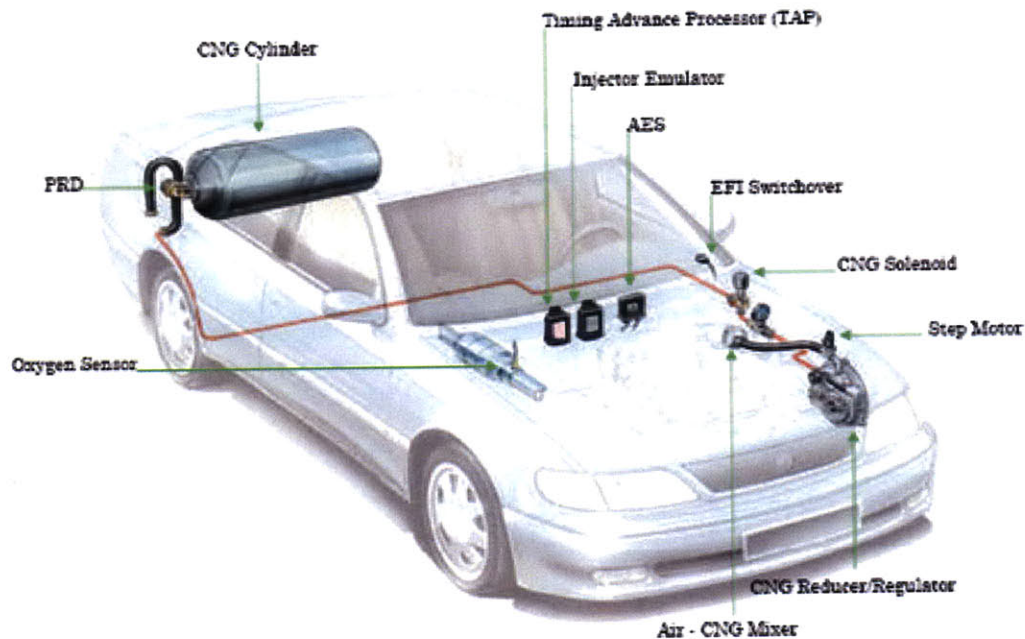
Chapter 4 introduces models of various policy and non-policy scenarios for natural gas vehicle penetration into the private transportation sector. I will assess how vehicle prices and fuel availability will affect the future of natural gas vehicles, and put dedicated NG vehicles in competition with alternate vehicle technologies such as electric hybrids. The various scenarios show the effects of natural gas vehicles on household



transportation emissions, gas consumption, fuel prices and oil imports. Chapter 5 concludes the paper with a summary of the previous chapter's results.

## 2. COMPRESSED NATURAL GAS (CNG) VEHICLES

This thesis is focused on light duty private household transportation, for this reason the compressed natural gas vehicle will be used for analysis.<sup>1</sup> Natural gas is compressed to less than 1 percent of its initial volume at atmospheric pressure of 200 bar and stored in a carbon fiber or steel tank (Engerer, Horn, 2009). Comprised mainly of methane (typically 97 to 99 percent), natural gas has lower carbon intensity and energy density than gasoline. While this means a larger volume of CNG is needed to drive the same distance as gasoline, it also means that CNG will produce less carbon dioxide emissions even with a higher level of fuel consumption. CNG vehicles are also able to operate at higher compression ratios, being more knock resistant than gasoline.



**Figure 1:** Components of a Bi-Fuel Compressed Natural Gas Vehicle

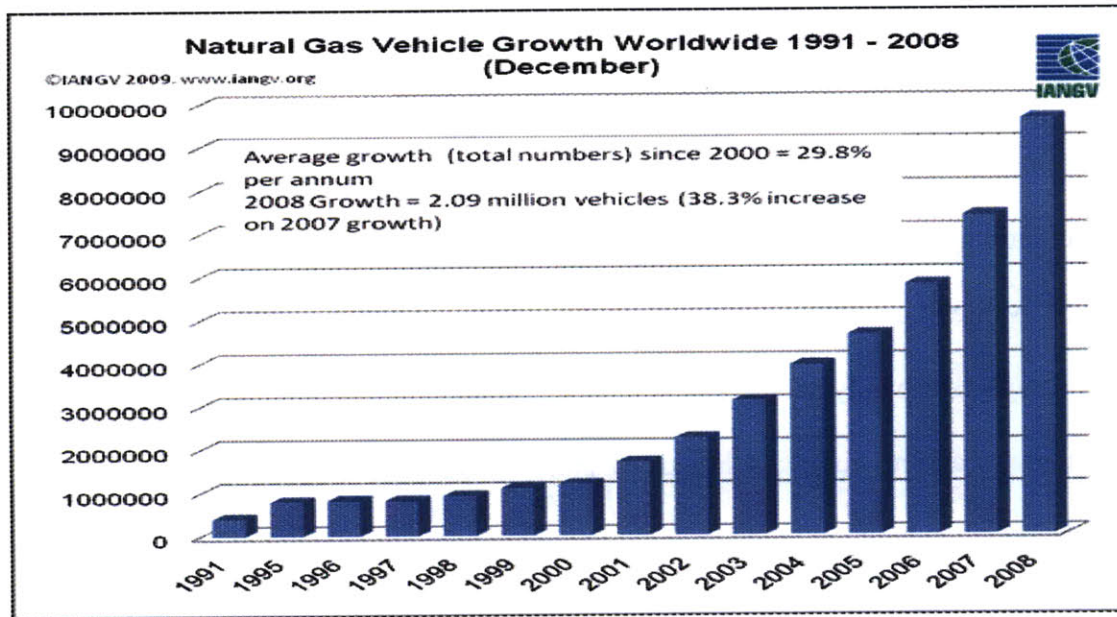
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<sup>1</sup> Liquefied Natural Gas (LNG) vehicle technology has been proposed mainly for the heavy duty transportation fleet, and is therefore less relevant to this study.

Figure 1 shows the typical components of a bi-fuel compressed natural gas vehicle. The CNG storage tank is kept in the trunk, with a timed solenoid that allows for transitions between gasoline and CNG. A separate Air-CNG mixer is used to maintain the air-fuel ratio needed for natural gas combustion.

CNG vehicles are available as dedicated, bi-fuel, and flex-fuel. Dedicated CNG vehicle engines use only natural gas as their fuel source. Bi-fuel engines operate on either natural gas or another fuel (gasoline or ethanol, for example), and are available either as aftermarket conversions or as original equipment manufacturer (OEM) vehicles. Dual-fuel or flexible fuel engines use a mixture of natural gas and diesel, with the share of natural gas between 0 to 80 percent. At lower engine loads, diesel use tends to be higher whereas at higher engine loads it is possible to use a larger proportion of gas. Dual-fuel engines are usually the result of a conversion of a diesel engine.

As illustrated in Figure 2, natural gas vehicles have seen remarkable growth around the world in the past two decades. With an annual growth of 30 percent within the last decade, the global natural gas vehicle fleet has increased tenfold (IANGV, 2009). It is important to assess the current and future positions of the U.S. in this burgeoning vehicle technology.



**Figure 2:** Natural Gas Vehicle Growth Worldwide (IANGV, 2009)

## ***2.1. Natural Gas as a Fuel***

Natural gas is an often-overlooked vehicle fuel alternative to gasoline and diesel. Initially considered a waste product of oil production and refining, natural gas has grown into a valuable globally traded commodity. Although natural gas vehicles were first used in Italy in the 1940s, they were used minimally until after the energy crisis in the 1970s. The escalating global oil prices in the 1970s caused international concern for energy security and led to the exploration and support of alternate vehicle fuel technology. There are significant benefits to natural gas vehicles including the reduction of vehicular pollution by switching to a less emissive fuel, abundance of domestic or nearby sources of natural gas, and a resulting reduction in foreign oil dependency (Yeh, 2007).

### ***2.1.1. Domestic Natural Gas Availability***

Although the U.S. is a net importer of natural gas, the majority of the natural gas used is produced domestically with supplemental pipeline imports from Canada and LNG

imports. In recent years there has been a ramping up of domestic natural gas production (EIA, 2009). Another significant development favoring domestic production is the advent of unconventional natural gas, which is comprised mainly of tight gas, coal-bed methane, and shale gas. Originally considered too expensive to produce on a large scale, new upstream extraction technologies such as horizontal drilling and hydraulic fracturing have drastically improved prospects for unconventional natural gas production.

Unconventional gas is estimated to account for almost 42 percent of all domestic gas production by 2010 (WoodMackenzie, 2006). Of all the types of unconventional gas, shale gas in particular has the most potential in the U.S., given the optimistic reserve estimates from the EIA and USGS. Significant new shale discoveries in Marcellus, Barnett and Uinta-Piceance basins bolster natural gas reserves and resources.

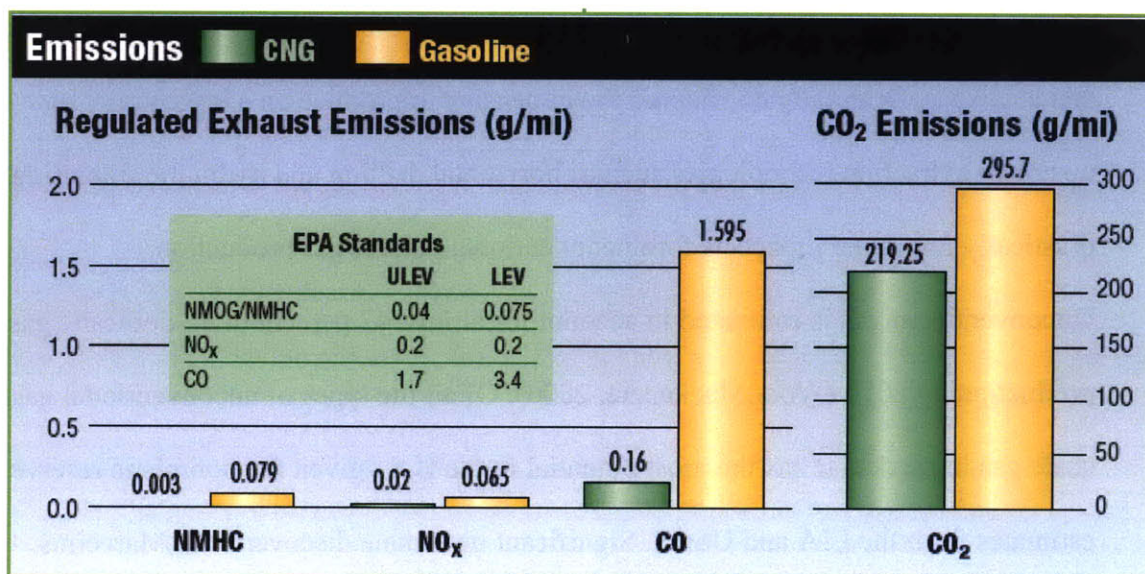
Finally, importation of LNG can augment U.S. gas supply. Three major LNG regasification terminals were completed in recent years, and there are new LNG sources in Africa and Europe. With the significant domestic conventional gas resources, prospects of unconventional gas, and an increasingly competitive global LNG market, natural gas can be viewed as the cheap and abundant fuel solution to significant energy and transportation needs.

### ***2.1.2. Emissions***

In the United States, the transportation sector is responsible for about a third of all carbon dioxide, nitrous dioxide, and non-methane volatile organic compound (NMVOC) emissions (EPA, 2009). Transportation also contributes to approximately 77 percent of carbon monoxide emissions and 45 percent of nitrogen oxide emissions. The majority of



these emissions comes from gasoline utilized in most of the 235 million passenger and light duty vehicles driven in the United States.



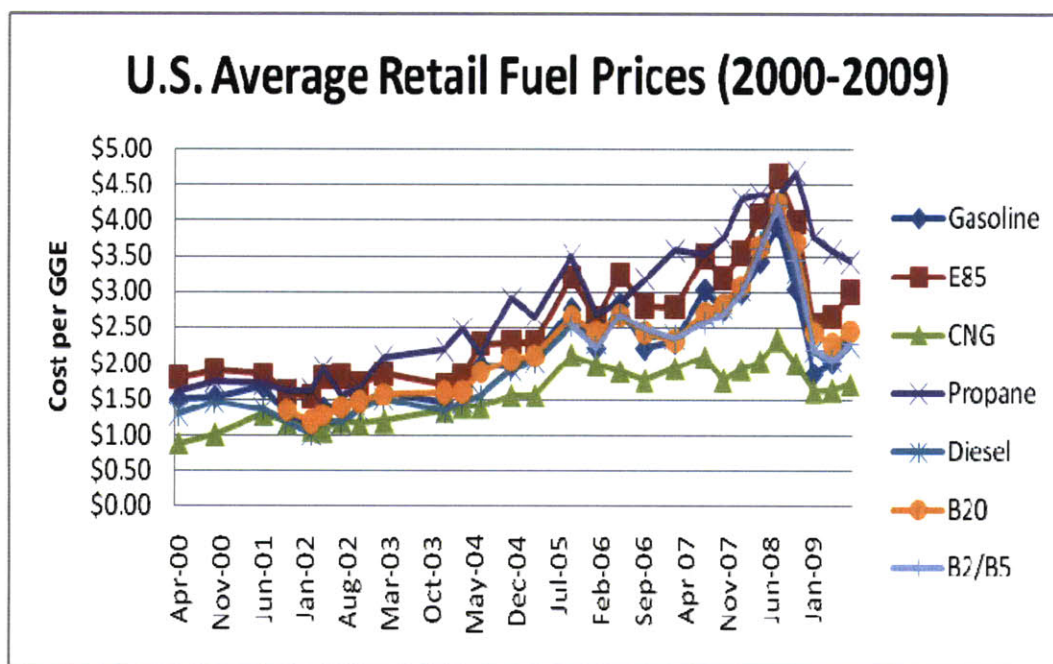
**Figure 3:** Emissions for CNG and Gasoline Vehicles (DOE, 2003)

According to DOE, CNG vehicles have 90 percent less carbon monoxide emissions, 25 percent less carbon dioxide emissions, 35 percent less nitrogen oxide emissions, and 75 percent less non-methane hydrocarbon emissions than gasoline vehicles (see Figure 3 above). CNG vehicles also emit fewer toxic and carcinogenic pollutants and drastically reduce particulate matter and evaporative emissions (EPA, 2002).

### **2.1.3. Economics of NG Vehicles: Fuel Prices & Vehicle Costs**

The allure of NG vehicles comes not only from emissions reduction and abundant supply, but also the relatively cheap price of CNG. As seen in Figure 4 below, it has typically been about 20 to 40 percent less costly than gasoline (per gallon of gasoline equivalent; or GGE) in the past decade and is also currently cheaper than all other alternative fuels, including: diesel, ethanol, propane and biodiesel (AFDC, 2009). Some of the competitiveness of CNG prices may be as a result of the seasonality of natural gas

use and its underutilization in the transportation sector. Is the development of a more concrete demand for natural gas in transportation going to result in higher prices or are volatile prices going to stunt the growth of the natural gas vehicle industry?

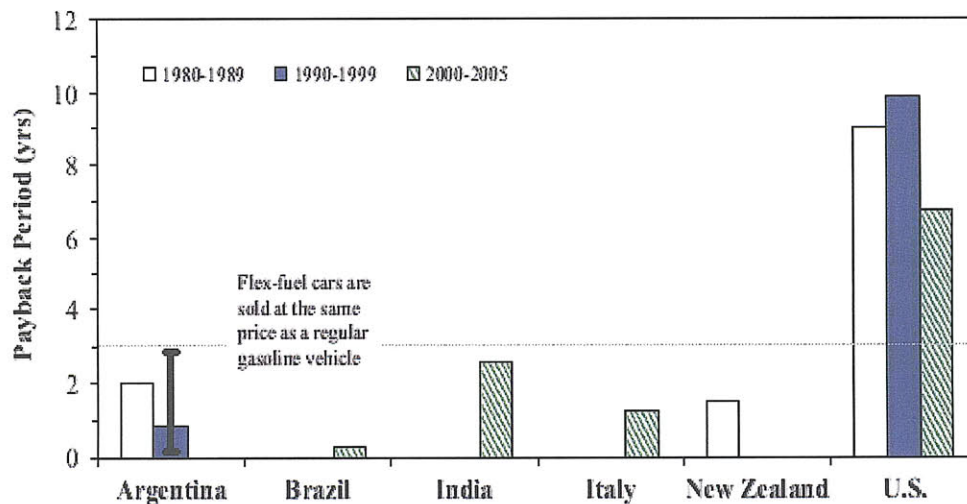


**Figure 4:** US Average Retail Fuel Prices in the U.S. (AFDC, 2009)

Despite their potential to save money on fuel expenditure, natural gas vehicles are expensive relative to gasoline vehicles. Incremental costs of new NG vehicles in the U.S. are currently more than \$6,000 higher than equivalent gasoline vehicles. Most of this cost is as a result of the expensive fuel storage tank required to store natural gas safely and effectively. In contrast, however, the average incremental cost of retrofitted or manufactured light duty natural gas vehicles outside the U.S. is between \$2,000 and \$4,000. NG vehicle conversions in the U.S. cost over \$10,000 due to a provision in the revised Clean Air Act, which lists any changes to the fuel system or engine of a vehicle as ‘tampering’. This prohibition requires all after-market NG vehicle conversions be

individually certified by EPA to ensure that emissions from the vehicle will not increase after the conversion is made. If this certification was not required, or a standard conversion could be approved, costs would be much lower, and might be similar to those outside the U.S.

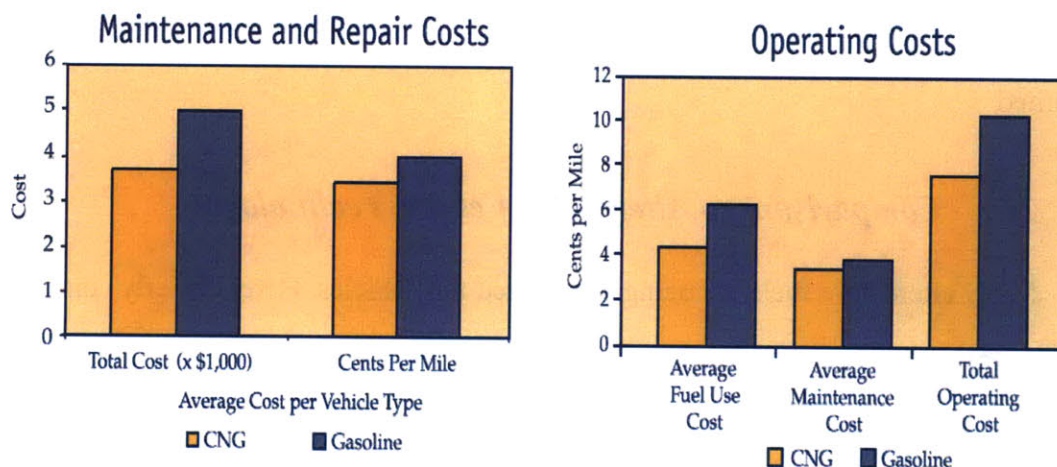
These upfront costs change the economics of NG vehicle, whether OEM or after-market conversion. A shorthand way to assess economics of an investment that saves money over time is to estimate the vehicle's payback period, which is the length of time it takes to amass savings on a cheaper fuel equal to the incremental cost of the natural gas vehicle. In this case: how long does it take for the 25 to 40 percent annual savings on fuel to fully recover the extra \$6,000 to \$10,000 spent on the alternative fuel vehicle? Studies suggest that most consumers want a payback period of less than 3 years for an investment in fuel economy (Yeh, 2007). Figure 5 shows the difference in payback periods in different parts of the world, reflective of the differences in incremental vehicle costs.



**Figure 5: Payback periods of NGVs (Yeh, 2007)**



Assuming an average of 15,000 miles traveled per year and an average fuel economy of 31 mpg for the Honda Civic, an optimistic estimate of yearly savings would be approximately \$300 (using an average of U.S. fuel prices from the year 2000 to 2009). With savings of 2 cents per mile, my estimated payback period will be 21 years for an incremental vehicle cost of \$6,000. It is clear that there is little economic incentive for purchasing NG vehicles in the US except where conditions vary considerably from this average. NG vehicles will only be selected if the difference in gasoline and CNG prices grows more significantly, or the consumer commutes appreciably more than the average U.S. VMT (e.g. commercial taxis travel as much as 52,000 miles per year).



**Figure 6:** Total Operating Costs for CNG and Gasoline Vehicles (DOE, 1999)

Figure 6 shows the comparative costs of gasoline and CNG vehicles, based on the Barwood Cab Fleet study conducted by the National Renewable Energy Laboratory (NREL) of the Department of Energy. The study was conducted on 10 dedicated CNG and 10 gasoline-only 1996 Ford Crown Victoria sedan taxicabs, assuming fuel costs of \$0.75/gge for CNG and \$1.10/gge for gasoline (DOE, 1999). No carbon dioxide price was used in this study. While taxicabs typically travel greater distances and require more

maintenance than average household vehicles, a relative cost analysis of the study highlights NG vehicles' advantages over their gasoline counterparts. NG vehicle owners spend less on maintenance and repair because NG vehicle engines are more knock resistant than gasoline engines (as a result of the difference in compression ratios). In summary, the total operating cost for a CNG vehicle is approximately 25 percent less than the operating cost of a gasoline vehicle. This operating cost difference will be used later in the EPPA model analysis.

Though NG vehicle owners spend less on operating costs, the upfront cost of this technology may still dissuade consumers. Without regularizing the conversion costs to avoid costly individual certification, or monetizing the environmental and security costs in fuels to produce a level playing field for CNG, the competitiveness of NG vehicles is limited.

## ***2.2. Comparisons to Alternative Vehicle Technologies***

Many alternative fuels are being considered for vehicles. Here, I briefly compare some of the main advantages and disadvantages of these alternative fuel options. Alternative fuel vehicles offer the potential for significant greenhouse gas emissions reduction, however, they have some disadvantages relative to gasoline vehicle counterparts, such as smaller trunk space (due to large fuel storage tanks), shorter driving ranges as a result of lower fuel density, and fewer refueling outlets (EIA, 1996).

Ethanol vehicle technology has undergone rapid development in recent years, and provides potential for GHG reduction, but it still offers a number of challenges. There are land issues associated with ethanol, because it requires almost 300 to 500 million hectares (or 17 to 28 percent of the entire land area of the lower 48 states) to produce enough

ethanol for the entire U.S. light duty fleet at current fuel efficiency (Lave et al., 2001). The significant amount of waste that is generated from bio-fuel production and the typically higher prices for bio-fuel technology make it a problematic alternative to gasoline. There are also unintended consequences of increased bio-fuel development that may contribute to greenhouse gas emissions, such as the intensified use of fertilizers and pesticides (Melillo, 2009).

Hydrogen fuel cell technology can reduce energy use by 15 percent when compared to gasoline engines and almost completely eliminate GHG emissions if feed-stocks are not carbon-based, but like bio-fuels, the use of hydrogen fuel cell technology has drawbacks. Emissions of hydrogen fuel consist mostly of water vapor, and the cost of fuel is projected to be cheaper than gasoline if produced efficiently (EIA, 2008). However, hydrogen fuel vehicles have problems with on-board energy storage. In order for current compressed hydrogen tanks to store the same amount of energy as gasoline they usually have to be about ten times larger and nearly four times heavier (Greene et al, 2003).

Electric vehicles offer a third alternative to gasoline consumption but in addition to having energy storage issues associated with battery use, this technology has its own set of limitations (Karplus, 2008). Despite little to no vehicle emissions from vehicle operations, electric vehicles rely on U.S. electricity production and current U.S. electricity production relies mainly on fossil fuels such as coal. The utilization of such fossil fuels for electricity generation is projected to continue well into the near future, making electric and hybrid vehicles somewhat disadvantageous to CNG and gasoline vehicles, according to the National Academy of Sciences (NAS, 2009). There are also

problems associated with the production, lifecycle and disposal of batteries used in electrical vehicles.

Natural gas vehicles are a relatively mature vehicle technology compared to hydrogen, ethanol, and plug-in hybrid vehicles. In contrast to a lean-burn gasoline engine producing the same power, engines designed specifically for alcohol fuels or CNG offer 10 percent higher energy efficiency (Greene et al, 2003). To highlight the differences between gasoline and CNG, I summarize two separate comparisons of light duty gasoline vehicles and their corresponding CNG vehicle counterparts at various points in time. In 1999, the DOE's Clean Cities compared the dedicated CNG model of the Ford Crown Victoria to its gasoline model to assess their similarities and differences (DOE, 1999). In EIA, the 2009 Annual Energy Outlook compares the Honda Civic gasoline and CNG vehicles. These studies revealed that although the cost and fuel capacity of CNG vehicles could be improved upon, the compression ratios and fuel economies of these vehicles make CNG a competitive alternative to gasoline. In the U.S., CNG vehicles have typically cost 10 to 40 percent more than gasoline vehicles. Additional costs are typically due to the specialized tanks required for CNG storage. For example, the Honda Civic GX costs approximately \$6,500 more than its gasoline counterpart, 35 percent more than its gasoline counterparts (As seen in Table 1). Because of the relative density of natural gas and size of CNG storage containers, CNG vehicles typically have 40 to 50 percent less fuel storage capacity per gallon (resulting in a much shorter refueling range of about 220 miles).

Both the Ford Crown Victoria and the Honda Civic have comparative compression ratios and fuel economies, with only about 20 percent less torque and horsepower than

gasoline vehicles. Although natural gas vehicles have a high octane rating of 130, the NG vehicle horsepower and torque are reduced by the rate at which natural gas can be injected into the piston cylinders because of its lower energy density (EIA, 2009). Table 1 shows a comparison of gasoline and dedicated CNG versions of the commercially available Honda Civic.

|  | 2009 Honda Civic |        |     | 1996 Ford Crown Victoria |        |     |
|--|------------------|--------|-----|--------------------------|--------|-----|
|  | Gasoline         | CNG    | %   | Gasoline                 | CNG    | %   |
| <b>Vehicle Price</b><br>( <b>\$</b> )  | 18,855           | 25,190 | 34  | 19,850                   | 21,930 | 10  |
| <b>Fuel Tank Capacity</b><br>(gallons) | 20               | 10     | -39 | 20                       | 10     | -50 |
| <b>Passenger Space</b><br>(cubic ft)   | 91               | 91     | 0   | -                        | -      | -   |
| <b>Cargo Space</b><br>(cubic ft)       | 12               | 6      | -50 | 21                       | 14     | -32 |
| <b>Horsepower</b><br>(at 6,300 rpm)    | 140              | 113    | -19 | -                        | -      | -   |
| <b>Torque</b><br>(at 4,300 rpm)        | 128              | 109    | -15 | -                        | -      | -   |
| <b>Fuel Economy</b><br>(mpg)           | 31               | 30     | -3  | 21                       | 21     | 0   |
| <b>Curb Weight</b><br>(lb)             | 2,754            | 2,910  | 6   | 3,780                    | 3,814  | 1   |

**Table 1:** Comparisons of Gasoline Vehicles and CNG Vehicles (EIA, 2009; DOE, 1999)

### ***2.3. Natural Gas Vehicles Outside the US***

Natural gas vehicles have had varied degrees of acceptance and implementation around the world, with equally varied policies assisting or impeding their market penetration. The push for NG vehicles has historically been motivated by a combination of the quest for oil independence, and more recently green house gas and conventional pollutant emissions. Early efforts to promote NG vehicles slowed down shortly after the



oil crisis in the 1970s (Yeh, 2007). Starting in the 1990s, renewed environmental and energy security concerns led to a rapid resurgence of NG vehicles around the world.

Figure 7 shows the growth in the number of NG vehicles in various continents over the past two decades.

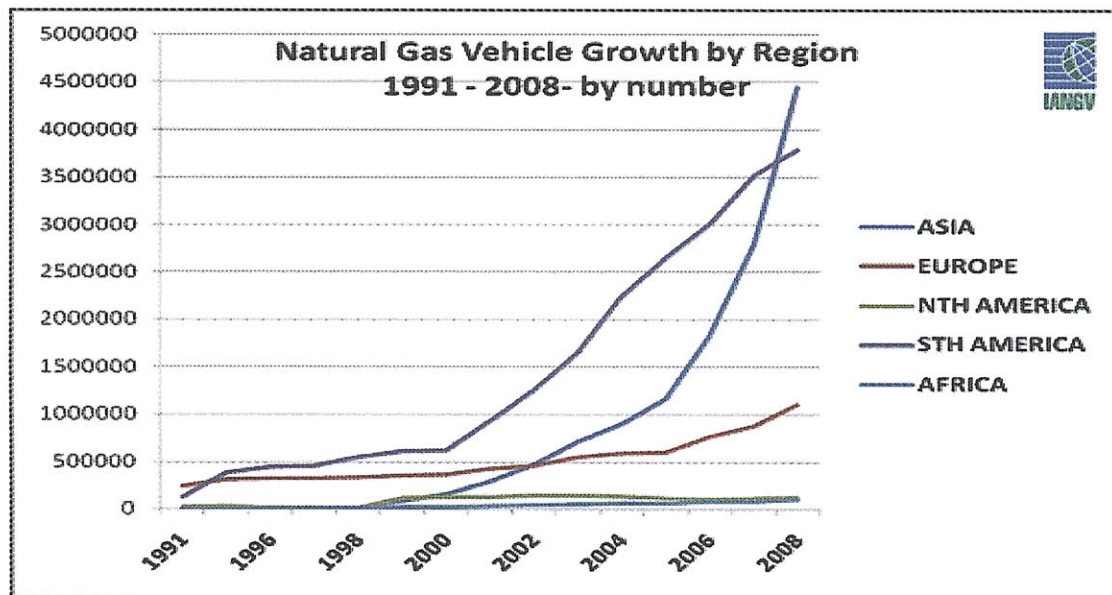


Figure 7: Natural Gas Vehicle Growth by Region (IANGV, 2009)

South American countries, such as Brazil and Argentina, used aggressive government promotion of indigenous natural gas to replace gasoline and diesel in vehicles (Yeh, 2007). Argentina, for example, instituted a high gasoline tax to incentivize the use of natural gas over other fuels (World Bank, 2001). These two countries currently account for more than a third of the world's natural gas vehicles (IANGV, 2009).

Asian countries, such as India, Pakistan and China, are also seeing a very rapid growth in their NG vehicle market despite a limited domestic natural gas supply. Motivated by a 1985 civil lawsuit decrying air pollution, the Indian government issued a ban on diesel-powered transportation and implemented CNG vehicles in 1998 (Dursbeck

et al, 2001). China's escalating energy demand and environmental concerns have spurred the growth of its natural gas vehicle market. For example, the Beijing Transportation Authority committed to replacing 90 percent of its fleet with CNG vehicles before 2008, and other major Chinese cities have followed suit (Yeh, 2007). Despite the rapid growth in their vehicle markets, NG vehicle development in Asia has been unfortunately characterized by substandard vehicle conversions and an underdeveloped refueling infrastructure, which has resulted in methane leakage, safety concerns, and long waiting lines at fuel stations (World Bank, 2001; Yeh, 2007).

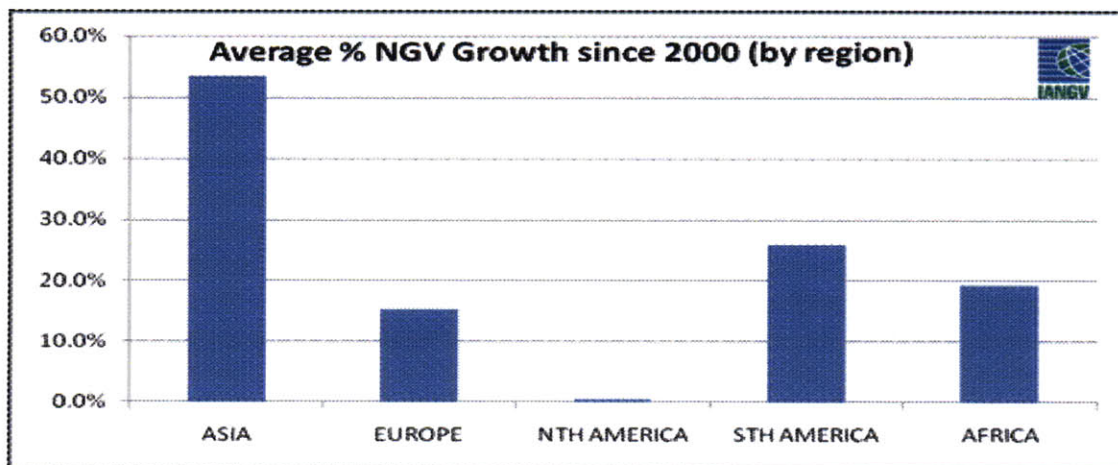
Europe has not had significant success with CNG vehicles, despite Italy pioneering CNG vehicle technology. The transportation debate in Europe is currently centered on electric and biodiesel vehicles, with little to no policy incentivizing NG vehicles (Engerer, et al., 2009). A lack of infrastructure, combined with a limited natural gas supply and myriad transportation options may limit the growth of NG vehicles in Europe.

Africa has experienced a high NG vehicle growth rate in recent years, despite having a relatively small number of NG vehicles. At its current annual NG vehicle growth rate of 20 percent, Africa is poised to overtake the number of NG vehicles in North America by 2015 (IANGV, 2009). The lack of a pre-existing transportation may prove beneficial to Africa's development of NG vehicles. Most vehicular technology in Africa is imported and pre-owned, so the growth of the NG vehicle industry in the continent will most likely be concurrent with the growth of NG in more developed regions.

#### ***2.4. History & Policy of Natural Gas Vehicles in the US***

There are approximately 120,000 natural gas vehicles and 778 natural gas refueling stations in the United States. Government policies in the 1990s, which incentivized or

mandated the use of NG vehicles in government and commercial fleets, spurred the growth of the U.S. natural gas vehicle usage. Significant growth followed for the rest of the 1990s, but the lack of refueling infrastructure and limited vehicle availability proved detrimental to the large-scale adoption of NG vehicles. In relation to the rest of the world, NG vehicle growth has been constrained in the U.S. over the past decade in large part because of the popularity of other alternative fuel vehicle options like ethanol and electric hybrids. Figure 8 shows the average growth rate in different regions of the world over the past decade. Currently there is only one dedicated NG vehicle production model available in the U.S., the Honda Civic GX. Other automobile manufacturers in the U.S. have drastically reduced production of their natural gas fleet, with a few vehicle models qualifying for retrofitting as bi-fuel CNG vehicles.



**Figure 8:** Average NG Vehicle Growth (IANGV, 2008)

The Clean Fuel Vehicle provisions of the Clean Air Act of 1990 (CAA), a revision of the initial 1970 Act, set the stage for "clean alternative fuels" from natural gas (such as compressed natural gas, liquefied natural gas, methanol, and liquefied petroleum gas) to



reduce air pollution and delegated states to implement their own pollution reduction strategies. The 1988 Alternative Motor Fuels Act established incentives for alternative vehicle manufacturers by allowing these vehicles to count towards CAFE credits. Dedicated and bi-fuel NG vehicles were allowed up to 1.2 mpg credit for model years 1993 through 2004 under this policy. While alternative vehicles did not become a major share of new vehicles sold, automobile manufacturers such as Ford and Chrysler took advantage of the incentives and increased their production of bi-fuel vehicles.

The Energy Policy Act of 1992 (EPAAct 1992), adopted immediately after the conflict in the Persian Gulf, emphasized energy security and the reduction of foreign oil consumption by adopting initiatives such as the Clean Cities program. The EPAAct promoted alternative-fuel vehicles (AFVs) by mandating steady annual increases in the proportion of AFVs used in federal and state government fleets, the objective being to increase alternative fuel use by 10 percent per year relative to the previous year. Under the Safe, Accountable, Flexible, Efficient Transportation Equity Act (SAFETEA) of 2005, the Alternative Fuel Excise Tax Credit was established. A tax credit in the amount of \$0.50 per gallon of gasoline equivalent is allotted to alternative fuel vehicle users.

The more detailed Energy Policy Act (EPAAct) of 2005 called for the development of grant programs, reports and test initiatives, and specific tax incentives that promoted the production and use of AFVs. EPAAct 2005 also amended existing regulations, including fuel economy testing procedures and EPAAct 1992 requirements for federal, state, and alternative fuel provider fleets. An Alternative Motor Vehicle Credit was established, providing a tax credit of up to 50 percent of the incremental cost of the vehicle to purchasers of new dedicated AFVs (approximately \$2,500 to \$5,000 for dedicated light

duty vehicles). The development of supporting alternative infrastructure was also incentivized, with the creation of an Alternative Fuel Infrastructure Tax Credit, which provided a tax credit of 30 percent of a maximum of \$30,000 of the cost of the alternative refueling property.

The Energy Independence and Security Act (EISA) of 2007 instituted a ban on federal fleet acquisitions that were not low-GHG emitters, and extended bi-fuel CAFE credits to 2020. The act also focused on informing the public on the array of alternative vehicle options available to them. The American Recovery and Reinvestment Act of 2009 resulted in nearly \$300 million toward competitive grants for state and local government AFV projects, and an increase in the Alternative Fuel Infrastructure Tax credit to a coverage of 50 percent of a maximum of \$50,000 of the cost alternative refueling property.

Currently, there is a proposed bill that will further benefit NG vehicles if passed: the New Alternative Transportation to Give Americans Solutions Act of 2009 (NATGAS Act 2009). This bill will extend the previously established alternative fuel and fuel infrastructure tax credit deadlines from 2020 to 2027, allow an income tax credit through 2027 for alternative fuel motor vehicles powered by CNG or LNG, and require half of all new vehicles purchased or placed in service by the U.S. government by 2014 to be capable of operating on CNG or LNG. It will also establish a new tax credit for the production of NG vehicles. This policy is currently under review by the Subcommittee on Energy and Environment.

## ***2.5. Central Issues affecting NG Vehicle Implementation***

Despite their potential to solve some of the transportation problems in the U.S., their widespread adoption of NG vehicles may prove difficult. Since their introduction into government and public transportation fleets in the early 1990s, NG vehicles have failed to account for a substantial share of household transportation in the United States. In comparison, NG vehicles have seen a dramatic rise in every other part of the world, and this rise has led to a reduction in vehicle emissions. While natural gas has infiltrated the power industry as a successful option, the penetration of natural gas vehicles into the transportation sector has proved elusive. In addition to high incremental OEM vehicle costs and costs of conversion, some of the relevant concerns or issues that may affect natural gas vehicle market penetration are discussed below.

### ***2.5.1. Refueling Infrastructure***

The potential demand for alternative vehicles is strongly dependent on refueling infrastructure. Without further expansions of the natural gas service station network, conventional vehicle technology will dominate road transportation well into the future (Achtnicht, et al., 2008). As discussed previously, NG vehicle fuel tanks can carry significantly less fuel than their gasoline counterparts (because of their higher storage density). The NG vehicle's limited fuel tank capacity results in shorter driving ranges, which necessitates a significant investment in developing a greater number of refueling stations. Fuel distributors are reluctant to build fueling stations until there are more NG vehicles on the road, and consumers will not purchase NG vehicles until there is a significant refueling infrastructure in place, a predicament that has been referred to as a 'chicken-egg' problem (EIA, 2009). In the United States there are currently 776 CNG refueling stations compared to the approximately 164,000 conventional refueling stations,

a ratio of less than 0.5 percent (Davis, et al., 2009). Studies have shown that a minimum ratio of 10 to 20 percent between CNG and conventional stations is necessary for the success of alternative fuel vehicles (Greene, 1997). CNG stations are also relatively expensive; the installation cost for an initial outlet ranges from \$250,000 to \$500,000 (DOT, 2002). Despite supportive initiatives from individual states such as California and Utah, the number of natural gas refueling stations continues to decline and is insufficient for the widespread adoption of NG vehicles.

#### ***2.5.2. Public Perception***

According to surveys conducted between 2002 and 2005 by the National Renewable Energy Laboratory (NREL), the general public is sufficiently informed about environmental and energy dependence concerns, however, consumers seem misinformed about all the alternative fuel technology options. While most people are knowledgeable about hybrids and ethanol vehicles, only 3 percent would favor natural gas as a replacement to gasoline and diesel (NREL, 2006).

The general public is willing to spend up to \$4,000 on effective alternative fuel technology, but most would prefer a payback of less than 3 years. Consumers are also willing to pay money towards the development of alternative fuel technology and many of them would switch to new technologies if the infrastructure improves (Achtnicht et al., 2008). The lack of availability and publicity behind natural gas vehicles may prove detrimental to their short-term market penetration. There is currently only one Original Equipment Manufacturer (OEM) of dedicated CNG vehicles, the Honda Civic GX. Several other automakers (such as Ford, Chevrolet, GMC, Isuzu, Lincoln, Mercury, and Hummer) have dedicated and bi-fuel CNG conversions available for retrofitting through

the qualified system retrofitters (QSRs). Publicity for these vehicles, in comparison with hybrid electric vehicles, has been minimal.

### **2.5.3. Safety**

NG vehicle technology has been around for decades, but the limited available information about these vehicles has prompted safety concerns among the general public. Since it is a combustible fuel, primary concerns about natural gas focus on its combustibility and the potential for explosion. According to the DOE (2008), CNG vehicles are as safe as, or safer than, gasoline vehicles. While natural gas has no distinct smell, an odorant has been added to the fuel so leakage is detectable at fuel-air mixture rates as low as 0.3 percent. The range of flammability for natural gas when mixed with air is between concentrations of 5 to 15 percent. Other fuels, such as diesel and gasoline, burn at lower concentrations and temperatures (CVEF, 1999). Natural gas is lighter than air, so natural gas evaporates quickly instead of collecting in liquid form, which eliminates ground or water pollution.

Although CNG storage steel tanks have to be pressurized at up to 3600 psi, they are thicker and stronger than gasoline and diesel tanks, and must undergo more rigorous industry and government safety testing standards (NHTSA, 2003). An extensive national underground pipeline infrastructure will almost eliminate the leakage associated with road transportation of natural gas (See Appendix 1). NG vehicle fleets have also been proven to have a vehicle injury rate of 37 percent less than gasoline vehicles (CVEF, 1999). The California Air Resource Board (CARB) and EPA have also established stringent standards for CNG vehicle conversion systems, making it illegal to install or use non-certified aftermarket conversion systems. With a CNG conversion certifications

costing up to \$10,000, the safety standards may prove to be more of a hindrance to NG vehicles in the U.S.

Despite the potential for reduction of GHG emissions with CNG vehicles, the gaseous nature of compressed natural gas and the possibility of leakage (typical rates of up to 1% of the fuel) are somewhat problematic (Greene et al, 2003). Methane is a greenhouse gas itself, with global warming potential 21 times greater than carbon dioxide over a period of 100 years (Greene et al, 2003). If the methane leakage is severe, it may undermine or offset the carbon dioxide reductions achieved by switching to CNG vehicles. However, the methane in exhaust can be reduced by 80 percent with the use of effective albeit somewhat expensive methane catalysts (Hellman, et al., 1994). Since natural gas is lighter than air, leakages in enclosed areas may accumulate natural gas and pose a potential fire or asphyxiation hazard. According to the National Fire Protection Association (NFPA), proper ventilation is compulsory for enclosed structures such as tunnels and parking garages (NFPA, 2000).

### **3. NATURAL GAS VEHICLES IN THE EPPA MODEL**

Before further investment or support for natural gas vehicle technology is made, it is important to assess the resulting effects of the introduction of this technology. There are other models such as Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, the Energy use in Transportation (GREET) model, and the EIA's Transportation Module in the National Energy Modeling System (NEMS) which have done some NG vehicle analysis. The GREET model accurately models GHG emissions and fuel consumption, and the Alternative Vehicle Sub-module of EIA's NEMS Transportation module captures market penetration and fuel prices (EIA, 2009). I will incorporate select components of these models to provide a thorough analysis of the potential and effects of NG vehicles in U.S. private transportation. The Emissions Prediction and Policy Analysis (EPPA) model will be used for this paper to assess the effects of vehicle costs and fuel availability on the promulgation of NG vehicles, and to determine the role of emissions targets and alternate fuel options on fuel consumption and petroleum imports. This chapter describes the EPPA model, and the modifications I have made to the system for the purpose of natural gas vehicle modeling.

#### ***3.1. Background on the EPPA Model***

The Emissions Prediction and Policy Analysis (EPPA) model is a recursive-dynamic general equilibrium model of the world economy designed by the MIT Joint Program on the Science and Policy of Global Change, to develop projections of economic growth and anthropogenic emissions of GHGs and aerosols (Paltsev et al., 2005). The EPPA model is built using the GTAP dataset (Hertel, 1997; Dimaranan and McDougall, 2002), and

additional data from the EPA for greenhouse gases and air pollutants. The GTAP dataset is aggregated into 16 regions and 23 sectors (see Table 2).

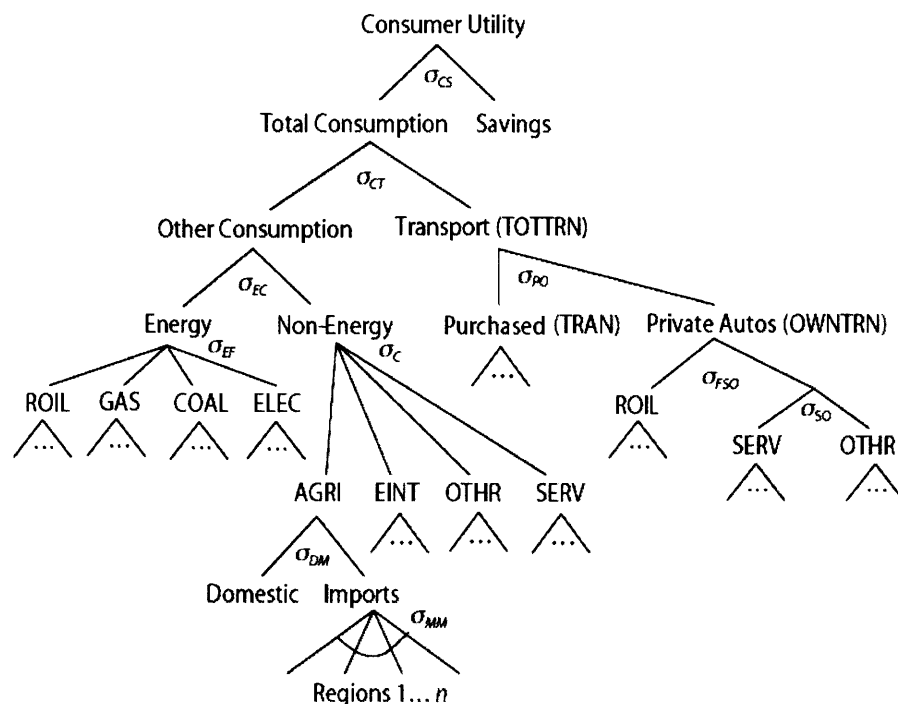
| SECTORS:  | COUNTRIES OR REGIONS:   |
|---|---|
| <b><i>Non-Energy</i></b><br>Agriculture<br>Services<br>Energy-Intensive Products<br>Other Industries Products<br>Transportation<br>Household Transportation   | <b><i>Developed</i></b><br>USA<br>Canada<br>Japan<br>European Union+<br>Australia & New Zealand<br>Soviet Union<br>Eastern Europe                   |
| <b><i>Energy</i></b><br>Coal<br>Crude Oil<br>Refined Oil<br>Natural Gas<br>Electric: Fossil<br>Electric: Hydro<br>Electric: Nuclear<br>Electric: Solar and Wind<br>Electric: Biomass<br>Electric: Gas Combined Cycle<br>Electric: Gas Combined Cycle with CCS<br>Electric: Coal Gasification with CCS<br>Synthetic Gas<br>Hydrogen from Coal<br>Hydrogen from Gas<br>Oil from Shale<br>Liquid Fuel from Biomass | <b><i>Developing</i></b><br>India<br>China<br>Indonesia<br>East Asia<br>Mexico<br>Central & South America<br>Middle East<br>Africa<br>Rest of World |

**Table 2:** Sectors and regions in the EPPA model

The model is calibrated based upon data organized into social accounting matrices (SAM) that include quantities demanded and trade flows in a base year (1997) denominated in both physical quantities and value terms. A SAM quantifies the inputs and outputs of each sector, which allows for the calculation of input shares, or the fraction of total sector expenditures represented by each input. Much of the sector detail in the EPPA model is focused on providing a more accurate representation of energy



production and use, because these factors may change over time or under policies that would limit greenhouse gas emissions.



**Figure 9:** Household Sector in EPPA (Paltsev et. al, 2005)

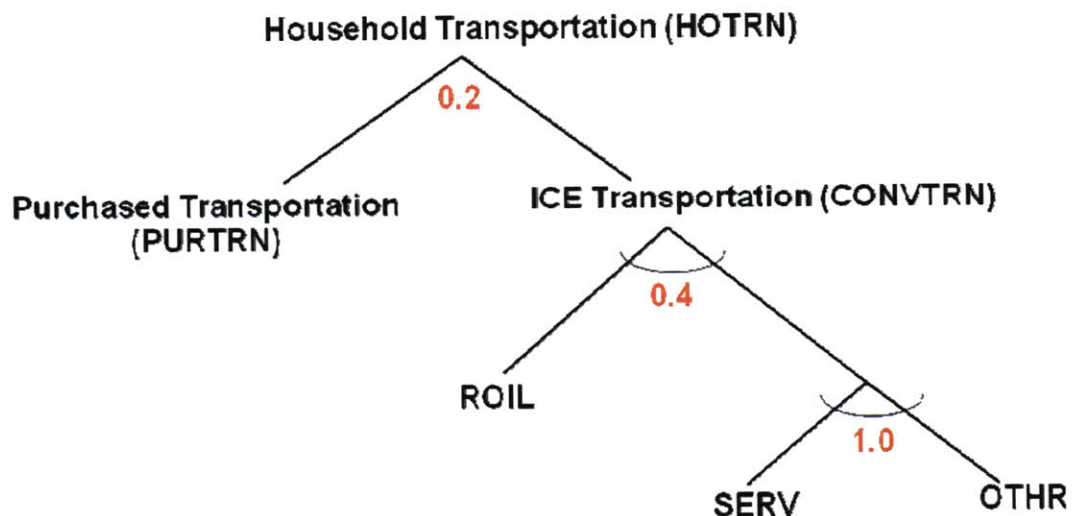
Figure 9 shows the household sector in the EPPA model in a nested CES structure. Household transportation is divided into purchased transport (which includes air travel, water travel, rail service, etc.) and private transportation (owned vehicles). This thesis focuses on privately owned transportation.

The EPPA model is written in the General Algebraic Modeling System (GAMS) software and solved using the Mathematical Programming System for General Equilibrium (MPSGE) in 5-year intervals from 2000 to 2100 after the base year 1997 (Mathiesen, 1985; Rutherford, 1995). Sectors are modeled using nested constant

elasticity of substitution (CES) production functions, with Cobb-Douglas or Leontief forms. The degree to which one input can be substituted for another in response to changes in their relative prices in the model is specified by an elasticity of substitution (Paltsev et al., 2005). The resulting equilibrium in each period must satisfy three conditions: zero profit, market clearance, and income balance (Paltsev et al., 2005).

### 3.2. *Transportation in the EPPA Model*

As seen in Figure 9, the most recent version of the EPPA model separates the transportation sector into purchased transportation and privately owned transportation. Private transportation data is composed of inputs from other industries' products (purchase of vehicles), services (maintenance, insurance, tires, oil change, parking, etc.) and fuel sectors (Paltsev, 2005). The GTAP data separates household expenditure on transportation into 'input shares' of refined oil fuel consumption, cost of services and vehicle rent (symbolized in EPPA by ROIL, SERV, and OTHR respectively).



**Figure 10:** The disaggregation of the transportation sector in the MIT EPPA model (Paltsev et al, 2005)

Figure 10 shows a closer look at the household transportation nesting structure and its elasticities of substitution. Between owned (or ICE as indicated) transportation and purchased transportation, a low elasticity of substitution (0.2) is used to indicate consumer reluctance to switch to purchased transportation in response to increases in the costs of own-supplied transportation. A relatively low elasticity of substitution (0.4) between refined oil and other own-supplied services show a limitation on the relationship between increasing expenditure on maintenance or purchasing a more expensive vehicle, and savings on vehicle fuel (Paltsev et al, 2004). A higher elasticity of substitution is used between vehicles and services, to indicate that less will typically be spent on services by purchasing a more expensive, higher quality vehicle.

### ***3.3. Implementing Natural Gas Transportation in EPPA***

The aim of this research is to determine whether NG vehicle technology should be implemented in the U.S. private transportation sector as a direct competitor with internal combustion engine (ICE) transportation. NG vehicles will be implemented as a ‘backstop’ technology in EPPA, meaning they are uneconomic in 1997 (base year of the EPPA model) but may prove competitive in the future if existing vehicle technologies grow too costly. While NG vehicle technology has been available for decades, for the purposes of modeling NG vehicles will be treated as a backstop technology that has become economically competitive after the EPPA base year (NG vehicle output is at zero until the technology is economically competitive). The NG vehicle technology will be assigned 0.06 percent of the household transportation expenditure when the backstop is

activated in 2005, to reflect its current share of household vehicle transportation (IANGV, 2008).

For the analysis, I will formulate the annual costs of owning a natural gas vehicle for base year 1997 for the EPPA model, which is comprised of the price of the vehicle, fuel costs (natural gas), and ancillary costs (services, maintenance, and insurance). The values of ICE gasoline transportation inputs for 1997 are based on disaggregating the GTAP dataset into household expenditure on fuel (symbolized by ROIL in EPPA), vehicle purchase (symbolized by OTHR), and automobile services (symbolized by SERV). In the model, each of these inputs is defined by its expenditure share, which is determined by its fraction of the total cost of producing a particular good or service. The input shares typically sum up to 1. The original U.S. expenditure values from the GTAP dataset are shown in Table 3a. The inputs to the NG vehicle sector will include natural gas as an energy input, as well as services, the vehicle itself, and a fixed factor. The calculation of the share of each input to NG vehicle transportation was based on similar calculations for the pre-existing household transportation sector.

An initial vehicle cost of \$20,000 is assumed for the EPPA base year of 1997 (Davis, et al., 2009). For the NG vehicle input share estimation, the vehicle contribution to transportation will be held constant. While NG vehicles typically cost up to 40 percent more than gasoline vehicles, NG vehicle price will initially be identical to gasoline vehicles. This expenditure share will be multiplied by a variable factor (a vehicle ‘mark-up’), which enables an analysis of scenarios with increasing vehicle costs to determine the effects of incremental (as seen later in Section 4.1.1).

In the model, the refined oil (symbolized in EPPA by ROIL) input share will be replaced by a natural gas input share (symbolized in EPPA by GAS). The refined oil input is divided by the average annual gasoline cost of \$1.24 per gallon of gasoline in 1997 (EIA, 2010(a)), in order to determine the total amount of fuel consumed by private household transportation in that year. The equivalent amount of natural gas (in gallons of gasoline equivalent) is multiplied by the 1997 natural gas price of 4.44 per tcf (EIA, 2010(b)) to estimate the reduction in vehicle fuel expenditure if natural gas is used. The estimated natural gas expenditure share is shown in Table 3b. For this thesis, fuel taxes in the EPPA model have been turned off. While fuel taxes vary by type of fuel and economic region, the policy analysis of this thesis will include a carbon tax, which may interact with an existing tax to produce counterintuitive effects (Paltsev et al., 2004). It is assumed that the differences in fuel expenditure shares incorporate fuel taxes.

From the 1999 NREL study discussed in Section 2.1, an NG vehicle's cost of services is approximately 25 percent less than the operating cost of a gasoline vehicle. NG vehicle engines require less maintenance than their gasoline counterparts because they use lower carbon intensity fuels and as a result are more knock resistant.

a)

| <b>ICE Gasoline Vehicles</b> | <b>Refined Oil</b> | <b>Vehicle</b> | <b>Services</b> |
|------------------------------|--------------------|----------------|-----------------|
| USA (\$10 billion, 1997)     | 4.595              | 13.907         | 38.871          |
| Input Share                  | 0.080              | 0.242          | 0.678           |

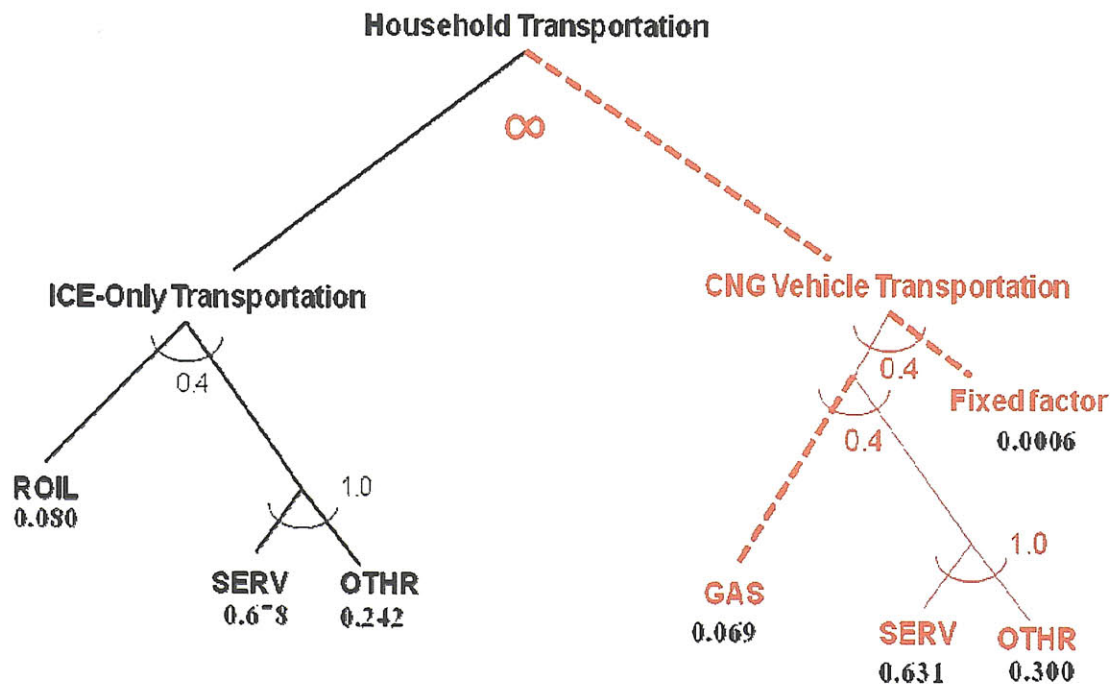
b)

| <b>Natural Gas Vehicles</b> | <b>Gas</b> | <b>Vehicle</b> | <b>Services</b> |
|-----------------------------|------------|----------------|-----------------|
| USA (\$10 billion, 1997)    | 3.217      | 13.907         | 29.153          |
| Equivalent Input Share      | 0.069      | 0.300          | 0.631           |

**Table 3: EPPA Transportation Input Shares**

The modified model assesses the effects of natural gas vehicles on greenhouse gas and carbon emissions by the introduction of the NG vehicle as a private household transportation substitute for the conventional internal combustion engine (ICE). The natural gas resource input data is varied to reflect recent developments of abundant unconventional natural gas domestically, and assess the effects of fuel availability and vehicle prices on the NG vehicle market entry.

The modified private transportation nest, including NG vehicle transportation can be seen in Figure 11:



**Figure 11: Modified EPPA Household Transportation Nest with NG vehicles**

The NG vehicle and ICE-only vehicle sectors are specified as perfect substitutes (infinite elasticity of substitution), forcing the two technologies to compete purely on a

cost basis. Aesthetics, vehicle size, and other consumer preferences not associated with cost will not be captured in this analysis. Once the total cost of NG vehicle transportation drops below the cost of ICE-only transportation, the NG vehicle enters the market.

Due to the life of the average automobile being up to 30 years, the availability of a cost competitive alternate vehicle technology will not result in an instantaneous conversion from the base technology to the novel technology (Higgins et al., 2007). To capture an approximately realistic estimation of the fleet turnover, a ‘fixed factor’ will be added to the NG vehicle input share production nest. The fixed factor’s elasticity of substitution was set to be relatively low (0.4), to ensure that the NG vehicles do not take over the entire private transportation fleet within less than 30 years in the most favorable scenarios (Karplus, 2008).

An acceptable adoption rate must be established for the NG vehicle based on select technological penetration trends. The fixed factor initially starts at .06 percent of the entire private transportation fleet, and grows proportionally as a function of the fraction of NG vehicles in the total private transportation fleet.

**Equation for Fixed Factor; F(r):**

$$F_0(r) = 0.0006 \times H_t(r)$$

$$F_t(r) = F_{t-1}(r) + I_0(r) \times \left( \frac{NGV_t(r)}{H_t(r)} \right)^{0.25}$$

Where:

$I_0(r)$  – Initial Share of fixed factor for NGV Sector

$F_0(r)$  – Value of fixed factor in the 1st period when NGV is available

$F_t(r)$  – Value of fixed factor in region  $r$  in year  $t$

$H_t(r)$  – Output of the household transportation sector in region  $r$  in year  $t$

$NGV_t(r)$  – Output of NGV sector in region  $r$  in year  $t$

The existence of fixed investment in vehicles, infrastructure, and manufacturing capacity may also mean that vehicles remain in use even if not economic in a specific period. To address this, the fixed factor declines over time with the following path:

Path of decline if PHEV stops producing:

$$F_{t+1}(r) = \text{Max} [F_{t=2005}(r), F_{t-1}(r) \times SS_t(r)]$$

Where:

$SS_t(r)$  – Surviving share, defined as  $(1 - d)^2$ , where  $d$  is the depreciation rate

A fixed factor sensitivity analysis is conducted to determine the appropriate growth rate for this analysis (See Appendix C). Global NG vehicle data from the IANGV was used to determine each country's growth rates and current shares of NG vehicles relative to their national fleet. A regionally diverse selection of growth rates is averaged, based on varied success with NG vehicle adoption. The countries selected of interest mirror the EPPA regions as closely as possible, as seen in table 4. Using a mean rate of 10 percent, tested for penetration rate under different sensitivities, a suitable estimate for the initial share of the fixed factor is established.

| Argentina   | 1,746,000 | 7,609,000   | 22.95 |
|-------------|-----------|-------------|-------|
| Bangladesh  | 150,000   | 293,000     | 51.19 |
| Brazil      | 1,588,000 | 14,278,000  | 11.12 |
| Canada      | 12,000    | 19,423,000  | 0.06  |
| India       | 650,000   | 14,554,000  | 4.47  |
| Indonesia   | 2,000     | 5,497,000   | 0.04  |
| Italy       | 580,000   | 39,090,000  | 1.48  |
| Japan       | 36,345    | 78,279,000  | 0.05  |
| Korea South | 17,123    | 11,400,300  | 0.15  |
| New Zealand | 300       | 2,329,000   | 0.01  |
| Pakistan    | 2,000,000 | 6,217,000   | 32.17 |
| Russia      | 103,000   | 33,600,000  | 0.31  |
| USA         | 115,000   | 234,000,000 | 0.06  |
| Average     |           |             | 10%   |

**Table 4:** Global NGV Market Shares (IANGV, 2008)



Given the growth rate of U.S. NG vehicles (as seen in Figure 8), using 10 percent growth rate is very optimistic. While 10 percent growth rate is less than the regional growth rates observed in other continents, it may be difficult to achieve in the U.S. without significant government policy intervention (as observed in successful NG vehicle regions). Using this growth rate will prove beneficial to the evaluation of NG vehicle technology in private transportation. The following questions will be addressed by this analysis: given this optimistic growth share, will NG vehicles grow to a significant share of the private household transportation fleet? Consequently, at the resulting market penetration rate, will NG vehicles have a significant effect on U.S. transportation emissions or oil imports? If NG vehicles fail to significantly contribute to reducing emissions or oil imports under this optimistic growth rate assumption, NG vehicles conclusively do not offer the best solution to transportation issues in the U.S.

## 4. POTENTIAL IMPACT OF NG VEHICLES IN THE U.S.

This chapter will examine how various factors- such as vehicle price, domestic fuel availability, competition with bio-fuels and PHEVs, and emissions policy- affect NG vehicle market penetration in the long term. Using the EPPA model, a detailed scenario analysis will assess the potential for natural gas vehicles in private household transportation. Subsequently, the impact of market penetration on natural gas consumption, household transportation emissions, gas consumption, fuel prices and oil imports will also be assessed. My natural gas vehicle analysis will center on the U.S. market, with NG vehicles in other EPPA regions disabled in EPPA.

### *4.1. Factors Affecting NG vehicle Market Penetration*

To investigate the role of the factors affecting NG vehicle penetration, a series of technological and economic scenarios will be analyzed. As seen in Table 5, the roles of vehicle price, plug-in hybrid vehicle technology, bio-fuels, and unconventional gas on NG vehicle market penetration will be assessed.

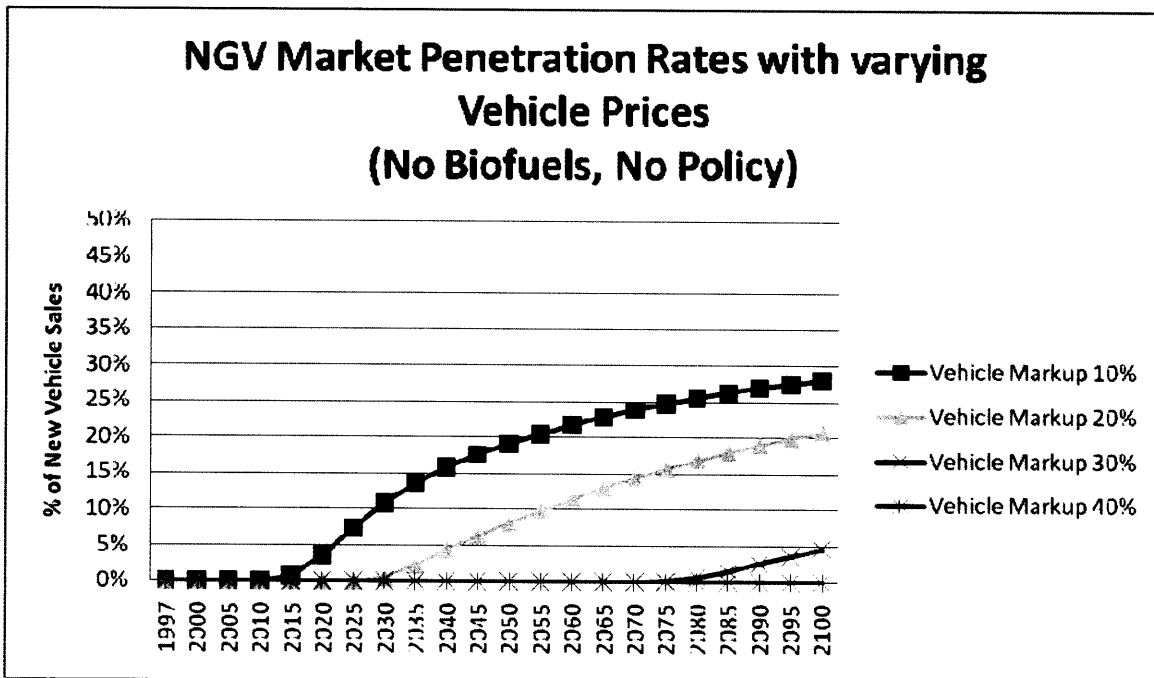
|               |  |
|---------------|--|
| Section 4.1.1 |  |
|               | NG Vehicle Markups - 10%, 20%, 30%, 40%, No Policy                       |
|               | NG Vehicle Markups - 10%, 20%, 30%, 40%, 450 ppm Policy                  |
| Section 4.1.2 |  |
|               | Bio-Fuel Markups – No Bio, Reference, +50%, -50%; No Policy              |
|               | Bio-Fuel Markups - No Bio, Reference, +50%, -50%; 450 ppm Policy         |
| Section 4.1.3 |  |
|               | NG Vehicle Markup: 10%, PHEV Markup: 30%, No Bio-Fuels, No Policy        |
|               | NG Vehicle Markup: 10%, PHEV Markup: 30%, Bio-Fuels, No Policy           |
|               | NG Vehicle Markup: 10%, PHEV Markup: 30%, No Bio-Fuels, 450 ppm Policy   |
|               | NG Vehicle Markup: 10%, PHEV Markup: 30%, Bio-Fuels, 450 ppm Policy      |
| Section 4.1.4 |  |
|               | NG Vehicle Markups, Low NG Resource Estimates - 10%, 30%, 10% + 450 ppm  |
|               | NG Vehicle Markups, High NG Resource Estimates - 10%, 20%, 10% + 450 ppm |

**Table 5:** Scenarios for NG Vehicle Market entry Analysis

With the development of unconventional gas, domestic natural gas resources increase by approximately 1,200 EJ (CERA, 2010). I assess the effects of current conservative estimates and optimistic gas resource estimates (CERA, 2010) on the penetration of NG vehicles. In addition, climate policy scenarios will be assessed on their complimentary or adverse effects on NG vehicle market entry. Throughout this analysis, I explore the effects of imposing a policy that constrains carbon emissions in the U.S. In the EPPA model's 450 parts per million (ppm) policy, U.S. emissions are capped at levels consistent with a global target of stabilizing atmospheric concentrations at 450 ppm. Rather than setting a specific carbon price, imposing a policy constraint results in a carbon price that is reflected in the cost of carbon-intensive fuels. By pricing carbon-intensive activities (such as private transportation), a climate policy could thus change the attractiveness of an otherwise uncompetitive technology if it offers significant emissions reductions, compared with their alternative (Karplus, 2008). Penetration rates represent the market share of NG vehicles sold in the new vehicle market.

#### ***4.1.1. Effects of Vehicle Price on Market Penetration***

The scenarios that are used in the model are described as follows. In these scenarios, I analyze how variability in vehicle price markup affects the entry and growth rate of NG vehicles under both regular market (No policy) and 450ppm policy scenarios. A vehicle cost of \$20,000 is used for the base year of 1997 to reflect a traditional ICE vehicle value (Davis, et al., 2009). Vehicle price markups represent scenarios ranging from 10 to 40 percent above an average ICE light duty vehicle. In these scenarios, I assume that bio-fuels are not available to provide a possible fuel substitute.

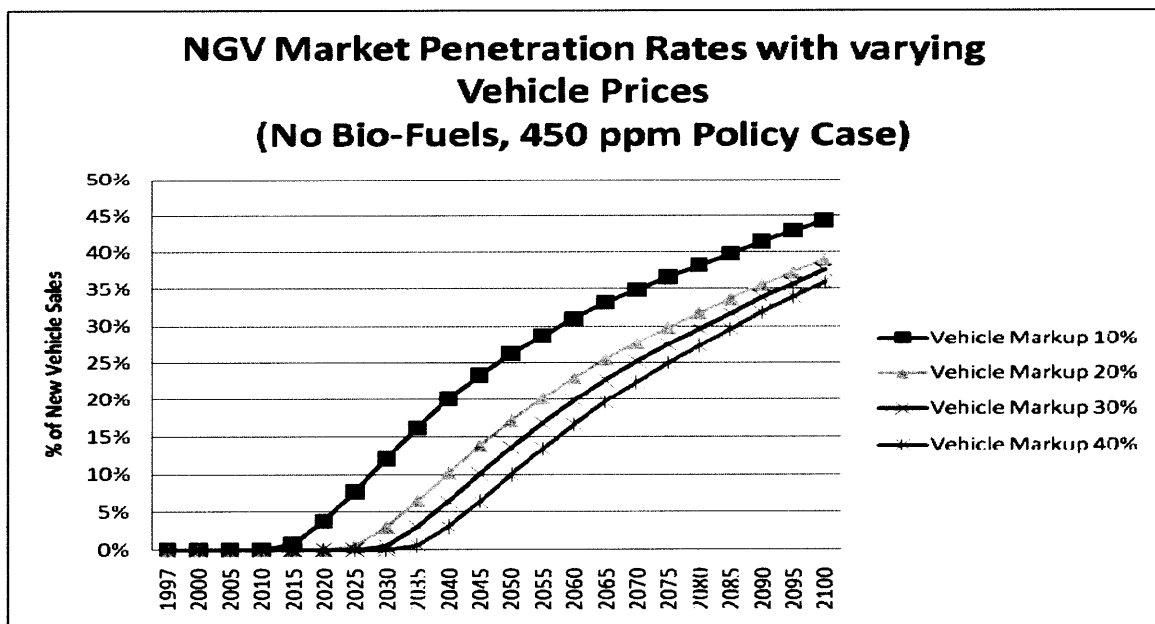


**Figure 12:** Market Penetration Rates with varying vehicle prices

Figure 12 shows the percentage of new vehicles sold that are NG vehicles, at varied NG vehicle prices. From my analysis, I determined that vehicle price is an important factor in the timing and penetration of natural gas vehicles into the market. While natural gas is cheaper than gasoline, the incremental cost of the vehicle may impede NG vehicle growth if it is too high. When the incremental cost is more than 40 percent higher than a gasoline vehicle, consumers opt to stay with gasoline vehicles. An affordable range of NG vehicle prices would lie between 10 to 30 percent more than gasoline vehicles. Since an NG vehicle costs \$6,000 to \$10,000 more than an average \$20,000 gasoline vehicle, a mark-up of 40 percent or higher is more reflective of current vehicle cost difference. Minimal to no market penetration is observed at these vehicle costs, and NGVs are conclusively uneconomical.

However, with current policy incentives for NG vehicles reaching up to \$4,000 in tax credits (up to half of the incremental vehicle cost in cases), consumers will be more motivated to purchase NG vehicles. If these tax credits are sustained well into the future (year 2030 as proposed by the NATGAS Act), the mark-ups will mirror the range of \$2,000 to \$6,000 (or 10 to 30 percent). At an optimistic 10 percent mark-up above gasoline vehicles, NG vehicles would grow to 20 percent of new vehicles sold in the U.S. by mid-century, and increase to 30 percent by 2100. The modified EPPA model illustrates that the growth rate would decrease by 2060 and that NG vehicles would never take over the entire new vehicle market.

A repeat of the vehicle price analysis was conducted to simulate a 450 ppm policy case. Rather than instituting a carbon price, an emissions target of 450 ppm was set and the price of carbon was determined by the market. The 450ppm policy scenario was selected to determine whether or not imposing strict carbon constraints would stimulate a reduction in emissions from various sectors, including transportation.



**Figure 13:** Market Penetration Rates with varying vehicle prices (Policy case)

Figure 13 shows the percentage of new vehicles sold that are NG vehicles, at varied NG vehicle prices under the 450 ppm policy case scenario. In the absence of bio-fuels or other alternative transportation options, NG vehicles gain significant market advantage in the 450 ppm policy case. NG vehicles grow to account for as much as 25 percent of new vehicles sold in the U.S. by 2050, and 45 percent by 2100. There would also be a steady growth rate up to 2100. While the fleet percentage under emissions policy increases significantly, NG vehicles still would not take over the new vehicle fleet. To conclude, the infrastructure associated with natural gas might impede its growth, and while emissions would be reduced, they are not completely eliminated with NG vehicles.

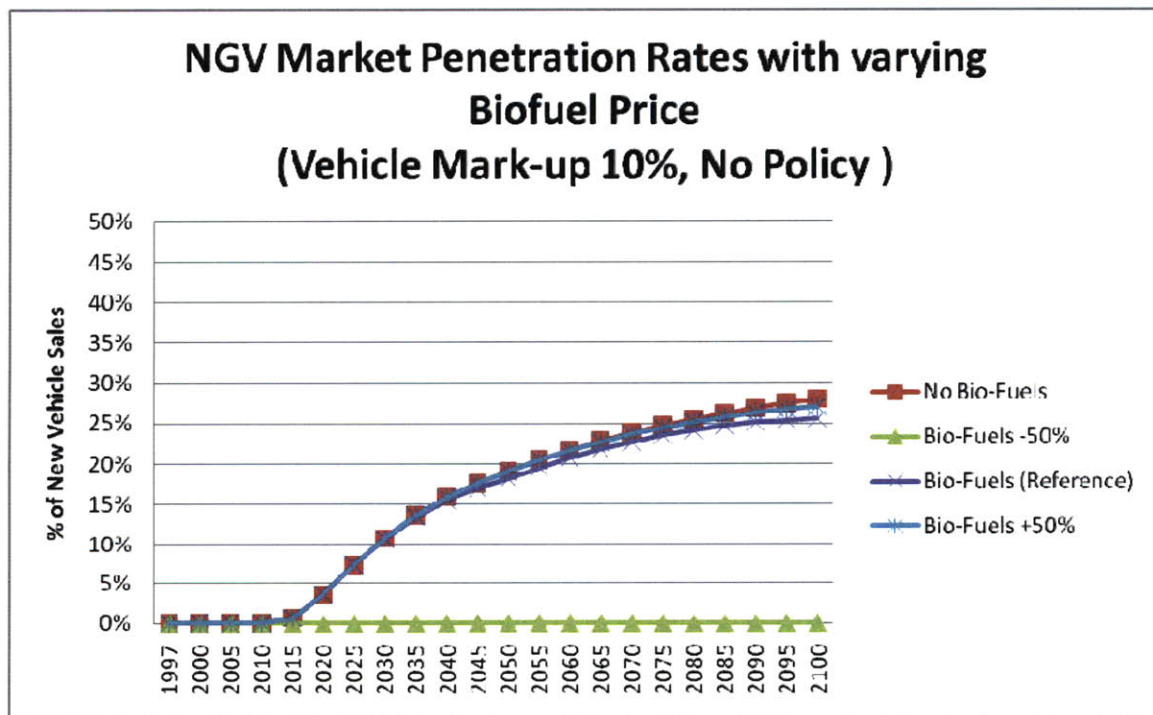
The effect of vehicle price is a pivotal issue, and may prevent the adoption of the vehicle altogether. Subsequent analysis will continue to use these optimistic mark-ups to assess the maximum effect NG vehicles can have on emissions, fuel price and oil imports.

#### ***4.1.2. Effects of Bio-fuels on Market Penetration***

In this scenario, the effects of the development of advanced lignocellulosic bio-fuels (referred to as bio-fuels) are analyzed. Bio-fuels, usually mixed with gasoline, provide a low carbon fuel option for refined oil in the future. Bio-fuels are treated as a ‘backstop’ in EPPA, becoming economically available from 2010 onward. Perfect substitutes for refined oil (ROIL), bio-fuels can also be used in transportation and other direct applications of refined oil. In the EPPA model, bio-fuel crops are constrained by land prices, which rise as demand of bio-fuels and as general economic activity increases.

Figure 14 shows the percentage of new vehicles sold that are NG vehicles, with varied bio-fuel prices (a reference price, 50 percent above reference price, and 50 percent

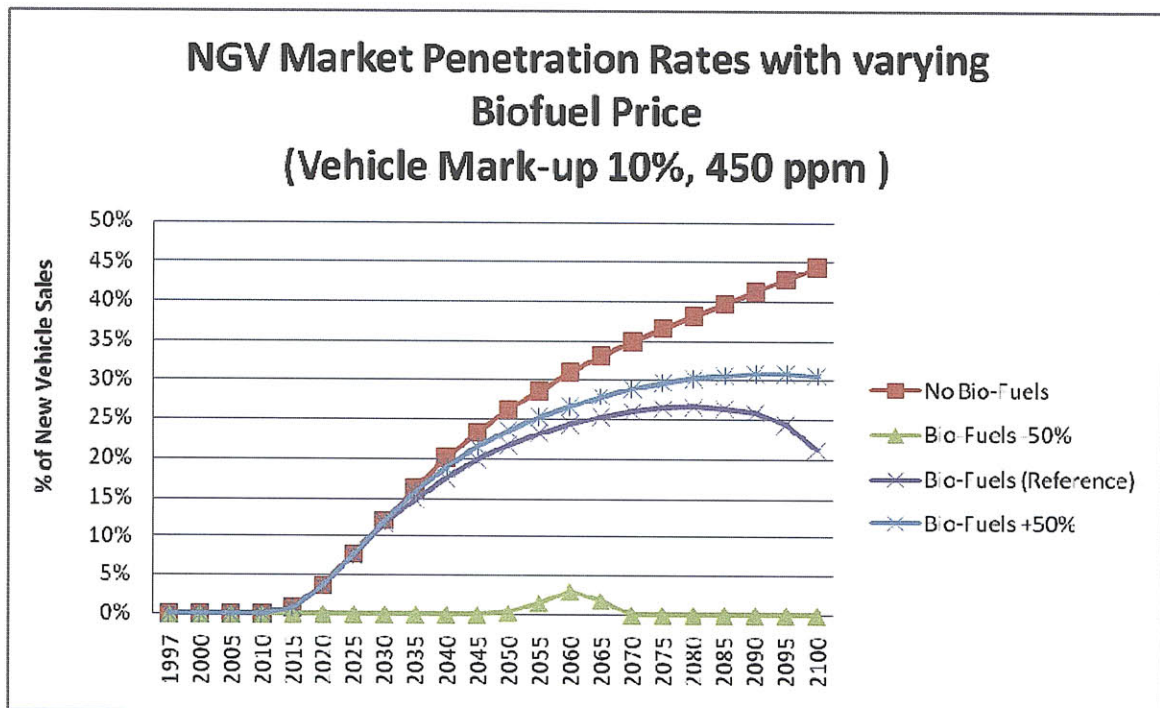
below reference price). The analysis in this thesis highlights the competitiveness of bio-fuels in comparison to natural gas. At high prices, bio-fuels provide a negligible reduction in NG vehicle market penetration. However, as the cost of bio-fuels is decreased, a rapid decline in the use of NG vehicles occurs. If bio-fuels are expensive, natural gas is preferred as a vehicle fuel because of its lower relative costs. If they become inexpensive, bio-fuels will act as a perfect substitute for gasoline. Bio-fuels will gain a competitive edge over natural gas, because natural gas usage requires additional infrastructure investment to increase its market share.



**Figure 14:** Market Penetration Rates with varying bio-fuel prices

Figure 15 shows the percentage of new vehicles sold that are NG vehicles, with varied bio-fuel prices under the 450 ppm target policy case. Similar patterns appear under the policy case. While NG vehicles gain more significant market advantage under carbon

constraints, the inclusion of bio-fuels results in varied levels of reduction in NG vehicle market penetration. NG vehicles will grow rapidly until 2060, followed by a decline in their market share of new vehicles; the decline in the NG vehicle market share after 2060 would be more aggressive under carbon constraints because bio-fuels would become a more cost competitive fuel alternative. Natural gas vehicles can be looked at as a near-term solution to transportation emissions, with bio-fuels being a more permanent long-term vehicle fuel solution.



**Figure 15:** Market Penetration Rates with varying bio-fuel prices (Policy case)

#### 4.1.3. *Effects of Competing Alternative Vehicle Technologies*

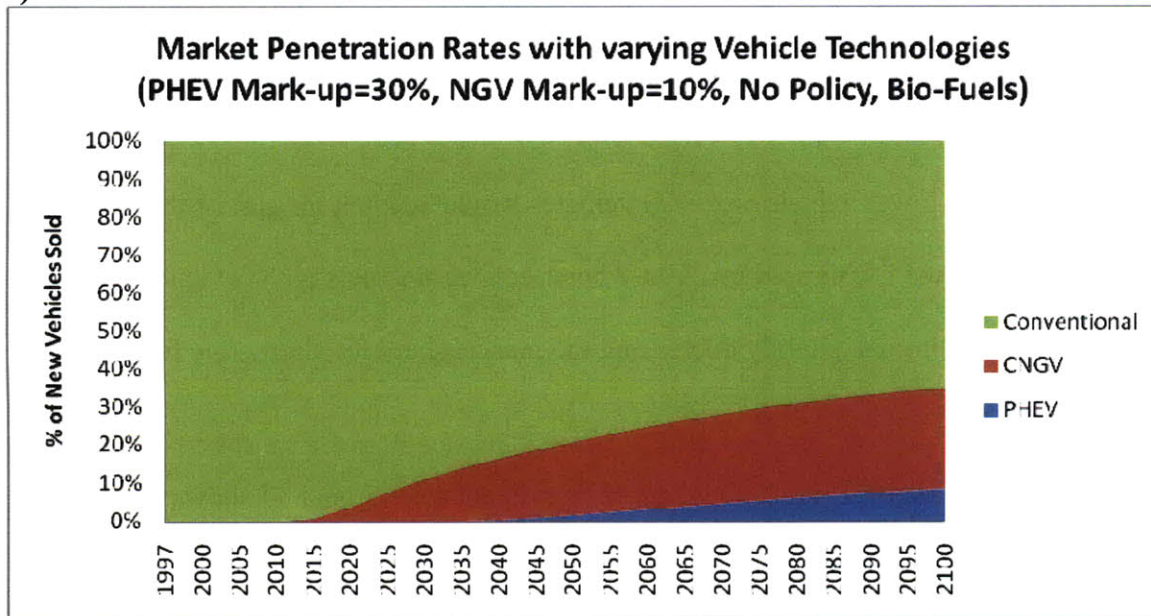
In addition to analyzing the effects of competing alternative fuels, these effects must be analyzed in comparison to feasible emerging vehicle technologies such as plug-in electric hybrid vehicles (PHEVs). PHEVs are vehicles that are capable of using gasoline



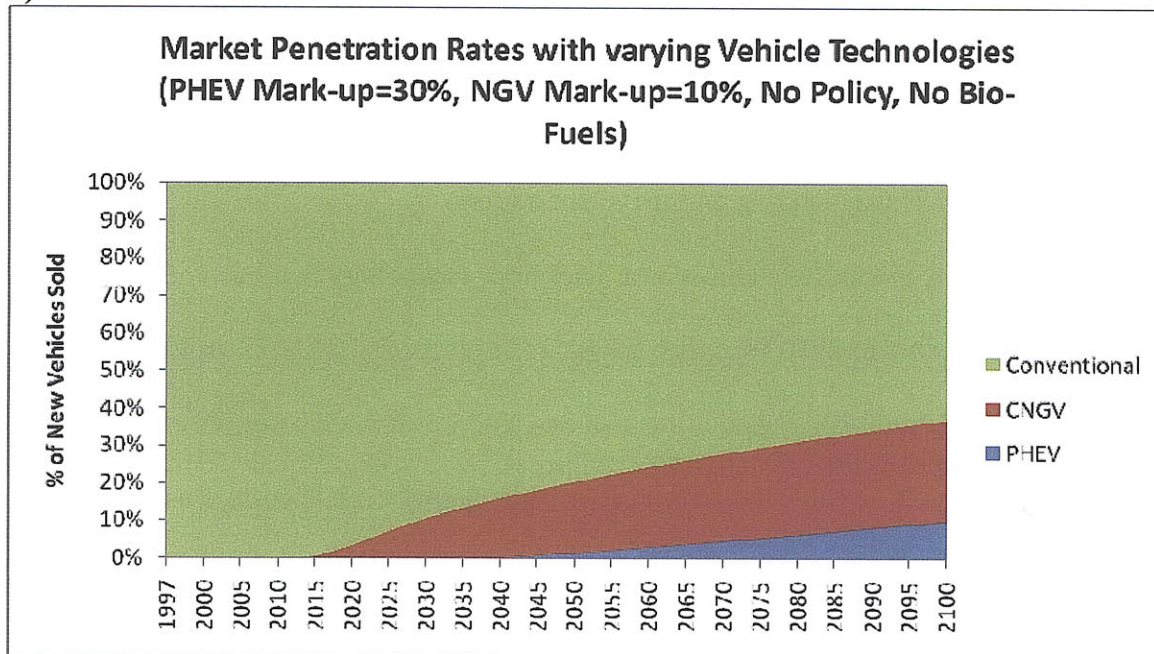
and electricity. As a viable vehicle option with gaining popularity, the hybrid electric vehicle may encroach on the new vehicle market at the detriment of the natural gas vehicle. PHEVs, however, typically have significantly higher incremental costs than NG vehicles. Incremental cost (or vehicle markup) is typically 30 to 60 percent above regular ICE gasoline vehicles, depending on the type of battery.

In my analysis, I included PHEVs as a ‘backstop’ technology that becomes economically feasible in 2010 (Karplus, 2008). I use electricity (‘ELEC’ in EPPA) and refined oil (‘ROIL’ in EPPA) as fuel input shares, employed interchangeably to represent hybrid technology. To reflect the difference in incremental vehicle costs, I used a mark-up of 30 percent for PHEVs and a mark-up of 10 percent for NG vehicles. I assessed the new vehicle market penetration of both technologies under policy scenarios, and reviewed the effects of the inclusion of bio-fuels on the competitiveness of PHEVs.

a)



b)



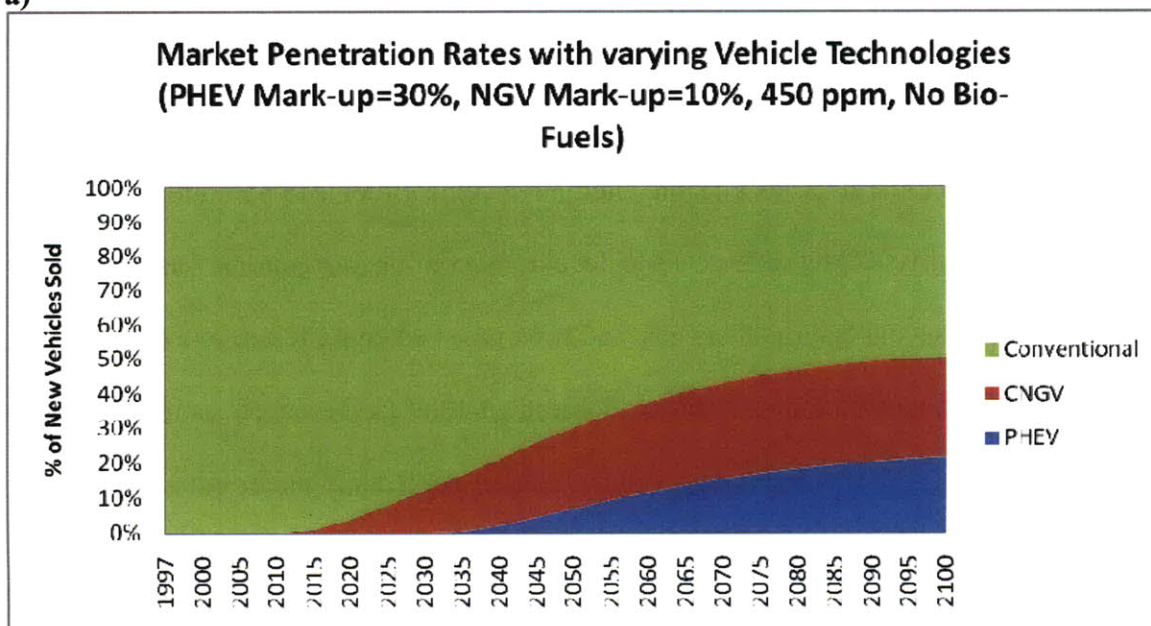
**Figure 16:** Market Penetration Rates with varying Alternative Vehicle Technologies, Non-Policy Case a) With Bio-Fuels b) Without Bio-Fuels

Figure 16 shows the percentage of new vehicles sold that are NG vehicles or PHEVs in comparison to conventional ICE vehicles, with and without biofuels. My analysis demonstrates that without policy, compressed natural gas vehicles are favored over plug-in hybrids due to lower vehicle cost. NG vehicles would account for almost three times the number of new PHEVs sold by 2100. The effects of bio-fuels on NG vehicle market penetration are minimal, slightly decreasing the market share for alternative fuels with their presence.

In the policy case, bio-fuels play a more significant role. Figure 17 shows the percentage of new vehicles sold that are NG vehicles or PHEVs in comparison to conventional ICE vehicles under a 450 ppm policy, with and without biofuels. Due to the price of carbon, alternative vehicles gain an increased percentage of the new vehicles

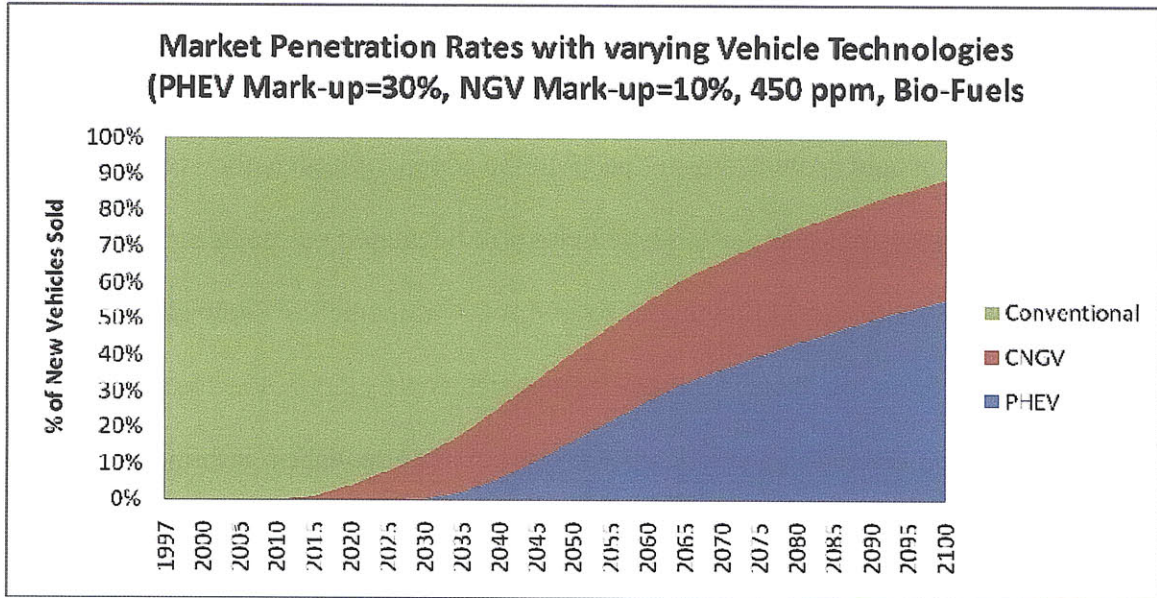
sold; hybrid vehicles grow at a faster rate than NG vehicles after 2050, reaching a highly competitive penetration rate of approximately 20 percent by 2100. With the exclusion of bio-fuels, PHEVs would grow at a faster pace. In the advent of high carbon prices caused by stringent emissions policies, gasoline vehicles will be phased out without bio-fuels providing a cleaner alternative fuel that utilizes similar infrastructure. New gasoline vehicles will represent less than 15 percent of new vehicles by 2100. The electric hybrid would be preferred alternative vehicle technology, having established gasoline refueling infrastructure and requiring less infrastructural investment for electricity than natural gas. PHEVs grow to over 50 percent of new vehicles sold by 2100, compared to the 30 percent of new vehicles that use natural gas. With the inclusion of bio-fuels, conventional gasoline vehicles will maintain a majority of the new vehicle market. This is because gasoline vehicles will be able to use the cleaner, less emissive bio-fuels without major vehicle or infrastructural modifications.

a)



b)





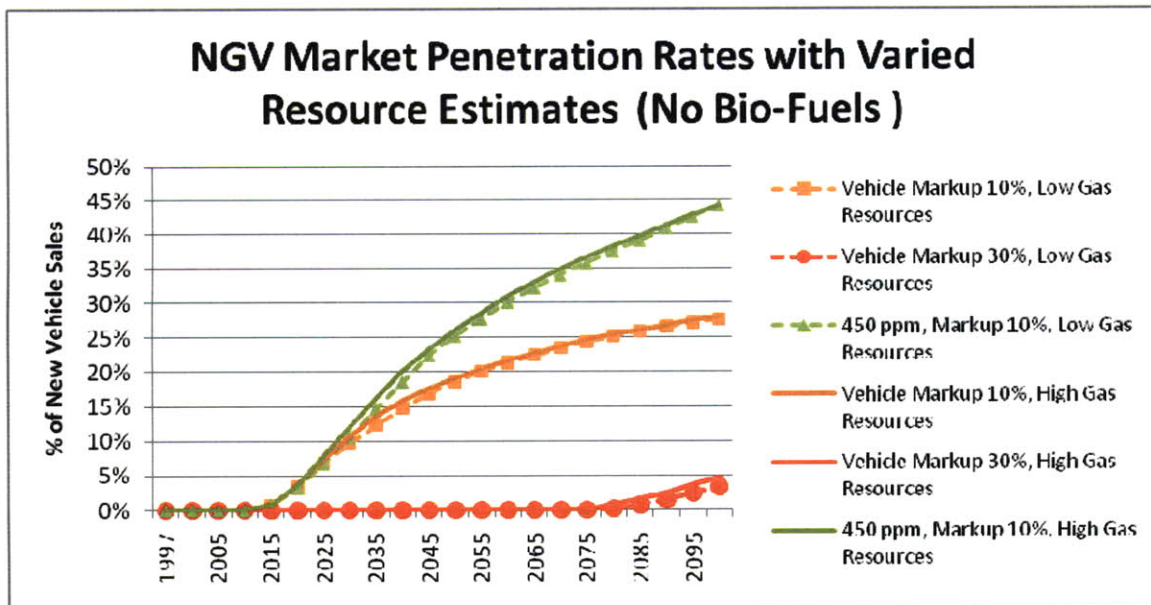
**Figure 17:** Market Penetration Rates with varying Alternative Vehicle Technologies, 450 ppm Policy Case a) With Bio-Fuels b) Without Bio-Fuels

NG vehicles are a viable alternative vehicle option. However, if bio-fuels are available, the cost of additional natural gas infrastructure investment will make the next logical vehicle choice a PHEV or a regular ICE vehicle that can run on a mixture of gasoline and bio-fuels.

#### ***4.1.4. Effects of Unconventional Gas Resources on Market Penetration***

The appeal of natural gas as a viable alternative vehicle fuel is in part due to its domestic availability. With the large scale development of unconventional gas resources (such as shale gas, coal bed methane gas, and tight gas) becoming feasible in the near future under certain economic conditions, domestic natural gas resources estimates have almost doubled in recent years. An analysis of market penetration under initial conservative natural gas resource estimates of 1,112 exajoules (Paltsev et al. 2005) and more recent optimistic resource estimates (approximately 2,300 exajoules, according to CERA) is used to determine the dependence of NG vehicles on the availability or

abundance of natural gas resources. Vehicle mark-up prices of 10 and 30 percent were used, as well as 450 ppm policy case.



**Figure 18:** Market Penetration Rates with varying natural gas resource estimates

Figure 18 shows the percentage of new vehicles sold that are NG vehicles, with varied natural gas resources. The presence or absence of unconventional resources seem inconsequential to the growth of NG vehicles. While there is a very slight reduction in market penetration as a result of the use of the lower resource estimates, NG vehicle market share is dependent on factors other than availability of unconventional gas resources. This outcome may occur because NG vehicles will consume a small percentage of the U.S. gas resources at current estimates. With an estimated vehicle price 10 percent above gasoline vehicles, annual natural gas vehicle fuel consumption is estimated to be approximately 1.5 exajoules by 2100 (to be discussed further in Section 4.2).

## ***4.2. Effects of NG vehicle Market Penetration***

To construct adequate policy, the true value of NG vehicles in transportation must be measurable well into the future. Using conditions from section 4.1, I assessed the effects of NG vehicles under the following criteria to determine their benefit: the consumption of natural gas fuel, the reduction in household transportation emissions, and the reduction in oil imports. The scenarios used in this analysis are summarized in Table 6.

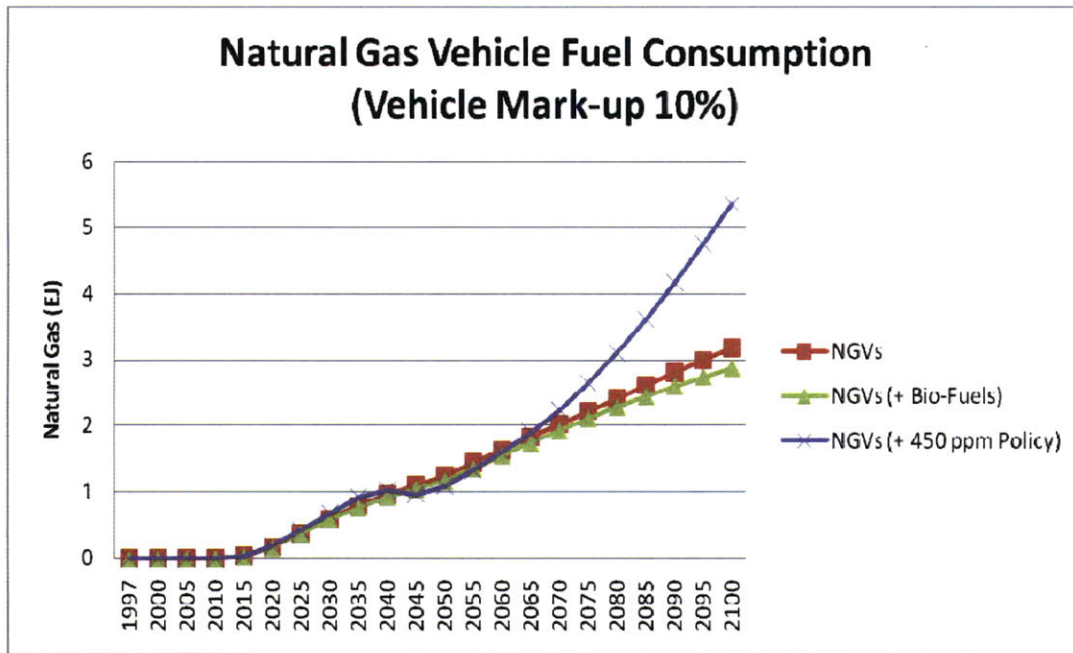
|                      |   |
|----------------------|---|
| <b>Section 4.2.1</b> | <b>Natural Gas Fuel Consumption</b>                     |
|                      | NGV Markup 10%: No bio-fuels, 450 ppm Policy, No Policy |
| <b>Section 4.2.2</b> | <b>Emissions Reduction</b>                              |
|                      | NGVs: 450 ppm Policy, No Policy                         |
|                      | No NGVs: 450 ppm Policy, No Policy                      |
| <b>Section 4.2.3</b> | <b>Oil Imports</b>                                      |
|                      | Change in Oil Imports: 450 ppm Policy                   |
|                      | Change in Oil Imports: No Policy                        |
| <b>Section 4.2.4</b> | <b>Fuel Prices</b>                                      |
|                      | Oil Prices: With NGVs                                   |
|                      | Natural Gas Prices: With NGVs                           |

**Table 6:** Scenarios for Effects of NGV Market entry

### ***4.2.1. Effects on Natural Gas Fuel Consumption***

With a vehicle price of 10 percent above gasoline vehicles, NG vehicles are expected to take over 30 percent of new light duty vehicles sold in the U.S. by 2100. Using a 1997 natural gas price of \$4.44 per tcf (EIA, 2010), the expenditure on natural gas vehicle fuel is determined. Subsequently, the amount of fuel consumed is calculated using natural gas price projections in EPPA.





**Figure 19:** Natural Gas Vehicle Fuel Consumption

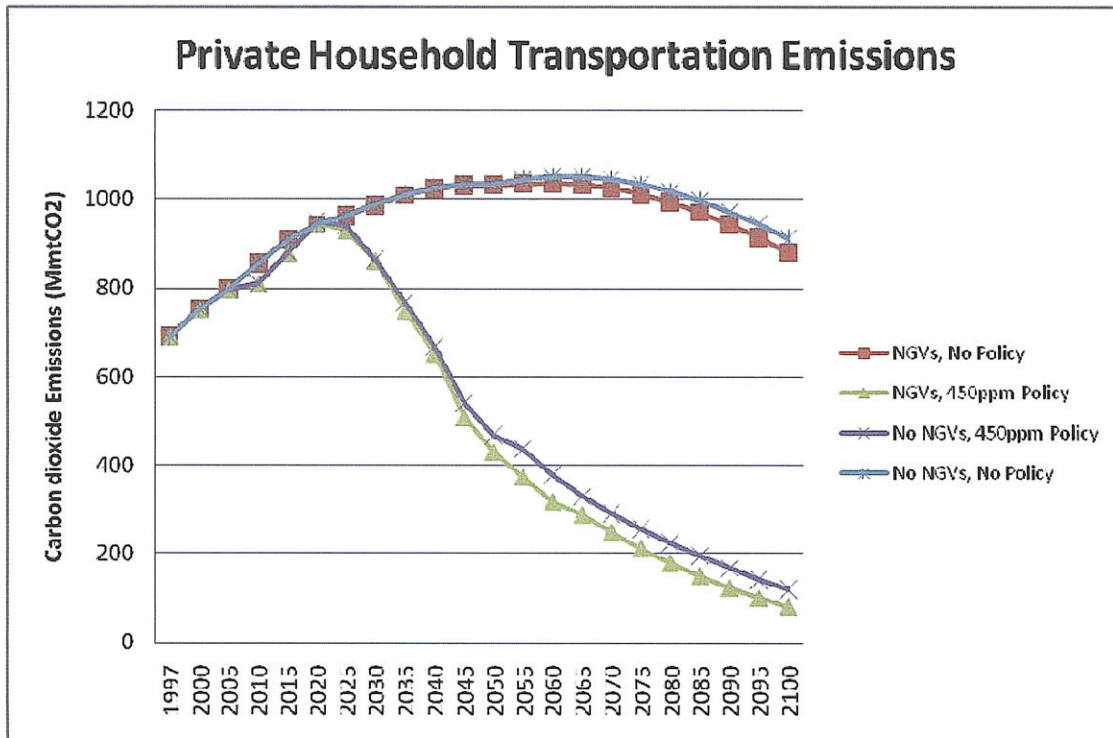
Figure 19 shows the natural gas fuel consumption under various assumptions.

Without a 450 ppm target policy, NG vehicles are projected to consume up to 1.2 EJ of natural gas annually by 2050, and 3.1 EJ by 2100. Altogether, NG vehicles will consume up to 125 EJ of natural gas over the rest of the century. This is a not a large number, considering the domestic natural gas resources available to the U.S. There is enough natural gas to support natural gas vehicles well into the future, with or without unconventional natural gas discoveries (See section 4.1.3). With the 450 ppm target policy, NG vehicles will consume up to 5.3 EJ of natural gas annually by 2100.

#### **4.2.2. Effects on Transportation Emissions**

The change from gasoline vehicles to natural gas vehicles is expected to reduce vehicle emissions. Using the EPPA model and its standard energy efficiency

improvements, an analysis was conducted on the effects of NG vehicle inclusion on transportation emissions policy and non policy scenarios.



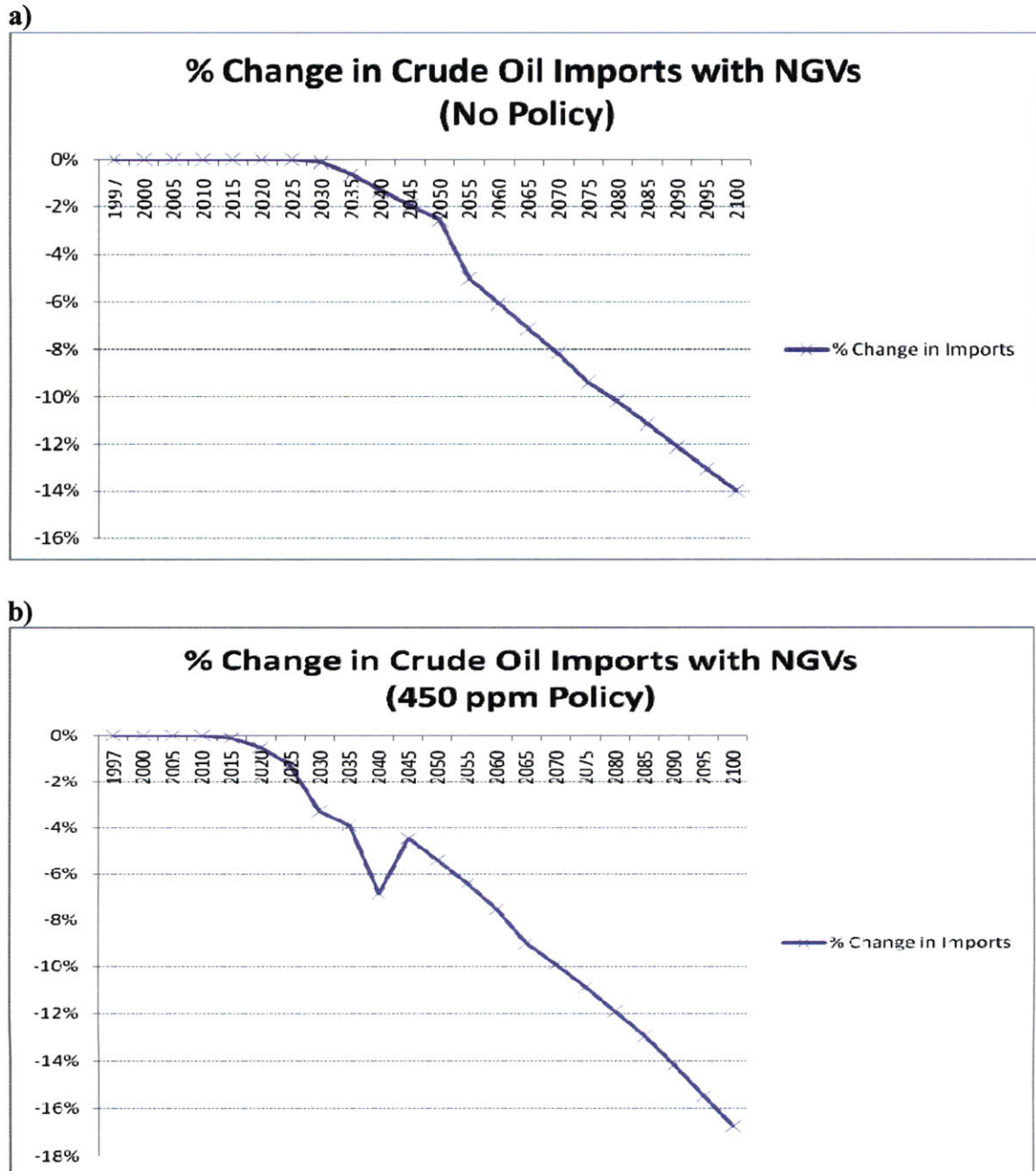
**Figure 20:** Private household Transportation Emissions

Figure 20 shows the change in from private household transportation emissions from NG vehicles. As seen in section 4.1, NG vehicles grow to approximately 30 percent of new vehicles sold in the U.S. by 2100 without emissions policy. Since NG vehicles would not take over the entire private household transportation fleet, the effects on overall household vehicle emissions are minimal, with a reduction in carbon dioxide emissions by 2 to 5 percent in policy and non policy scenarios over the next century.



#### 4.2.3. Effects on Oil Imports

Energy independence may be difficult to measure, but the reduction in oil imports is a potential indicator. A comparison of oil imports with and without NG vehicles was assessed for policy and non policy scenarios.



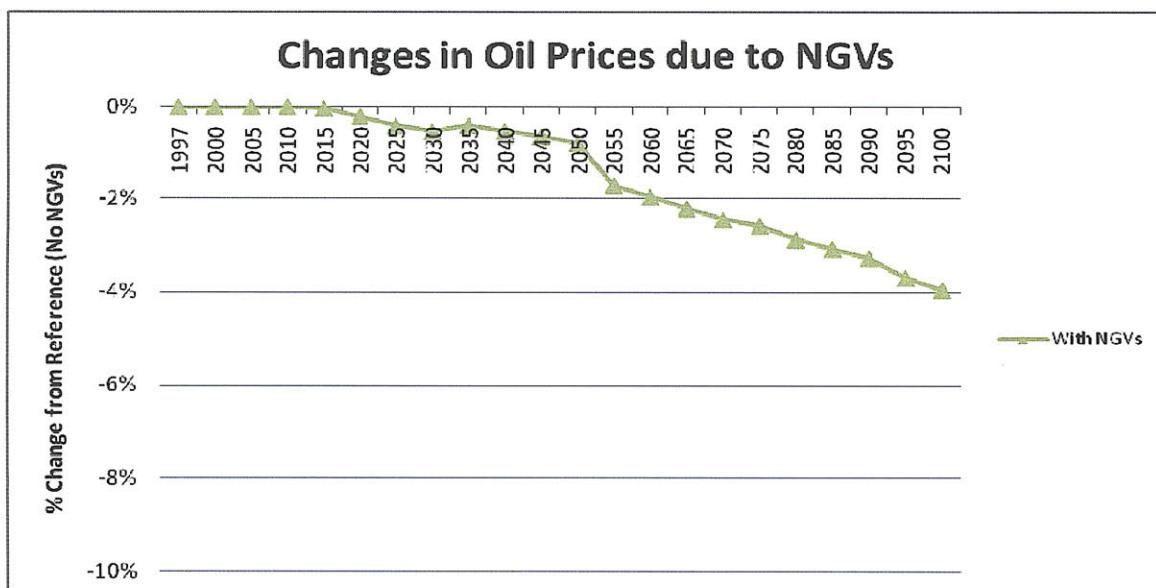
**Figure 21:** Effects of NGVs on Oil Imports a) Without Policy b) With Policy

Figure 21 shows the changes in oil imports with the the inclusion of NG vehicles with and without a 450 ppm policy. A reduction of up to 15 percent in oil imports occurs when NG vehicles are introduced. While the reduction of oil imports is a possible indication of a decrease in importation, it is difficult to use this as a metric for energy independence. For example, it is difficult to ascertain how much of the reduction in imports is due to emissions policy or the addition of NG vehicles in the 450 ppm policy case. Oil may also be going toward commercial transportation.

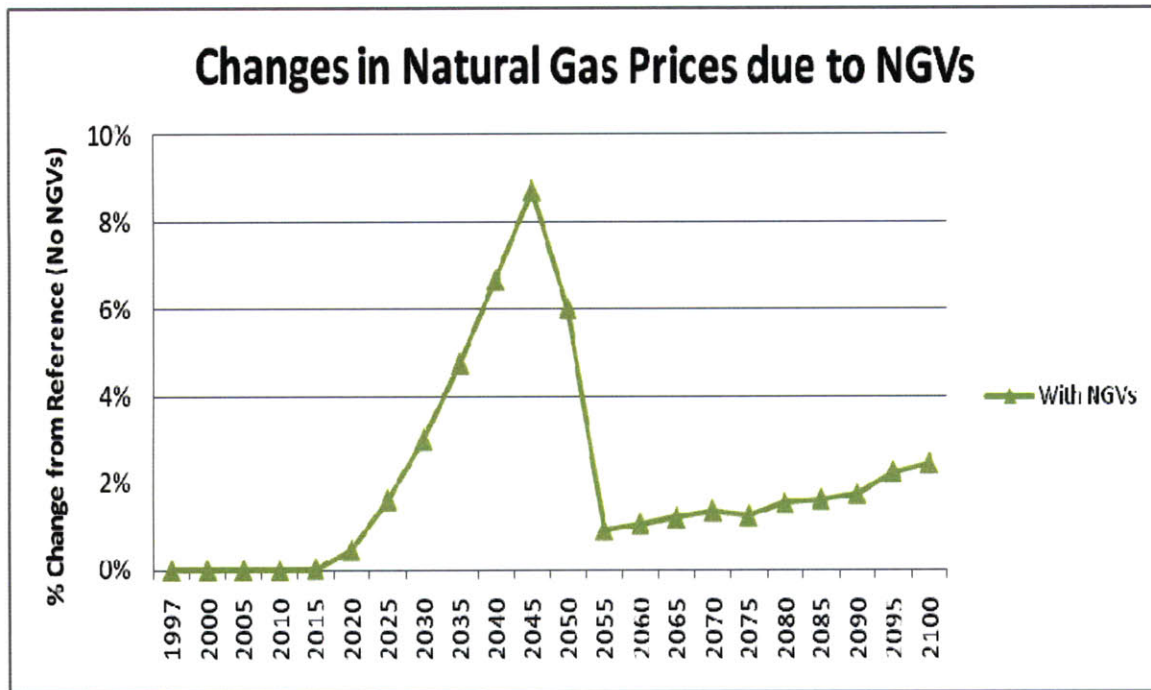
#### 4.2.4. *Effects on Fuel Prices*

The growth of natural gas vehicles will result in increased demand for and consumption of natural gas. Increased NG vehicle usage in the U.S. will also displace traditional vehicles and their associated gasoline consumption. The resulting changes in consumption will result in changes in estimated domestic fuel price projections. The percentage increase or decrease in fuel prices will be measured in comparison to a reference scenario without natural gas vehicles.

a)



b)



**Figure 22:** Effects of NGVs on Fuel Prices a) Oil Prices b) Natural Gas Prices

Figure 22 shows the changes in fuel prices with the the inclusion of NG vehicles.

With the inclusion of natural gas vehicles at a 10 percent vehicle mark-up, a reduction in domestic oil prices is observed in Figure 22a. Due to the decrease in the gasoline vehicle fleet, refined oil prices drop by 4 percent to remain competitive as a vehicle fuel. As seen in Figure 22b, natural gas prices in the U.S. experience an increase of up to 10 percent by 2050 with the inclusion of natural gas vehicles. This increase coincides with the acceleration of NG vehicle market penetration as seen in section 4.1. Since a portion of infrastructure will come from the fuel input share, it is logical that a rise in price occurs during the early stages of adoption. Coinciding with the decrease in the rate of growth of the percentage of new vehicles sold after 2060 (as seen in Figure 12), the change in domestic natural gas prices due to NG vehicles will lessen. As NG vehicles become more

commonplace in year 2060 and beyond and less is spent on infrastructure, natural gas prices deviate less from the original estimates.

## **5. SUMMARY & CONCLUSIONS**

Ultimately, I have argued that, even though a widespread adoption of NG vehicles in the United States would reduce greenhouse gas emissions and dependency on foreign oil, the significant government support required for large-scale adoption prevents NG vehicles from being a viable solution to the country's current energy concerns. In this section, I will review the major points of this thesis and make the case that the adoption of NGVs in the United States is primarily contingent on government incentives and support, and that this contingency limits the viability of NG vehicle use. NG vehicles ultimately have little to no effect on the end goal of emissions or oil import reduction.

As noted earlier, the transportation sector accounts for a significant percentage of energy use in the United States. When this energy comes from gasoline the transportation sector also accounts for a significant percentage of the country's greenhouse gas emissions. In addition, this reliance on gasoline entails a dependence on foreign oil, which makes oil prices vulnerable to geopolitical instability. Natural gas, as this thesis makes the case, is an option amongst alternative fuels for curbing the energy problems that face the United States for the following reasons. First, natural gas is available domestically. With abundant resources that are projected to double as unconventional gas development becomes less expensive, reliance on foreign oil for transportation in the U.S. will lessen. Second, natural gas is usually less expensive than most other transportation fuels. And third, the use of NG vehicles would lower the current level of greenhouse gas emissions.

In order to bring to light the factors that contribute to the adoption of NG vehicles, I considered the reasons for their utilization or lack of utilization outside of the United States. Thanks to aggressive government promotion and policy, the use of NG vehicles is widespread in South America. In Asia, government support has stimulated the growth of the NG vehicle market even though vehicle conversions are substandard and there is a limited local supply and refueling infrastructure. In Europe, with the lack of policy incentivizing NG vehicles and a focus on electric and biodiesel vehicles, the use of NG vehicles has been minimal.

The history of NG vehicles in the United States and the central issues affecting their implementation were delineated in the second section of this thesis to highlight the reasons behind the current level of usage. Starting in the 1990, when policies were made that incentivized the use of natural gas in government and commercial fleets; there was a significant rise in NG vehicles. However, the widespread adoption of NG vehicles has primarily been constrained by the lack of a large-scale refueling infrastructure and the limited availability of NG vehicles. In addition, the general public is not aware of the long-term environmental and financial benefits of NG vehicles. Unwarranted safety concerns have also affected the use of NG vehicles in the United States.

In section three, I presented my analysis of the potential and effects of the adoption of NG vehicles in the U.S. private transportation sector. Drawing on select components of previous models, I modified the EPPA model to assess the role of vehicle cost, fuel availability, emissions targets and alternative fuel options for consumption and importation, on the promulgation of NG vehicles. The annual cost of owning an NG vehicle and the ratio of this cost to a household's total expenditures was calculated. My

modified EPPA model determined the impact of NG vehicles on greenhouse gas and carbon emissions in relation to ICEs.

The fourth section of this thesis examined how vehicle price, domestic fuel availability, competition with bio-fuels and electric hybrids, and emissions policy, impact long-term NG vehicle market penetration. I conducted scenario analysis, using the EPPA model, to determine the potential of NG vehicles in the private household transportation sector in the United States. In order to evaluate the potential for NG vehicles in the U.S., an analysis was performed to assess the factors necessary for their successful large-scale deployment, and to determine the effects of this deployment. These factors were evaluated on the following criteria: vehicle price, availability of domestic natural gas, and the development of bio-fuels as a competing alternative fuel. The effects of NG vehicles were assessed by their fuel consumption, and their ability to reduce emissions and oil imports.

My analysis from the EPPA model indicates that natural gas vehicles have the potential to grow to approximately 30 percent of all new vehicles sold without an emissions policy by 2100, but their deployment is heavily reliant on vehicle price. If the price of an NG vehicle is significantly higher than that of a gasoline vehicle, the savings on fuel costs are notably less than the incremental vehicle cost of the NG vehicle. High NG vehicle costs will effectually negate the fuel price advantage of natural gas over gasoline. From a policy standpoint, the current alternative vehicle tax credits are essential to the sustainable deployment of NG vehicles. The tax credit displaces a substantial amount of the incremental cost, and should be extended to 2030 under the

NATGAS act. Notably, NG vehicles do not completely take over the new vehicle fleet, even with extended vehicle tax credits.

Modifications should be done to the EPA safety standards and processes in order to reduce the costs transferred to consumers, otherwise at current incremental cost little to no market penetration occurs. Stringent emissions policies also facilitate the development of NG vehicles, with a potential increase of up to 45 percent in the share of new vehicles sold for the 450 ppm limit policy case. With a carbon tax, the cost difference between natural gas and gasoline grows significantly, making NG vehicles even more attractive to consumers.

This study also establishes that the development of bio-fuels, which have a better infrastructural tie-in with gasoline, may prove detrimental to NG vehicle deployment in the long term. Also, despite higher vehicle costs, electric hybrids have a higher affinity for growth than natural vehicles, especially in policy scenarios. The lack of an existing refueling infrastructure is a hindrance to NG vehicle fuels, and necessitates the development of refueling stations (station or home) as a priority. Without a refueling infrastructure, the long distances that motorists would have to travel to refuel may offset the savings and emissions reduction of NG vehicles.

Since natural gas vehicles would not take over the entire new vehicle market share by 2100, their effect on the total transportation fleet would remain minimal. At the most optimistic of assumptions, the implementation of NG vehicles could reduce carbon dioxide emissions from the U.S. light duty fleet by 2 to 5 percent, and in all likelihood reduce oil imports as well. NG vehicle adoption may raise natural gas prices up to 8 percent above projected value, and reduce oil prices by as much as 5 percent below EPPA



estimates. However, the significant benefits of NG vehicles use are unattainable without large scale adoption. Barring a ban on high emissions vehicles (such as in India), or significant taxation on gasoline and diesel (such as in South America), it will be difficult to maximize the advantages of NG vehicles in the short term. This combined with high cost of infrastructure, will prove insurmountable to NG vehicles.

### ***5.1. Limitations of the Study***

The EPPA model that is used in this thesis is limited for a number of reasons. Like most recursive modeling systems there is a level of uncertainty in the EPPA model, which is further compounded with time. Stock and turnover of the vehicle fleet is not modeled in the current EPPA model. The payback analyses typically used for alternative vehicles cover a period of two to three years, while the EPPA model has 5-year intervals. Also, the volatility of natural gas prices over long periods further complicates any fuel expenditure estimations. My analysis is also limited to OEM dedicated CNG vehicles, and does not take into account bi-fuel or after-market conversion CNG vehicles.

### ***5.2. Future Work***

The fixed factor presented here is only an approximation for the actual turnover of vehicle capital stock. Ongoing work at the Joint Program is aimed at developing an explicit representation of the vintaging of car fleets. I also intend to separate the cost of fuel infrastructure from the GAS share, making it possible to analyze how much of an investment into infrastructure is necessary for the adoption of an alternative fuel vehicle technology. A further stratification of household transportation by mode and vehicle weight would also be important to analyze in the future.

## 6. REFERENCES

Achtnicht, M.; Buhler, G.; Hermeling, C. (2008). *Impact of Service Station Networks on Purchase Decisions of Alternative-fuel Vehicles*. Centre for European Economic Research, Mannheim, Discussion paper no.08-088. Retrieved on May 4, 2010, from <ftp://ftp.zew.de/pub/zew-docs/dp/dp08088.pdf>

Alternative Fuels and Advanced Vehicles Data Center [AFDC] (2009). *Annual Average Retail Fuel Prices in the U.S.* Alternative Fuels and Advanced Vehicles Data Center; Data, Analysis & Trends. Retrieved on May 4, 2010, from <http://www.afdc.energy.gov/afdc/data/>

Bandivadekar A., Bodek K., Cheah L., Evans C., Groode T., Heywood J., Kasseris E., Kromer M., Weiss M. (2008). *On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions*. Laboratory for Energy and the Environment, Massachusetts Institute of Technology. Retrieved on May 4, 2010, from [http://web.mit.edu/sloan-auto-lab/research/beforeh2/otr2035/On%20the%20Road%20in%202035\\_MIT\\_July%202008.pdf](http://web.mit.edu/sloan-auto-lab/research/beforeh2/otr2035/On%20the%20Road%20in%202035_MIT_July%202008.pdf)

Cambridge Energy Research Associates [CERA](2010). Diegel S.W.; Boundy R. G. (2009). *Fueling North America's Energy Future: The Unconventional Natural Gas Revolution and the Carbon Agenda*. IHS Cambridge Energy Research Associates. Retrieved on May 4, 2010, from <http://www.cera.com/asp/cda/client/mcs/MCSChapter.aspx?KID=231&CID=10959>

Clean Vehicle Education Foundation [CVEF] (1999). *How Safe are Natural Gas Vehicles?* Technology Committee Bulletin, Clean Vehicle Education Foundation [CVEF]. Retrieved on May 4, 2010, from <http://www.cleanvehicle.org/committee/technical/PDFs/Web-TC-TechBul2-Safety.pdf>

Davis, S.C.; Diegel S.W.; Boundy R. G. (2009). *Transportation Energy Data Book: Edition 28*. Center for Transportation Analysis, Energy and Transportation Science Division. Retrieved on May 4, 2010, from [http://cta.ornl.gov/data/tedb28/Edition28\\_Full\\_Doc.pdf](http://cta.ornl.gov/data/tedb28/Edition28_Full_Doc.pdf)

Department of Energy [DOE] (2003). *Natural Gas: Just the Basics*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Retrieved on May 4, 2010, from [http://www1.eere.energy.gov/vehiclesandfuels/pdfs/basics/jtb\\_natural\\_gas.pdf](http://www1.eere.energy.gov/vehiclesandfuels/pdfs/basics/jtb_natural_gas.pdf)

Department of Energy [DOE] (2008). *Clean Cities: Natural Gas Fact Sheet*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Retrieved on May 4, 2010, from <http://www.afdc.energy.gov/afdc/pdfs/42946.pdf>

Department of Energy [DOE] (1999). *Barwood Cab Fleet Study Summary: Alternative Fuel Case Study*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Retrieved on May 4, 2010, from <http://www.nrel.gov/docs/fy99osti/26334.pdf>

Department of Transportation [DOT] (2002). *Effects of the Alternative Motor Fuels Act CAFE Incentives Policy*. U.S. Department of Transportation. Retrieved on May 4, 2010, from <http://www.nhtsa.dot.gov/cars/rules/rulings/CAFE/alternativefuels/AMFAReporttoCongress.pdf>

Department of Transportation [DOT] (2008). *Transportation Vision for 2030*. U.S. Department of Transportation, Research and Innovative Technology Administration. Retrieved on May 4, 2010, from [http://www.rita.dot.gov/publications/transportation\\_vision\\_2030/pdf/entire.pdf](http://www.rita.dot.gov/publications/transportation_vision_2030/pdf/entire.pdf)

Dimaranan, B. & McDougall, R. (2002). *Global Trade, Assistance, and Production: The GTAP 5 Data Base*. Center for Global Trade Analysis, Purdue University, West Lafayette, Indiana. Retrieved on May 4, 2010, from [http://www.gtap.agecon.purdue.edu/databases/v5/v5\\_doco.asp](http://www.gtap.agecon.purdue.edu/databases/v5/v5_doco.asp)

Dursbeck ,F.; Erlandsson, L.; Weaver, C. (2001). *Status of Implementation of CNG as a Fuel for Urban Buses in Delhi*. Centre for Science and Environment, New Delhi. Retrieved on May 4, 2010, from <http://old.cseindia.org/campaign/apc/pdf/CNGEXPER.PDF>

Engerer, H.; Horn, M.; (2009). *Natural gas vehicles: An option for Europe*. *Energy Policy*. doi:10.1016/j.enpol.2009.10.054. German Institute for Economic Research. Retrieved on May 4, 2010, from <http://www.sciencedirect.com/science/article/B6V2W-4XSSV3C-2/2/dc74d2716232d06cddd09c9bf36e076e>

Energy Information Administration [EIA] (1996). *Describing Current and Potential Markets for Alternative-Fuel Vehicles*. Energy Information Administration, Washington, DC: U.S. Department of Energy. Retrieved on May 4, 2010, from [http://www.eia.doe.gov/oiaf/aeo/pdf/0383\(2009\).pdf](http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2009).pdf)

Energy Information Administration [EIA] (2008). *The Impact of Increased Use of Hydrogen on Petroleum Consumption and Carbon Dioxide Emissions*. Energy Information Administration, Office of Integrated Analysis and Forecasting; Office of

Coal, Nuclear, Electric and Alternate Fuels. Washington, DC: U.S. Department of Energy. Retrieved on May 4, 2010, from <http://www.eia.doe.gov/oiaf/servicerpt/hydro/pdf/oiafcneaf%2808%2904.pdf>

Energy Information Administration [EIA] (2009). *Annual Energy Outlook 2009*. Energy Information Administration, Office of Integrated Analysis and Forecasting, Washington, DC: U.S. Department of Energy. Retrieved on May 4, 2010, from [http://www.eia.doe.gov/oiaf/aeo/pdf/0383\(2009\).pdf](http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2009).pdf)

Energy Information Administration [EIA] (2009)(a). *Emissions of Greenhouse Gases in the United States 2008*. Office of Integrated Analysis and Forecasting. Washington, DC: U.S. Department of Energy. Retrieved on May 4, 2010, from <http://www.eia.doe.gov/oiaf/1605/ggrpt/pdf/0573%282008%29.pdf>

Energy Information Administration [EIA] (2009)(b). *Natural Gas Gross Withdrawals and Production*. Energy Information Administration, Independent Statistics and Analysis and Forecasting. Retrieved on May 4, 2010, from [http://tonto.eia.doe.gov/dnav/ng/NG\\_PROD\\_SUM\\_DCU\\_NUS\\_A.htm](http://tonto.eia.doe.gov/dnav/ng/NG_PROD_SUM_DCU_NUS_A.htm)

Energy Information Administration [EIA] (2010)(a). *Annual U.S. All Grades All Formulation Retail Gasoline Prices*. Energy Information Administration, Independent Statistics and Analysis. Retrieved on May 4, 2010, from [http://tonto.eia.doe.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=mg\\_tt\\_us&f=a](http://tonto.eia.doe.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=mg_tt_us&f=a)

Energy Information Administration [EIA] (2010)(b). *Annual U.S. Natural Gas Vehicle Fuel Prices*. Energy Information Administration, Independent Statistics and Analysis. Retrieved on May 4, 2010, from [http://tonto.eia.doe.gov/dnav/ng/hist/na1570\\_nus\\_3a.htm](http://tonto.eia.doe.gov/dnav/ng/hist/na1570_nus_3a.htm)

Environmental Protection Agency [EPA] (2002). *Clean Alternative Fuels: Compressed Natural Gas*. Washington, DC: U.S. Environmental Protection Agency. Retrieved on May 4, 2010, from [http://www.afdc.energy.gov/afdc/pdfs/epa\\_cng.pdf](http://www.afdc.energy.gov/afdc/pdfs/epa_cng.pdf)

Environmental Protection Agency [EPA] (2006). *Greenhouse gas emissions from the U.S. Transportation Sector, 1990-2003*. Washington, DC: U.S. Environmental Protection Agency. Retrieved on May 4, 2010, from <http://www.epa.gov/oms/climate/420r06003.pdf>

Environmental Protection Agency [EPA] (2009). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2007*. Washington, DC: U.S. Environmental Protection Agency. Retrieved on May 4, 2010, from [http://www.epa.gov/climatechange/emissions/downloads09/GHG2007entire\\_report-508.pdf](http://www.epa.gov/climatechange/emissions/downloads09/GHG2007entire_report-508.pdf)

Environmental Protection Agency [EPA] (2009)(b). *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2009*. Washington, DC: Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Retrieved on May 4, 2010, from <http://www.epa.gov/otaq/cert/mpg/fetrends/420r09014.pdf>

Greene D.L., Schafer A. (2003). *Reducing Greenhouse Gas Emissions from U.S. Transportation*. Pew Center on Global Climate Change. Retrieved on May 4, 2010, from <http://www.pewclimate.org/docUploads/ustransp.pdf>

Greene D.L. (1997). *Survey Evidence on the Importance of Fuel Availability to Choice of Alternative Fuels and Vehicles*. Center for Transportation Analysis, Energy and Transportation Science Division. Retrieved on May 4, 2010, from <http://ntl.bts.gov/lib/000/700/723/survey.pdf>

Hellman K.H., Piotrowski G.K., Schaefer R.M. (1994), *Evaluation of Specialized Methane Catalytic Converters on a CNG-Fueled Vehicle*, SAE Technical Paper Series 940473. Retrieved on May 4, 2010, from <http://www.sae.org/technical/papers/940473>

Hertel, T. (1997). *Global Trade Analysis: Modeling and Applications*. Cambridge University Press, Cambridge, United Kingdom. . Retrieved on May 4, 2010, from [https://www.gtap.agecon.purdue.edu/products/gtap\\_book.asp](https://www.gtap.agecon.purdue.edu/products/gtap_book.asp)

Higgins, C.J., Matthews, H.S., Hendrickson, C.T., & Small, M.J. (2007). Lead demand of future vehicle technologies. *Transportation Research Part D*. 12, 103-114. Retrieved on May 4, 2010, from <http://cat.inist.fr/?aModele=afficheN&cpsidt=18587404>

International Association for Natural Gas Vehicles [IANGV] (2009). *Natural Gas Vehicles Statistics 2009*. International Association for Natural Gas Vehicles. Retrieved on May 4, 2010, from <http://www.iangv.org/tools-resources/statistics.html>

Karplus V.J. (2008). *Prospects for Plug-in Hybrid Electric Vehicles in the United States: A General Equilibrium Analysis*. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change. [http://globalchange.mit.edu/files/document/MITJPSPGC\\_Rpt172.pdf](http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt172.pdf)

Lave L.B., Griffin W.M., Maclean H. (2001). *The Ethanol Answer to Carbon Emissions*. Issues in Science and Technology, Winter 2001. Retrieved on May 4, 2010, from <http://www.nap.edu/issues/18.2/lave.html>

Mathiesen, L. (1985). Computation of economic equilibrium by a sequence of linear complementarity problems. *Mathematical Programming Study*, 23,144-162.

Melillo J.M., Gurgel A.C., Kicklighter D.W., Reilly J.M., Cronin T.W., Felzer B.S., Paltsev S., Schlosser C.A., Sokolov A.P., Wang X. (2009). *Unintended Environmental Consequences of a Global Biofuels Program*. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change. Retrieved on May 4, 2010, from [http://globalchange.mit.edu/files/document/MITJPSPGC\\_Rpt168.pdf](http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt168.pdf)

National Academy of Sciences [NAS] (2009). *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*. Committee on Health, Environmental, and Other External Costs and Benefits of Energy Production and Consumption; National Research Council. Retrieved on May 4, 2010, from <http://www.nap.edu/catalog/12794.html>

National Petroleum Council [NPC] (2007). *Facing the Hard Truths about Energy*. National Petroleum Council. Retrieved on May 4, 2010, from <http://www.npchar truthsreport.org/download.php>

National Renewable Energy Laboratory [NREL] (2006). *Consumer Views on Transportation and Energy (Third Edition)*. Technical Report NREL/TP-620-39047. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy <http://www.nrel.gov/docs/fy06osti/39047.pdf>

National Fire Protection Association [NFPA] (2000). *NFPA 52 –Compressed Natural Gas Vehicular Fuel Systems Code –2000*. National Fire Protection Association. Retrieved on May 4, 2010, from [http://www.nfpa.org/aboutthecodes/list\\_of\\_codes\\_and\\_standards.asp](http://www.nfpa.org/aboutthecodes/list_of_codes_and_standards.asp)

Paltsev, S., Reilly, J., Jacoby, H.D., Eckaus, R.S., McFarland, J., Sarofim, M., Asadoorian, M. & Babiker, M. (2005). *The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. Report 125*. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change. Retrieved on May 4, 2010, from [http://globalchange.mit.edu/files/document/MITJPSPGC\\_Rpt125.pdf](http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt125.pdf)

Paltsev, S., Viguiier, L., Babiker, M., Reilly, J. & Tay, K.H. (2004)(a). *Disaggregating household transport in the MIT EPPA model*. Technical Note 5. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change. [http://web.mit.edu/globalchange/www/MITJPSPGC\\_TechNote5.pdf](http://web.mit.edu/globalchange/www/MITJPSPGC_TechNote5.pdf)

Paltsev, S., Viguiier, L., Jacoby H.D., Babiker, M., Reilly, J. (2004)(b). *Modeling the Transport Sector: The Role of Existing Fuel Taxes in Climate Policy*. Report No. 117. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change. [http://web.mit.edu/globalchange/www/MITJPSPGC\\_Rpt117.pdf](http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt117.pdf)

Rosencranz A., Jackson M. (2003) *The Delhi Pollution Case: The Supreme Court of India and the Limits of Judicial Power*. Columbia Journal of Environmental Law [http://www.cleanairnet.org/caiasia/1412/articles-69423\\_delhi\\_case.pdf](http://www.cleanairnet.org/caiasia/1412/articles-69423_delhi_case.pdf)

Rutherford, T.F. (1995). *Extension of GAMS for complementarity problems arising in applied economic analysis*. Journal of Economic Dynamics and Control, 19(8), 1299-1324.

Schäfer A., Heywood J. B., Jacoby H.D., Waitz I.A. (2009). *Transportation in a Climate-Constrained World*. The MIT Press, Cambridge, Massachusetts.

Whalen P., Kelly K., John M. (1999). *Barwood Cab Fleet Study: Final Results*. NREL/TP-540-26035. National Renewable Energy Laboratory, U.S. Department of Energy. Retrieved on May 4, 2010, from <http://www.osti.gov/bridge/purl.cover.jsp?purl=/6733-A1qqLK/native/>

(WoodMackenzie, 2006). *Unconventional Hydrocarbons: The Hidden Opportunity*. Wood Mackenzie Consulting  
<http://www.petroleum-economist.com/default.asp?Page=14&PUB=279&SID=700775&ISS=24502>

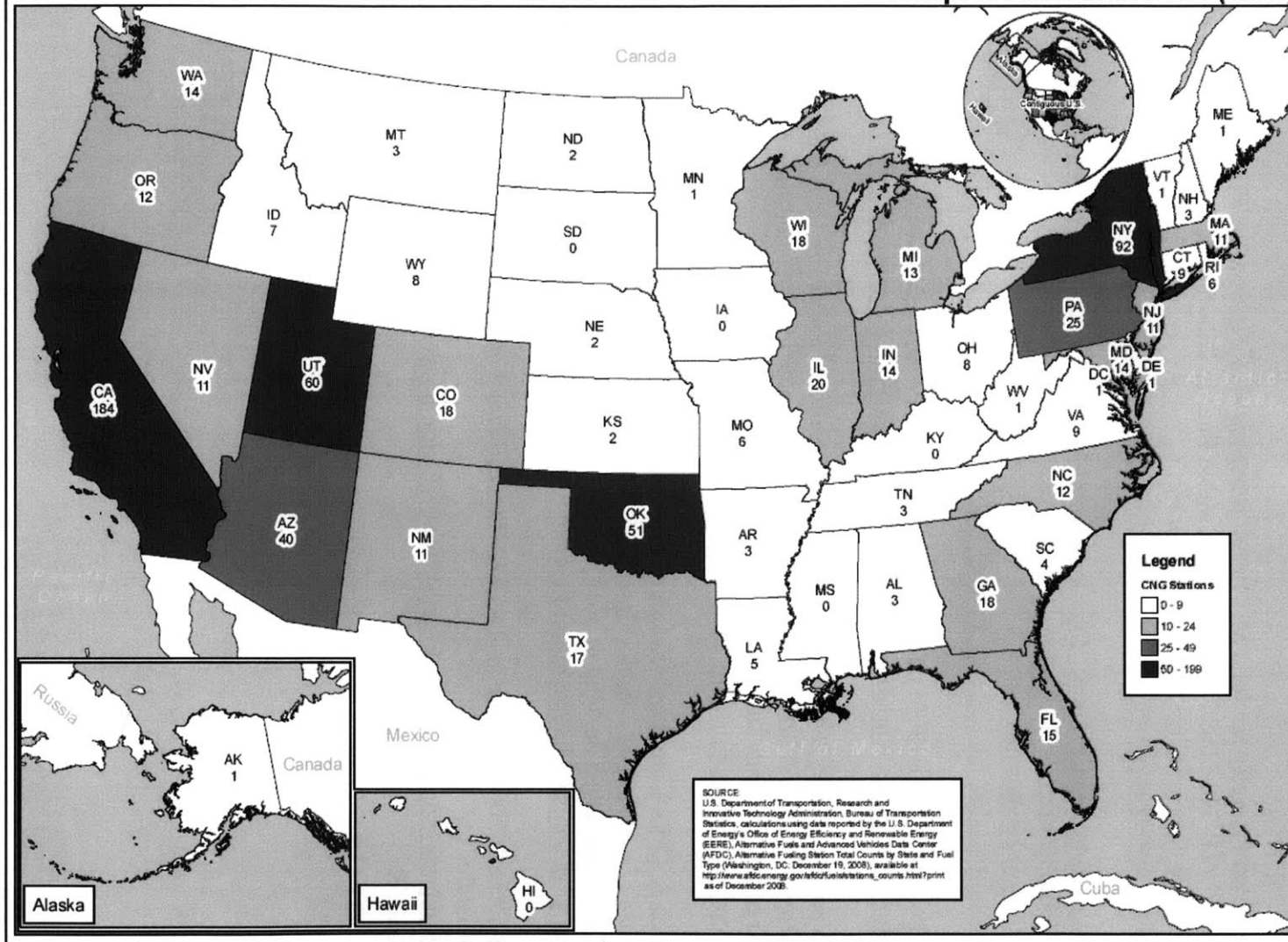
The World Bank (2001). *International Experience with CNG vehicles*.  
<http://www-wds.worldbank.org/external/default/WDSPContentServer/WDSP/IB/2002/05S>

Wang M. (1999). *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model Version 1.5*. Center for Transportation Research Argonne National Laboratory. Retrieved on May 4, 2010, from <http://www.transportation.anl.gov/pdfs/TA/264.pdf>

Yeh S. (2007). *An empirical analysis on the adoption of alternative fuel vehicles: The case of natural gas vehicles*. Institute of Transportation Studies, University of California Davis. Retrieved on May 4, 2010, from [http://pubs.its.ucdavis.edu/publication\\_detail.php?id=1109](http://pubs.its.ucdavis.edu/publication_detail.php?id=1109)

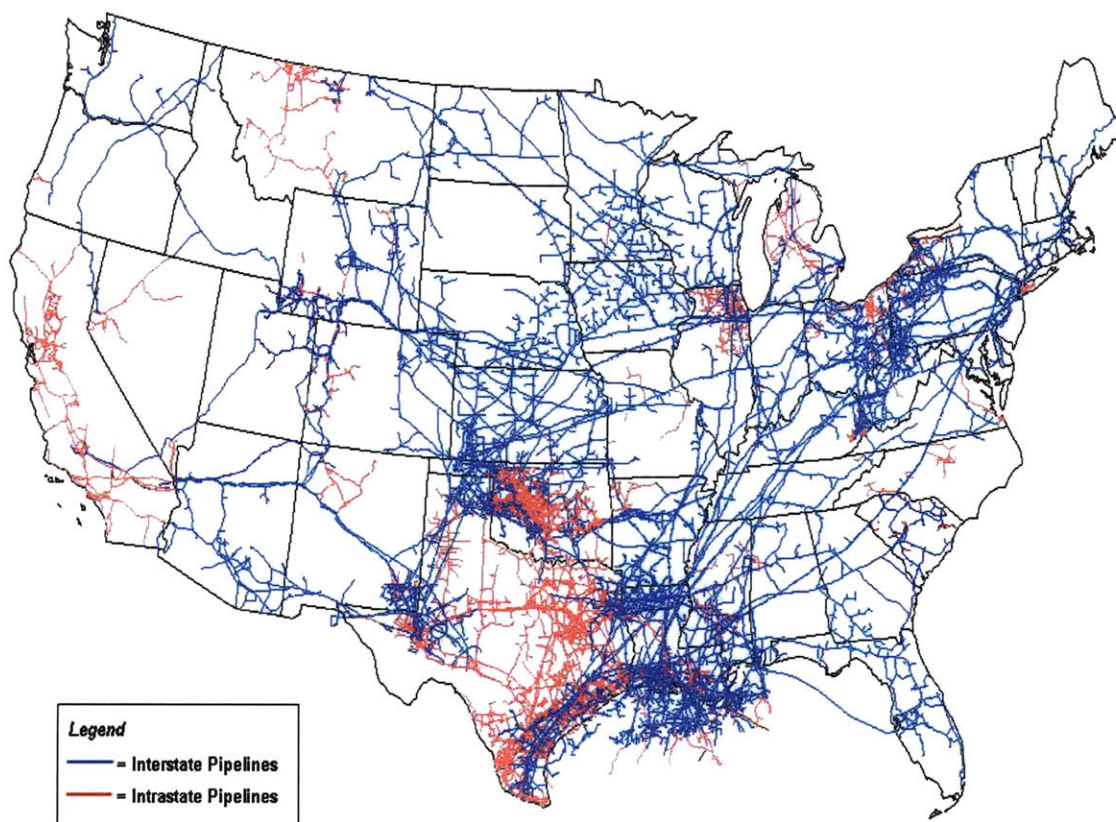
Yborra S (2008). *Guide to Available Natural Gas Vehicles and Engines*. Natural Gas Vehicles for America.  
<http://www.docstoc.com/docs/20016803/Guide-to-Available-Natural-Gas-Vehicles-and-Engines>

## Alternative Fueling Stations by Type and State Compressed Natural Gas (CNG)





## APPENDIX B: U.S. Natural Gas Pipeline Infrastructure



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

## APPENDIX C: Backstop Sensitivity Analysis

$$F_t(r) = F_{t-1}(r) + \boxed{I_0(r)} \times \left( \frac{NGV_t(r)}{H_t(r)} \right)^{\boxed{0.25}}$$

Initial Share
Exponential

