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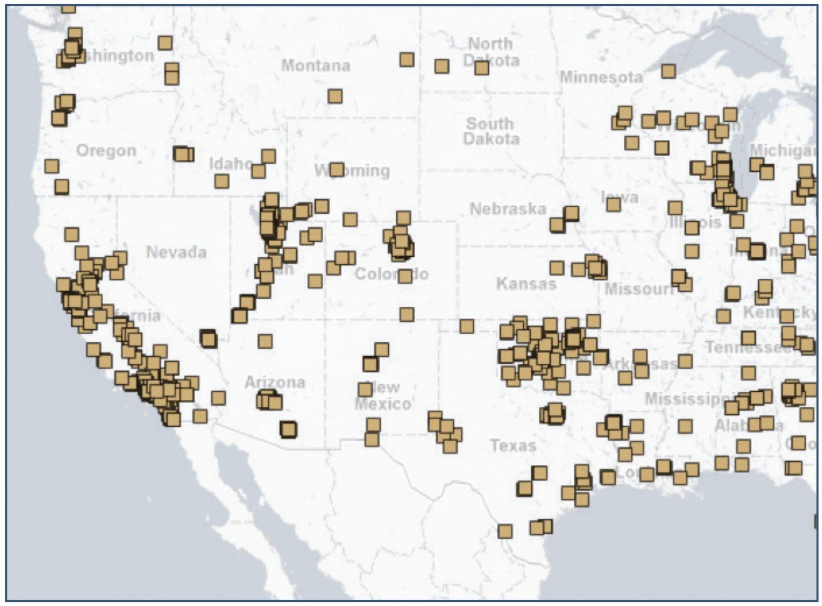

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DO CHANGING PRICES PORTEND A SHIFT IN FUEL CONSUMPTION, DIMINISHED GREENHOUSE GAS EMISSIONS, AND LOWER FUEL TAX REVENUE?

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ABSTRACT

The growing uncertainty about oil prices and availability has made long-range transportation planning more challenging. Rather than relying on trend extrapolation, this study uses market mechanisms to evaluate key long-range transportation planning assumptions. Although the Washington Department of Transportation (WSDOT) is pursuing alternative fuels and energy sources, this study focuses primarily on natural gas. In particular, this study will help WSDOT assess the likelihood natural gas will substitute for petroleum fuels and estimate the impact changes in fuel prices will have on travel demand, fuel consumption, emissions, and tax revenues.

The results of the modeling show that the impacts of natural gas vehicles (NGV) have the potential to affect vehicle miles traveled (VMT), emissions, and fuel tax revenue. The effects of NGVs are muted by the limited use of them in the fleet. Challenges with widespread integration include the increased upfront capital costs associated with NGVs, decreased power for heavy vehicles, and range anxiety in locations without developed natural gas fueling infrastructure. The NGV market in the state of Washington is hampered by these factors. The modeling and analysis in this report can be used to analyze changing conditions in the market and the effects on key transportation metrics.

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EXECUTIVE SUMMARY

This report responds to an inquiry by the State of Washington about the viability of natural gas as an alternative source of energy for transportation. The report is organized around responses to several key research tasks. These tasks are to: (1) document the increase in the supply of natural gas and estimate future price and availability; (2) assess the extent to which natural gas is likely to substitute for petroleum; (3) estimate the extent to which price and performance effects will influence VMT trends in Washington State; (4) estimate changes in GHG emissions in Washington State attributable to increased use of natural gas; (5) estimate potential loss of fuel tax revenue attributable to substitution of natural gas for petroleum fuels.

The report finds that natural gas enjoys a per-BTU cost advantage over petroleum in the United States and this price advantage is likely to persist for the foreseeable future. This price advantage is largely the result of the lower natural gas prices that have followed the increased supply created by new extraction technologies. Moreover, petroleum prices are likely to remain at or near historically high levels due to increasing demand and rising extraction costs. This price difference is also likely to persist because of the high cost of transporting a pressurized gas over long distances where pipelines are not present. Unlike petroleum, which is relatively low cost to transport, natural gas markets tend to be regionalized, with low prices in areas that are near large reserves of natural gas. The relative abundance of natural gas in the United States and the extensive domestic pipeline network suggest that natural gas prices will enjoy a significant price advantage over petroleum as an energy source for many years.

Although natural gas is a low-cost source of energy, as a transportation fuel, natural gas competes with many alternatives, including some that have been (or are) the recipients of heavy government subsidies. These alternatives include gasoline-hybrid vehicles as well as alternatives like plug-in electric and bio-fuel vehicles. Moreover, widespread adoption of natural gas vehicles (NGVs) requires substantial investment in natural gas fueling infrastructure. While some states have been particularly aggressive in creating this infrastructure, natural gas vehicles represent only a small fraction of the vehicle fleet even in these areas.

Observed adoption rates for natural gas vehicles are low for several reasons. On the supply side, very few natural gas vehicles are available directly to consumers from manufacturers, and fueling infrastructure is undeveloped in many areas. On the demand side, natural gas vehicles have several disadvantages and limitations that limit appeal to consumers. In particular, natural gas vehicles tend to be substantially more expensive (or are expensive to retro-fit), and are typically less powerful, heavier, have less storage/trunk space, and have more limited range due to the smaller capacity fuel tanks. Despite the fuel cost savings, these disadvantages tend to make natural gas vehicles an uneconomical choice for most consumers. These models of consumer preferences suggest that a substantial decrease in the price of natural gas vehicles would be necessary to induce a notable increase in light-duty NGV adoption rates. Moreover, the model predicts that, even at very low conversion costs or manufacturer price differentials, NGVs are likely to remain a minority in the vehicle fleet. In contrast, natural gas may represent an attractive alternative for a substantial portion of the heavy-duty vehicle fleet, and there is evidence of increasing adoption rates in this sector. However, data limitations preclude estimating the adoption rates in this sector using the same techniques used to estimate adoption rates in the light-duty sector.

Vehicle miles traveled (VMT) and VMT per capita in Washington State were modeled. It has been found that VMT is more highly sensitive to variables that are correlated with overall population size (the number of registered vehicles and total employment) than to fuel prices. Additionally, it has been found that per-capita VMT has been declining in recent years and aggregate VMT in Washington State has been increasing steadily due to increased population. Higher fuel prices do have a negative effect on VMT, although the estimated elasticity is relatively low. Finally, the results indicate that adoption of natural gas vehicles is unlikely to have a substantial effect on VMT.

On a per-unit of energy basis, natural gas is about 20% less carbon intensive than gasoline. NGV adoption therefore represents an opportunity for the State of Washington to reduce carbon emissions from the transportation sector. The potential for reduced carbon emissions are estimated based on this model of consumer adoption of light-duty NGVs and based on reasonable assumptions about NGV adoption in the heavy-duty vehicle sector. Also, under current price conditions, these models suggest only about a 0.02% decrease in carbon emissions from the light-duty vehicle sector due to NGV adoption. If price conditions become much more favorable, this figure could rise to 1.16%. Emissions from the heavy-duty vehicle fleet depend heavily on adoption rates, which, unfortunately, are not directly estimable with existing data. However, reasonable assumptions suggest that reductions from this sector of the fleet are unlikely to exceed 7%, even under conditions of extremely optimistic adoption rates. Overall, transportation sector emissions (light- and heavy-duty fleet combined) are unlikely to be reduced by more than 4% overall.

Finally, the report investigated the threat of increased fuel efficiency on fuel tax revenues. Alternatively fueled vehicles such as natural gas vehicles and electric vehicles have started to erode fuel tax revenues. In addition, as a result of federal fuel efficiency standards, automobile manufacturers have started to make all vehicles more fuel efficient. If the current taxing structure continues into the 2020s, WSDOT will experience significant decreases in the amount of revenue generated by the current state fuel tax. This reduction in revenue may necessitate shifting to other revenue sources to replace the fuel tax revenue that is no longer collected.

1. INTRODUCTION

The Washington State Department of Transportation (WSDOT) is responsible for planning, operating, and maintaining a highway network consisting of over 18,500 lane-miles of highway. About 86 million vehicle miles per day operate on this highway network. Planning and building highways is a long-range enterprise. It requires making many assumptions about future travel demand as well as estimating future fuel tax revenue. In recent years, growing uncertainty about oil prices and changing automobile technology has made long-range transportation planning even more challenging.

Rather than relying on trend extrapolation, this study will use market mechanisms to shed light on key long-range transportation planning assumptions. Although WSDOT is pursuing a variety of alternative fuels and energy sources including Electric Vehicles (EVs), biofuels, propane, natural gas, and their respective infrastructures, this study focuses primarily on natural gas. In particular, this study will help WSDOT assess the likelihood that natural gas will substitute for petroleum fuels. The study also estimates the impact changes in fuel prices are likely to have on travel demand, fuel consumption, greenhouse gas (GHG) emissions, and fuel tax revenues.

With oil prices rising, it is natural for drivers to conserve funds by driving less and/or purchasing more fuel-efficient vehicles. Two immediate effects of reduced fuel usage are the reduction in fuel tax revenue and lower GHG emissions. Reduction of GHG emissions is an important goal of WSDOT.

In several important respects, natural gas has the potential to be an attractive substitute for petroleum. Natural gas prices in the U.S. have fallen more than 60% from their peak in 2008. Proven reserves are approaching all time high levels (despite reduced exploration). The increasing price for petroleum and decreasing price for natural gas, at BTU parity quantities, means there is a growing cost advantage for natural gas. Natural gas also has the attractive feature of emitting fewer GHG, specifically CO_2, increasing progress toward climate change goals. Electric vehicles are another option that may become more attractive if the price of oil continues to increase. This is particularly true in the parts of the Pacific Northwest that have low-cost hydropower. Major manufacturers have only recently begun marketing electric vehicles, and public response to these offerings may provide insight into acceptance of electric vehicles. Forecasting adoption of electric vehicles is complicated by the considerable uncertainty regarding future advances in battery technology and lifecycle prices to consumers. (Al-Alawi & Bradley, 2013)

One important item is the degree to which consumers and suppliers respond both to price changes and to a changing regulatory environment. Forecasting changes in natural gas usage in vehicles over time is complicated by the fact that consumers cannot easily, given the current infrastructure, switch fuel types in response to short-run price changes. These price and regulatory changes can therefore have sharply different short- and long-run effects. Moreover, substantial uncertainty exists with respect to future regulation and technology as well as prices. Even forecasts that are based on accurate models of consumer behavior are still subject to uncertainty regarding price and policy changes. Current research indicates that increased gasoline prices lead to the purchase of more fuel-efficient vehicles. (Li et al., 2009) A key feature of the proposed study will be to assess the degree to which price can be expected to result in increased use or adoption of Compressed Natural Gas (CNG).

The report first presents two sections on transportation energy production, supply, and demand with a following section providing specific analysis on the markets for natural gas. Sections follow on the availability of natural gas vehicles and a model for consumer response to changing natural gas vehicle prices. Following the presentation of the consumer choice model, models are presented on the effect of natural gas vehicles on vehicle miles traveled (VMT), transportation emissions, and fuel tax revenue. The report closes with conclusions for WSDOT.

2. ENERGY PRODUCTION, SUPPLY AND DEMAND

New drilling and recovery techniques have resulted in a dramatic increase in the amount of recoverable natural gas and a consequent decrease in domestic natural gas prices (Paltsev et al., 2011). These increased levels of production have influenced outcomes in many sectors of the domestic and global economy. Because natural gas is a substitute for oil, coal, and other energy sources, it is important to consider these changes in the context of global energy demand.

Figure 2.1 shows yearly world, OECD (Organization for Economic Cooperation and Development), and U.S. oil demand (consumption) over the period 1997-2012. Although consumption levels for economically developed countries have remained relatively flat over this period, world demand has increased as world populations have grown and less-developed economies have experienced accelerated growth rates. This is consistent with general predictions from the developing world concerning the dramatic life improving changes that appliances and vehicles offer as a growing number of individuals enter the global middle class (Wolfram et al., 2012). Future demand for oil as well as the future demand for all energy will correspond with the growth of wealth in the rest of the world.

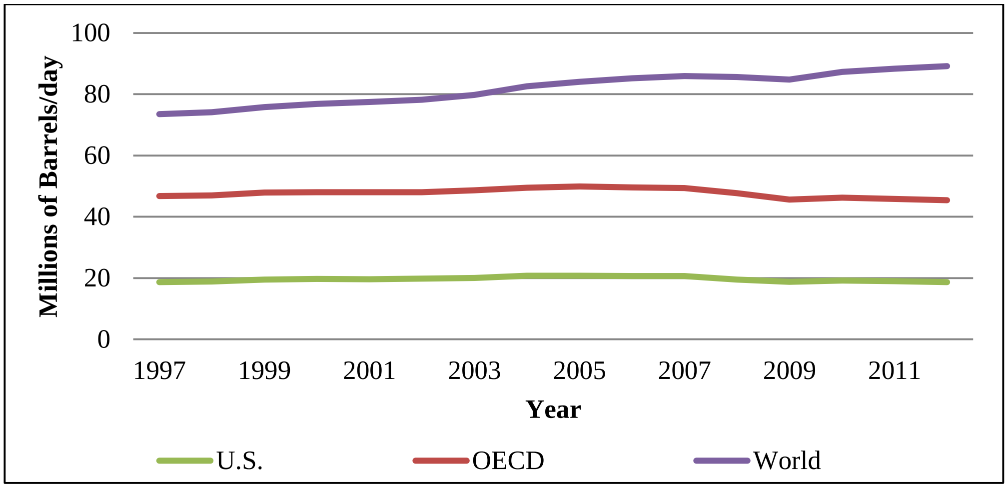


Figure 2.1 World, OECD, and U.S. Oil Demand (U.S. EIA, 2012)

2.1 Costs of Energy

Global economic growth has led to rising prices for many energy sources. The recession that started in 2007 contributed to a slight dip in the overall trend, but global demand for oil has continued to increase. The fact that world oil demand is more resistant to recessionary pressure than oil demand in advanced economies indicates the future of oil demand is likely to be very strong.

One solution to the increased demand for oil is to seek an increase in oil supply. Increases in supply would offset increases in demand and moderate price increases. This is occurring to some extent; price increases tend to spur increased extraction from more costly sources. One recent example of this increase in supply is Canada's oil sands. However, the cost of extracting usable fuel from this source is far in excess of the cost of creating the same quality fuel from Saudi Arabian light sweet crude (Maugeri, 2012). Another example is that the U.S. has experienced a rapid growth in onshore crude oil production since 2010, which results primarily from the development of tight oil resources, mostly in the Eagle Ford and Bakken shale formations. The tight oil production is expected to grow continuously to 4.8 million barrels per day in 2021 and then decline to 3.3 million barrels per day in 2040, as high-productivity areas are depleted. As shown in Figure 2.2, the domestic crude oil production will grow to 9.5 million barrels per day in 2016, close to the historical high level of 1970 (EIA, 2014).

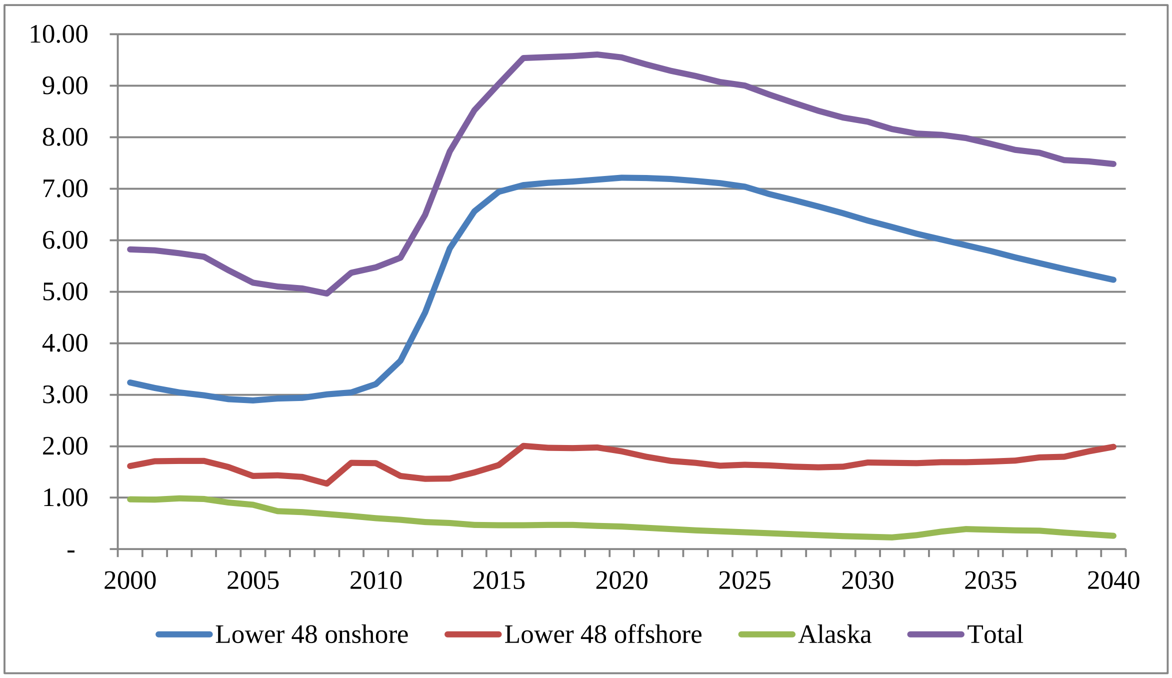


Figure 2.2 Domestic crude oil production by source (million barrels per day) (U.S. EIA, 2014)

2.2 The Cost of Extraction

Basic economics suggests the lowest cost resources of oil will be exploited when prices remain low. With low prices there is little incentive to innovate in the extraction of resources. As extraction gets costlier, the remaining resources are not extracted until the market rewards such costly behavior. In the oil and natural gas industry, rising prices are the mechanism that drives innovation in extraction techniques**.** The changes in extraction technologies should provide some relief to the cost curve and the supply curve for transportation energy. During the last dozen years these technological advances have enabled a very large increase in the economical production of natural gas. The following section provides more details of the technological advances in natural gas supply.

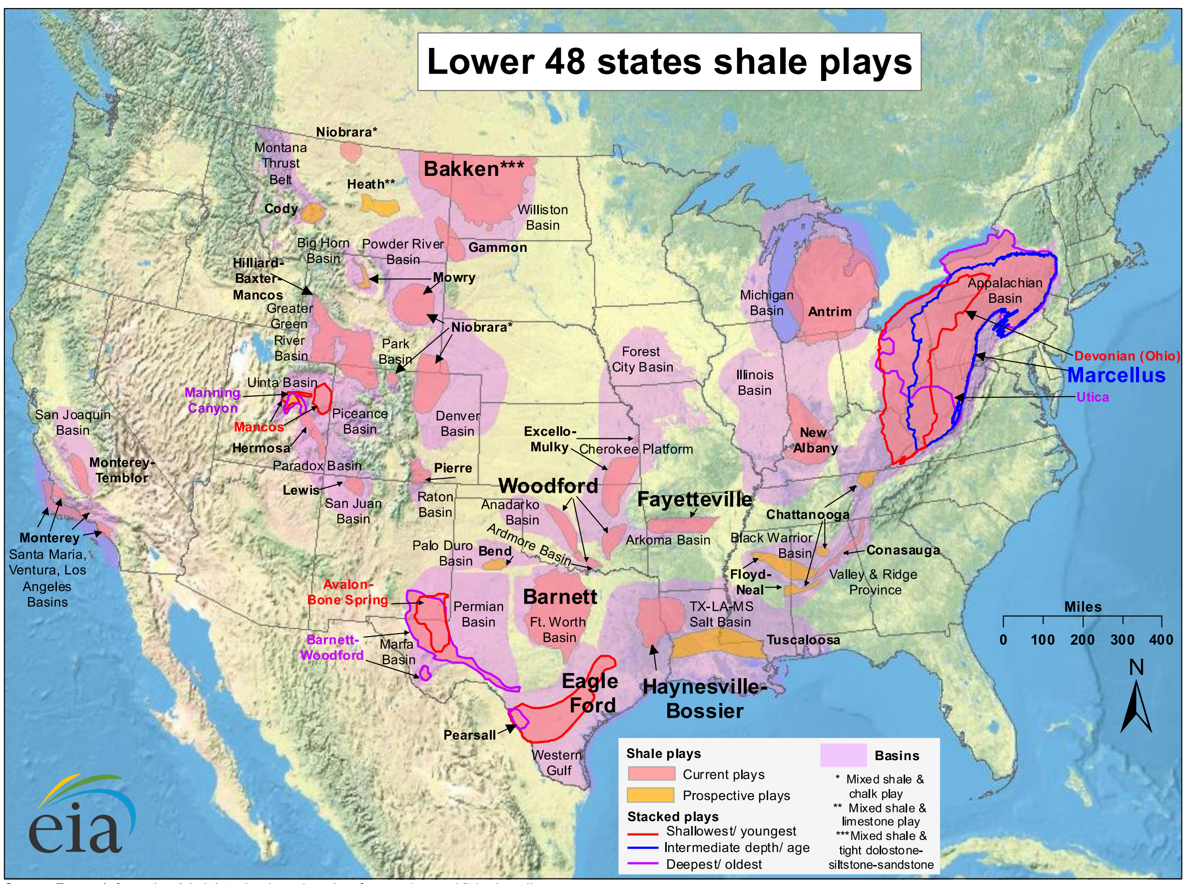
3. NATURAL GAS PRODUCTION, SUPPLY, AND PRICES

Although this report is primarily concerned with the use of natural gas as a vehicle fuel, it is important to consider that natural gas is primarily used for other purposes, including generating electricity, use in homes and restaurants, and powering industry. Demand for natural gas in these sectors can influence the use of natural gas as a transportation fuel.

3.1 Natural Gas Supply

Natural gas supply has dramatically increased in the last decade (Paltsev et al., 2011). The biggest change in the cost of natural gas extraction has been the development of hydraulic fracturing of gas reserves in shale formations. Shale is a porous stone with natural gas trapped as deposits in the stone. Accessing this with traditional drilling methods prior to hydraulic fracturing would have been far too costly considering the amount of gas extracted. Hydraulic fracturing allows for much of the gas to be displaced by injections of water, which allows for a dramatic increase in production per unit of cost.

The Potential Gas Committee, a nonprofit organization that receives guidance from the Colorado School of Mines, reported in its latest biennial assessment that the United States has a total natural gas resource base of 1,836 trillion cubic feet. Figure 3.1 provides a map detailing the areas of shale where natural gas can be extracted.



Source: Energy Information Administration based on data from various published studies.
Updated: May 9, 2011

Figure 3.1 Known U.S Natural Gas Reserves (EIA, 2012)

In the United States from 2006 to 2010 alone, the production of natural gas from shale rose 14%. Figure 3.2 shows aggregate U.S. natural gas production from 1997 to 2012. Figure 3.3 shows the trend in the number of natural gas wells in the U.S.

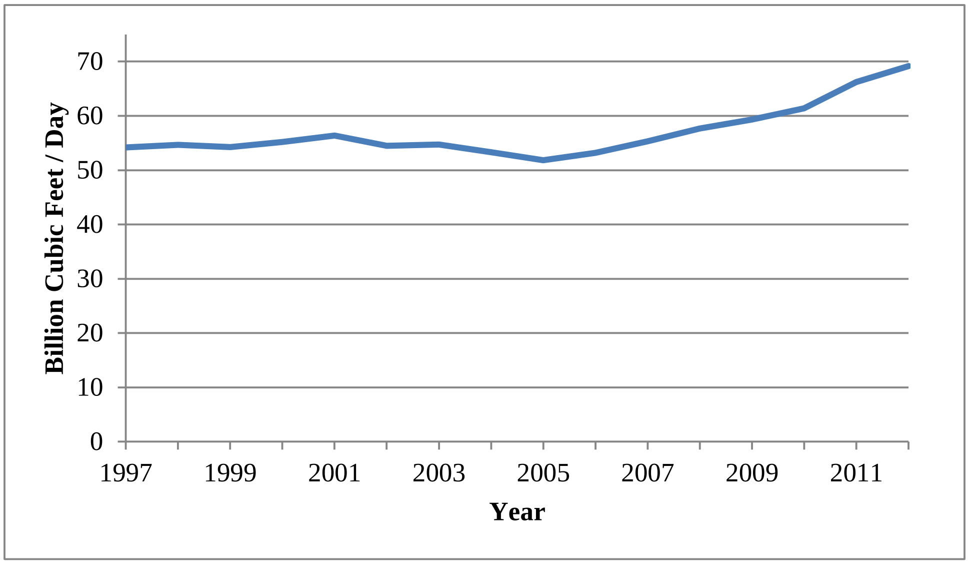


Figure 3.2 U.S. Natural Gas Production (Source: U.S. EIA)

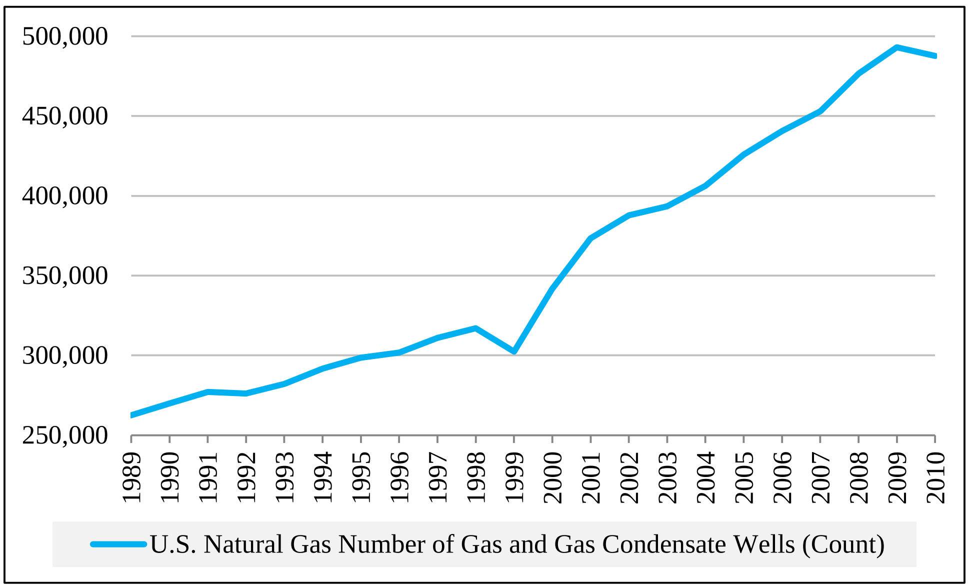


Figure 3.3 U.S. Natural Gas Number of Gas and Gas Condensate Wells (Source: U.S. EIA)

Most of the natural gas consumed in the United States is fossil fuel produced domestically by drilling. Significant additional reserves continue to be discovered mainly from unconventional resources, such as shale. Advanced drilling technologies are helping to spur increases in supply because they allow for the economic production of natural gas from complex geologic formations. From 1998 to 2007, the number of proven dry natural gas reserves in the United States rose every year for a total increase of 45% (74 trillion cubic feet); in contrast, U.S. proven oil reserves increased by only 1.3%.

3.2 Natural Gas in the State of Washington

Large-scale commercial production has never occurred in the state of Washington (McFarland, 1983) and is confirmed by data shown in Figure 3. However, small amounts of gas were produced from the Bellingham Gas Field and the Rattlesnake Hills Gas Field (McFarland, 1983). The most recent production, which was from the Ocean City Gas and Oil Field west of Hoquiam, ceased in 1962, and no oil or gas have been produced since that time. (Washington State Department of Natural Resources, 2014).

Figure 3.4 provides a comparison of natural gas prices for transportation fuel in the country and the state of Washington from 1989 to 2013. From 1990 to 2007, prices of natural gas used for transportation hovered below the national average. In 2008, this trend changed and the state of Washington average has stayed above the national average as natural gas usage for transportation has risen.

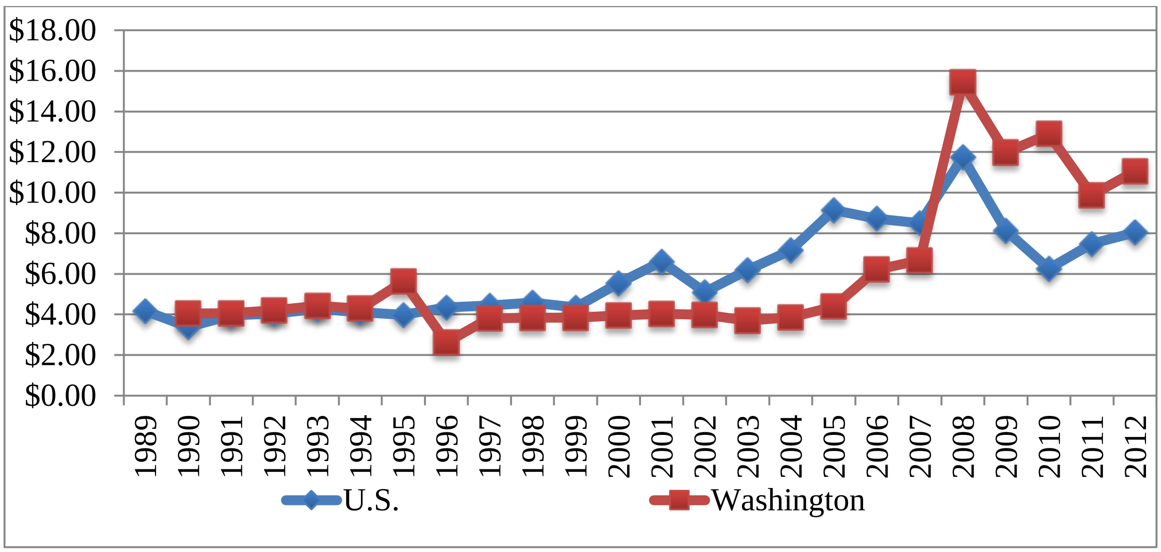


Figure 3.4 Natural Gas Vehicle Fuel Prices (In $ per Thousand Cubic Feet) (Source: EIA, 2014)

3.3 Natural Gas Prices and Energy Substitutability

The recent increase in natural gas production has led to a dramatic decrease in the price of energy produced from natural gas relative to other sources. In particular, natural gas now enjoys a large cost advantage over oil in the United States. Figure 3.5 shows the divergence in spot market prices over the period 1994-2012.

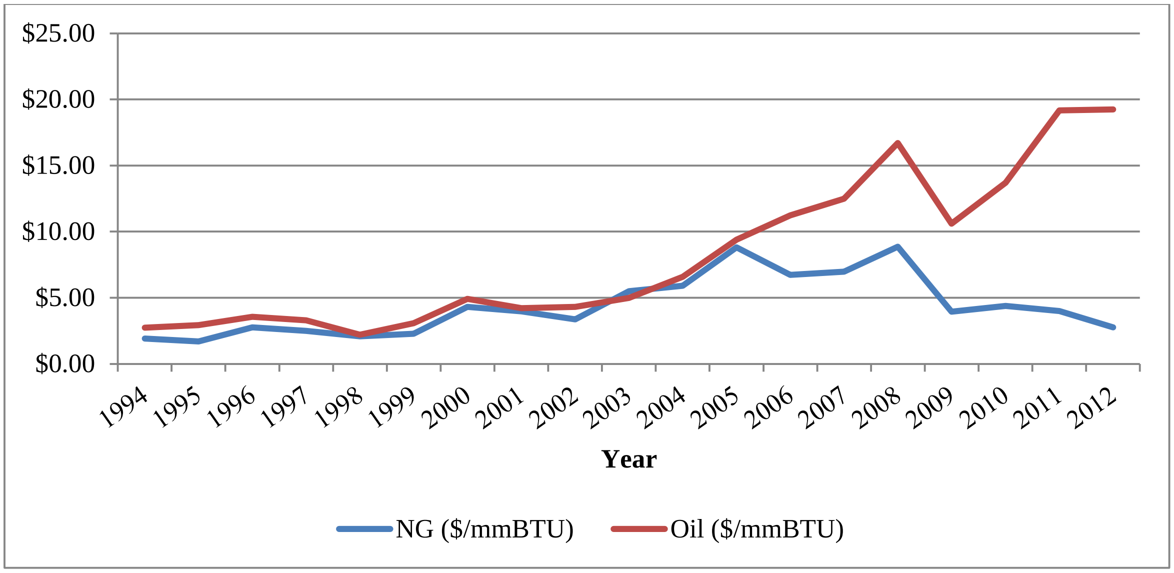


Figure 3.5 Energy Prices (Source: U.S. EIA)

Importantly, research suggests that natural gas will continue to enjoy a cost advantage over oil in the United States for many years. One reason for this is that, in contrast to world oil markets, natural gas markets are not highly integrated. Oil is transported across regions via pipelines, tankers, railways, and other means, and the research suggests that the world oil market is a single integrated market (Bachmeier & Griffin, 2006). In contrast, markets in coal, natural gas, and substitute energy sources tend to be more regional—they are not as integrated and regional price differences can persist for long periods of time (Bachmeier & Griffin, 2006; Siliverstovs et al., 2005).

For example, Paltsev et al. (2011) find that the supply of natural gas in the United States is projected to grow substantially between now and 2050, and that even a *low-end* estimate suggests supply growth through 2030. Summarizing their results, the authors find that "the outlook for gas over the next several decades is highly favorable" and that "[natural gas] resource supply is adequate to meet growing demand at moderate prices through 2050." Staub (2013) and Moniz (2011) also estimate growing resource supply and a long-term cost advantage for natural gas.

Growing natural gas supply, the regional nature of natural gas markets, increasing world demand for oil, and the existence of a world oil market suggest a natural gas price advantage will persist indefinitely. However, this cost advantage may be influenced by a number of factors. Moreover, some of these factors may influence the viability of natural gas as a transportation fuel.

3.3.1 Increased Electricity Generation via Natural Gas

Natural gas easily substitutes for coal in the production of electricity. This may put upward pressure on natural gas prices if electric utilities shift a large percentage of generating capacity from coal-fired to natural gas. Studies by Paltsev et al. (2011) and Moniz (2011) indicate the greatest value from increased natural gas supplies will be in displacing coal in generating electricity. Figure 3.6 shows the fall in the relative price of natural gas to coal and the subsequent increase in electricity generated via natural gas. Competitively priced natural gas has been gaining popularity and replacing power once supplied by coal plants. In 2000, natural gas accounted for 16% of the nation's electricity generation. The percentage jumped to 30% in 2012. On the other hand, coal accounted for 52% of the nation's electricity generation in 2000 and dropped to 37% in 2012 (EIA, 2014). It is expected that new programs encouraging renewable energy and regulations limiting greenhouse gas emissions will push coal-fired plants toward retirement. The nation's reliance on natural gas will increase, which may place upward pressure on natural gas prices depending on how much natural gas production increases. Moreover, the stagnation in electricity prices, coupled with economic growth, can result in an increase in the quantity of electricity demanded, reinforcing the upward pressure on natural gas prices. That being said, it is also worth noting that cheap coal puts a limit on the upward movement of natural gas prices. If natural gas becomes expensive, power plants would have an incentive to continue using coal.

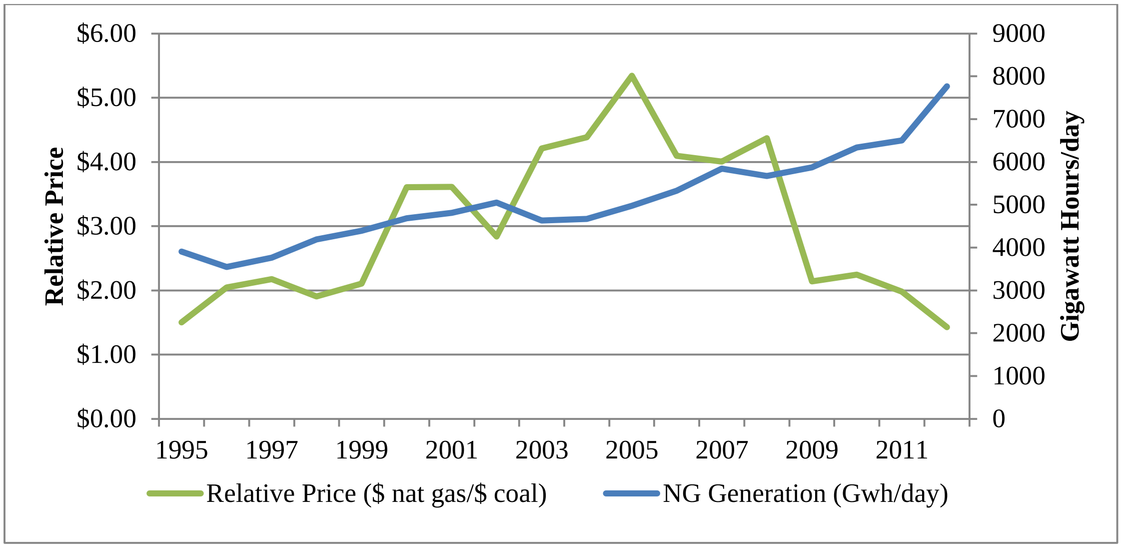


Figure 3.6 Relative Price in Dollars of Natural Gas to Coal and NG Generation

3.3.2 Integration of Natural Gas Markets

Natural gas markets are much more regionalized than oil markets. Research shows a high level of natural gas market integration within Europe, between the Europe and Japanese markets, as well as within the North American Market. The European and North American markets are not integrated (Siliverstovs et al., 2005). The domestic natural gas price may be influenced by the potential market integration over time (Neumann, 2012); however, the abundant supply of natural gas and low transportation costs domestically will likely keep natural gas prices low and stable in the U.S. for a long time. The low cost of natural gas production in Qatar, Libya, Algeria, and Iran may give those countries a competitive advantage over U.S. producers in supplying European and Asian markets.

3.3.3 Future Prices for Natural Gas and Oil

Figure 3.7 is the ratio of oil prices to natural gas prices defined in terms of Brent crude oil and the Henry Hub spot natural gas price on an energy-equivalent basis (EIA, 2013). It shows that natural gas will likely continue to enjoy a large cost/BTU advantage over oil through 2040, but the cost difference of the two fuels narrows over time. EIA estimates that even though both crude oil and natural gas prices will increase through 2040, the oil price will rise more slowly than the natural gas price. While this cost advantage of natural gas is likely to persist, it is important to note that, at current prices, CNG is not an economical option for most transportation uses and even small decreases in the price differential may strongly undermine the viability of natural gas as a transportation fuel.

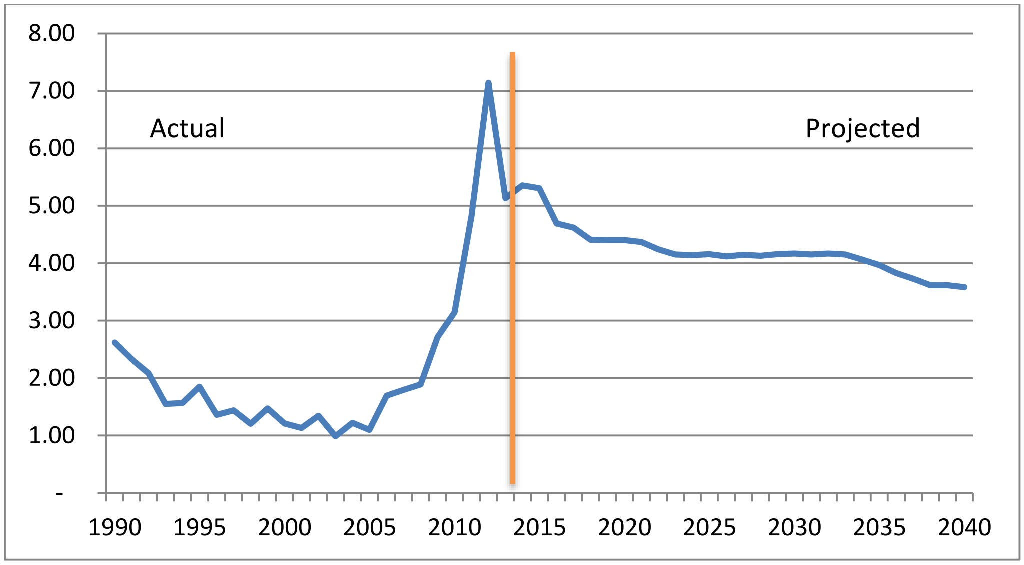


Figure 3.7 Ratio of Oil Price to Natural Gas Price in Energy-Equivalent Terms (EPA, 2013)

3.3.4 Changes in Government Policy

Although the natural gas supply is projected to increase in coming decades, several researchers have noted that natural gas prices, usage rates, and viability as a transportation fuel can be influenced by government policy. For example, government policies designed to aggressively reduce carbon emissions will strongly influence natural gas usage rates. Paltsev et al. (2011), Staub (2013), and Moniz (2011) note that the viability of CNG as a transportation fuel will depend on government policies in the areas of climate change, fuel taxes, and energy subsidies.

4. ALTERNATIVE FUEL VEHICLES: OPPORTUNITIES & TRADEOFFS

The price advantage enjoyed by natural gas relative to petroleum suggests an opportunity for consumers and industry to benefit by switching to CNG vehicles. However, natural gas currently accounts for a small percentage of the aggregate vehicle fleet. Moreover, consumers are increasingly presented with technologically advanced vehicles that utilize a variety of fuels and drivetrains. If CNG vehicles are to compete successfully in the marketplace, they must offer cost advantages over both ordinary gasoline vehicles as well as other alternatives. CNG presents opportunities for use in both passenger vehicles and heavy-duty commercial vehicles. Below is the discussion concerning these opportunities and trade-offs.

4.1 Natural Gas Vehicles: Current State of the Market

The U.S. lags many countries in the use of natural gas vehicles, as shown in Table 4.1, ranking 17th in NGV fleet size (NGV America, 2012). According to the Natural Gas Vehicle Association of America, there are currently approximately 120,000 NGVs in the U.S. fleet and 15.2 million NGVs worldwide (NGV America, 2012). There is a very small percentage of NGVs in Washington State. The Department of Energy (2012) reports that there are currently 519 public CNG stations in the United States and a total of 1,107 stations if private stations are included.

Table 4.1 Top 10 Countries for NGV Deployment and U.S. Ranking

Country	Number of Vehicles	% of Total NGVs Worldwide
Iran	2,859,386	18.82%
Pakistan	2,850,500	18.76%
Argentina	1,900,000	12.50%
Brazil	1,694,278	11.15%
India	1,100,000	7.24%
China	1,000,000	6.58%
Italy	779,090	5.13%
Ukraine	390,000	2.57%
Columbia	348,747	2.30%
Thailand	300,581	1.98%
United States (17th)	~120,000	> 1%

Adapted from Source: NGV America (2012)

Advantages to NGVs include the cost of fuel being $1.50 to $2.00 less than gasoline on a per-gallon equivalent basis. Home-fueling options are available to consumers that provide additional convenience to vehicle owners. According to the Natural Gas Vehicle Association of America (2012), replacing an older vehicle with a new NGV can provide the following reductions in emissions of:

- Carbon monoxide (CO) by 70%–90%
- Non-methane organic gas (NMOG) by 50%–75%
- Nitrogen oxides (NOx) by 75%–95%
- Carbon dioxide (CO2) by 20%–30%

The biggest markets for NGV in the United States to date include bus fleets, trash haulers, and taxis and shuttle-delivery, port, and airport vehicles. The American Public Transit Association (APTA) (2011) reports that nearly 19% of the nation's full-sized transit bus fleet operates on natural gas. In addition, 1.9% of U.S. para-transit fleets operate on natural gas. These percentages are down slightly from 2009 figures reported by APTA. The Clean Vehicle Education Foundation provided estimates of commercial vehicles in the U.S. vehicle fleet. Their estimates were:

- Approximately 3,000 natural gas refuse haulers
- 2,800 natural gas school buses
- 16,000–18,000 medium duty NGVs (such as airport shuttles and delivery vans)

4.2 Light-duty/Passenger Vehicles

4.2.1 CNG vs. Hybrid-Electric and Electric Plug-Ins

Higher gasoline prices have spurred interest in hybrid-electric vehicles. These vehicles typically utilize an ordinary gasoline-powered internal combustion engine supplemented with a battery-powered electric motor where the battery is charged partially by the capture of potential energy recovered during braking. Although hybrid-electric vehicles carry a price premium due to the expensive batteries and associated hardware, they have become a substantial part of the passenger vehicle market due to the substantial fuel savings generated. For example, in 2005, sales of the Toyota Prius topped 100,000 units.

The electric-plug in vehicle represents a new generation of alternative-fuel vehicles. While many electric cars are limited in range, the combination of the electric plug with a traditional gasoline engine extends the range of an electric plug-in/gasoline hybrid. This allows power to come from a source other than retaining potential energy and electricity generated via the vehicle's engine. This could be the next step toward a commercially viable electric vehicle. One of the advantages of this fueling method is that the car's battery can be charged at home in the owner's garage (level 1 charging), as opposed to the purchase of other charging systems (level 2 charging), which may be a cost prohibitive, albeit faster, alternative. In addition to relatively high costs, a major disadvantage for these alternative vehicles is the range limitation of a fully charged vehicle. Combining this with limited recharging options, the consumer base for plug-in vehicles would be limited to those demographics with relatively short commutes. The gasoline engine option extends this range, as does the increase in the complementary support structure of recharging stations, especially rapid charging stations of 240 volts and 480 volts. These higher voltage charging stations can be installed in places consumers are likely to park for extended periods.

Despite the limitations, electric plug-in vehicles are currently being marketed as an expanded hybrid model. The existence of two power plants on the vehicle will add weight and ultimately inhibit the fuel efficiency measures; however, this does improve upon existing gas/electric flexibility. Sales figures for these types of vehicle have been very low so far. During 2013, hybrid vehicle sales totaled 495,685 units, up 14.1% from 2012. However, hybrid vehicles only represent a market share of 3.19% of new car sales (Cobb, 2014).

Vehicles powered by compressed natural gas (CNG) also come with tradeoffs. As with other alternative fuel vehicles, consumers can expect a higher initial purchase price coupled with reduced fuel costs. In contrast to hybrid-electric vehicles, however, these cost savings do not necessarily result from improved fuel efficiency; rather the savings accrued because natural gas is generally cheaper, per gallon equivalent, than gasoline. The fuel cost advantage enjoyed by CNG vehicles depends on price differences, rather than on technological efficiency improvements because the basic engine technology is identical to gasoline engines (i.e., an internal combustion engine modified to run on natural gas). Figure 4.1 shows fuel prices for gasoline, diesel, and CNG over the period 1994-2013.

The Energy Management Institute reported that from 2004 to 2007, natural gas was 48.6% less expensive than gasoline. More recently, the percentage difference has declined. There are changes in price depending on the locations within the U.S. For example, Utah consistently has lower CNG prices than Washington because of the location of extraction and a subsidy by the state government.

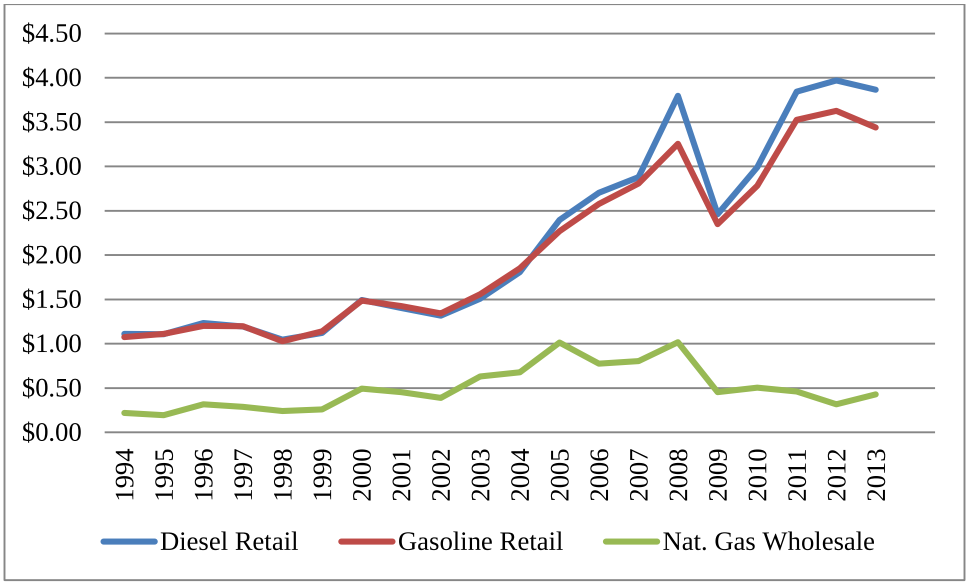


Figure 4.1 Cost of Gasoline, Diesel, and CNG Over Time (Source: U.S. EIA)

The purchase price for a CNG-powered vehicle is typically substantially higher because CNG vehicles must use a fuel system that is capable of handling a compressed gaseous fuel rather than a liquid fuel (Whyatt, 2010). The hardware and installation costs for these types of fuel systems are more expensive than comparable gasoline fuel systems. CNG-powered vehicles also are typically less powerful, have reduced trunk or storage space, and must be refueled more often (Whyatt, 2010, Walls, 1996). These disadvantages are not significant in many contexts but may be very significant for some drivers.

4.2.2 Limitations: New Vehicles and Retrofitting

The Honda NGV is the only factory ready NGV available to consumers in the United States. Other vehicles, mostly light-duty trucks and vans, are available for fleet special orders. Private consumers are left with the choice between buying the one factory ready model, buying a used fleet vehicle, or attempting to retrofit an existing vehicle with a special guest power source. Retrofitting existing vehicles can pose a problem due to regulations placed on street legal vehicles. Currently, all registered vehicles must comply with EPA standards in addition to state laws that vary greatly. For example, California imposes very stringent rules whereas some states do not provide enough regulation to ensure the safety of vehicles (California Air Research Board). Overall, retrofitting traditional engines in ways that comply with EPA and state regulations is less favorable than retrofitting engines in other countries where these changes are more common and regulations are not as strict.

With increased domestic demand for NGVs, Honda, Ford, GM, and other major original equipment manufacturers (OEMs) are returning to the market in the United States and continuing to offer their products elsewhere in the world. Table 4.2 provides the current CNG vehicles available for purchase from OEMs. The Ford vehicles require factory conversion in order for them to be operated by CNG.

Table 4.2 New CNG Vehicles Available for Purchase Currently

Model	Fuel	Type
Ford E-150, E-250, E-350	CNG/LPG Capable	Van/Wagon
Ford Transit Connect	CNG/LPG Capable	Van
Civic NGV CNG Dedicated Sedan	CNG Dedicated	Sedan
VPG	CNG Dedicated	SPV
Chevrolet Silverado 2500 and GMC Sierra 2500 HD	CNG/LPG Capable	Truck
Dodge Ram 2500 CNG	CNG Dedicated	Truck
GM Cargo Vans	CNG/LPG Capable	Van

Due to a limited number of CNG-powered vehicles on the market, considerable uncertainty exists regarding the price premium for CNG vehicles that would exist if there were more production and competition. However, the limited information available suggests the CNG price premium has not decreased over time and that higher volume manufacturing may not lower costs substantially. For example, Walls (1996) estimates (inflation-adjusted) incremental CNG vehicle costs of less than $5000. In contrast, the Honda Civic GX costs about $7,000 more than its gasoline counterpart (Cook, 2009). It is also important to note there have been no substantial cost-reducing technological improvements in CNG fuel systems in recent years. In previous years, medium- and heavy-duty NGVs have cost $20,000–$50,000 more than comparable diesel vehicles (Werpy et al., 2010).

4.3 Heavy-Duty/Commercial Vehicles

Heavy-duty and commercial vehicles burn large amounts of fuel, therefore, the potential cost savings from CNG adoption are very large for these vehicles. This is especially true for high-mileage or high-usage vehicles. However, a number of technical and practical considerations have so far limited wide-spread adoption of heavy-duty CNG vehicles.

4.3.1 Engine Availability and Limitations

As with passenger vehicles, a major constraint to the widespread adoption of CNG vehicles for heavy-duty use is the limited availability of vehicles or, more specifically, suitable engines. According to the Guide to Available Natural Gas Vehicles and Engines (published by Natural Gas Vehicles for America in 2009), the manufacturers listed in Table 4.3 currently produce natural gas engines for heavy-duty or commercial use.

Table 4.3 Current U.S. Manufacturers of Commercial NGV Engines

Manufacturer	Engine Type	Application
Cummins Westport, Inc.	5.9-L B Gas Plus (spark ignited)	Medium-duty (e.g., school buses/shuttles); production ended 12/31/09
Cummins Westport, Inc.	8.9-L ISL G (spark ignited)	Heavy-duty (e.g., refuse, transit/school, buses, street sweepers, yard hostlers)
Doosan Infracore America Corp.	11-L GK12-C (spark ignited)	Heavy-duty (e.g., refuse trucks and transit buses)
Doosan Infracore America Corp.	11-L GK12-S (spark ignited) w/SCR	Heavy-duty (e.g., refuse trucks and transit buses)
Emission Solutions, Inc.	7.6-L NG Phoenix (spark ignited) remanufactures the Navistar International MaxxForce DT diesel platform to natural gas	Medium-duty (e.g., school buses/heavy-duty cutaway shuttles and work trucks)
Westport Innovations	15-L GX (compression ignited) dual-fuel high-pressure direct-injection (95% natural gas, 5% diesel)	Heavy-duty (e.g., work trucks and line-haul applications)

Limited availability is due, in part, to technical limitations associated with CNG. A major consideration is that heavy-duty trucks have large power requirements. However, as explained by Deal (2012), "spark-ignited natural gas engines are not able to achieve the high compression ratio or horsepower of a diesel engine because of the need to prevent pre-ignition and engine damage." This problem results in a requirement for a larger displacement engine to provide the necessary power. This in turn results in a fuel efficiency penalty of about 10% (Deal, 2012). Table 4.4 shows an estimate of the present discounted value (PDV) of fuel cost savings for various MPG/VMT combinations that account for a 10% fuel efficiency penalty. Despite this penalty, Table 4.4 clearly shows that the potential fuel cost savings for heavy-duty trucks are very large.

Table 4.4 PDV of Fuel Cost Savings for Heavy-Duty Trucks*

		VMT							
		30000	40000	50000	60000	70000	80000	90000	100000
MPG	3	$58,450	$77,933	$97,416	$116,900	$136,383	$155,866	$175,350	$194,833
	4	$43,837	$58,450	$73,062	$87,675	$102,287	$116,900	$131,512	$146,125
	5	$35,070	$46,760	$58,450	$70,140	$81,830	$93,520	$105,210	$116,900
	6	$29,225	$38,967	$48,708	$58,450	$68,192	$77,933	$87,675	$97,416
	7	$25,050	$33,400	$41,750	$50,100	$58,450	$66,800	$75,150	$83,500
	8	$21,919	$29,225	$36,531	$43,837	$51,144	$58,450	$65,756	$73,062
	9	$19,483	$25,978	$32,472	$38,967	$45,461	$51,955	$58,450	$64,944
	10	$17,535	$23,380	$29,225	$35,070	$40,915	$46,760	$52,605	$58,450

*Estimates calculated using a 15% depreciation rate, 6% discount rate, and 5-year ownership time.

Despite these potentially large cost savings, barriers to widespread adoption of heavy-duty CNG and LNG vehicles remain. Deal (2012) summarizes some of the factors limiting the application of CNG and LNG in heavy-duty vehicles:

- Refueling infrastructure is still limited compared with diesel.
- Natural gas trucks are substantially more expensive than diesel trucks.
- There are high capital costs associated with upgrading a maintenance shop to deal with CNG vehicles.
- The limited capacity of economical CNG fuel tanks limits operational range and adds weight to the truck.

- LNG use is limited to situations where trucks are re-fueled every 1-2 days.
- Fleets are apprehensive about new "high risk" technology.

The price premium for heavy-duty trucks varies substantially with the size of the vehicle. For example, GM heavy-duty pickups (Chevrolet Silverado 2500 HD) with a bi-fuel option (can run on CNG or gasoline) cost about $11,000 extra (Bowman, 2012). However, larger trucks carry a substantially larger price premium. Deal (2012) reports that natural gas trucks with the ISLG 8.9L spark-ignited gas engine cost $30,000 to $40,000 more than comparable diesel engines. Trucks with the larger ISX-G 15L engine cost about $70,000 more. Part of this cost is due to more expensive engines and part is due to the fuel system that must be able to handle a highly compressed gaseous fuel. CNG operating costs are also increased due to the greater weight, more frequent refueling, and reduced range of the vehicles. Finally, it should be noted that CNG adoption may be viewed as risky because the benefits (reduced fuel costs) depend on price differences that can be unexpectedly influenced by market forces and government policy changes.

Despite these drawbacks, CNG adoption in the heavy-duty truck sector is accelerating. CNG vehicles are currently being successfully used in "short and medium range applications such as refuse trucks, straight trucks, and busses" (Deal, 2012). These applications are ideally suited to CNG at current prices because their high fuel requirements yield large cost savings, yet they are less constrained by the power requirements and range limitations of larger vehicles such as long-haul trucks. There is evidence that the price spread between diesel and CNG is now large enough that a *tipping point* has been reached and widespread adoption of CNG vehicles in the trucking sector is possible. For example, Deal (2012) calculates that fleets traveling 30,000-40,000 miles per year now see an attractive return on investment from CNG adoption of lower-cost spark-ignited engines. Ford Motor Company reports that sales of CNG trucks are up 350% since 2009 (McElroy, 2013) and new, more cost-effective CNG engines, especially an 11.9L spark-ignited engine, will be available in 2013.

4.4 Fueling Infrastructure: Stations and Home-Fueling Opportunities

One of the opportunities that natural gas shares with the electric plug-in vehicle is the ability to refuel at home. With an adaptor, it is possible to top-off a natural gas vehicle from a home already serviced by a natural gas utility. With plug-in varieties, the drawback would be the 4- or 8-hour charging window, typically overnight. With a natural gas hook-up, fueling could be achieved in a fraction of the time.
In support of the Honda Civic GX, a home-fueling device known as Phill, manufactured by FuelMaker Corporation, was available in limited markets; approximately 400 units were sold. "The Phill" costs between $3,000–$4,000, with an installation fee of $1,000–$2,000. In addition, a product called "The FuelMaker Q" was available for $10,000 plus installation. The Phill appliance is connected to home gas and electricity supplies and mounted either in garages or on outside walls. Depending on the amount of fuel already in a tank, 4–12 hours are required to fill the tank. This cost is still very high for the consumer market, but is sensible for small businesses like taxi and delivery services. Income tax credits for both electric charging and natural gas refueling stations may help to offset some of this installation cost.
Industrial CNG fueling stations are much larger and more costly. For example, Chesapeake Energy Corporation's "CNG in a Box" fueling station, described by CSP Daily News as "a gas compressor with storage, cooling, drying and controls, as well as GE Wayne dispensers with credit-card capability and provision for a POS interface." The station costs between $700,000 and $1.2 million, depending on options. Figure 4.2 shows per-vehicle capital costs for a station that costs $1 million.

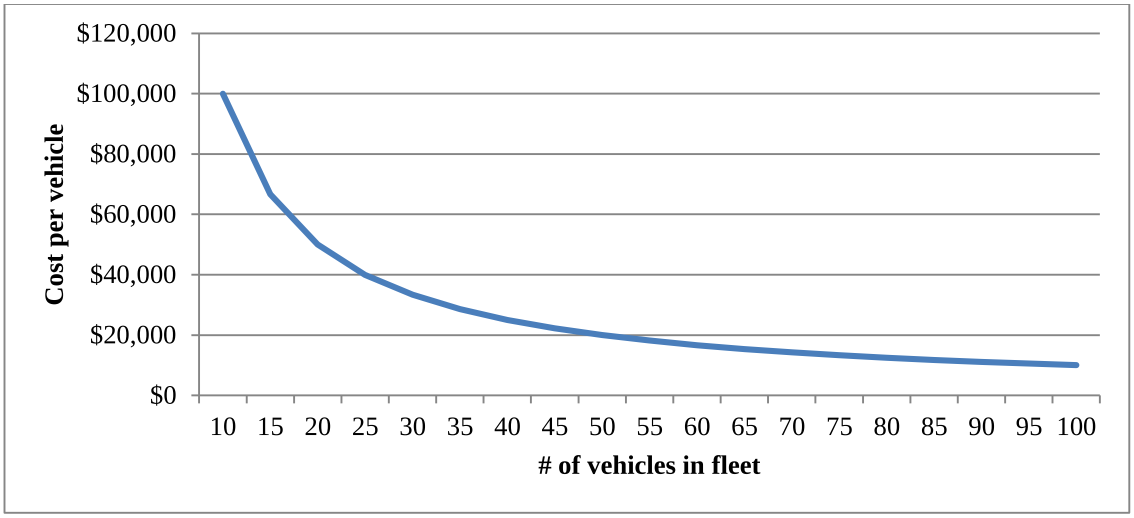


Figure 4.2 Per-Vehicle Refueling Stations Capital Costs ($1,000,000 Capital Costs)

4.5 CNG Fueling Infrastructure

NGVs are mostly fueled with CNG, which is delivered through the pipeline system. The fuel can be made available at public stations or private fleet facilities. In 2001, approximately 63% of U.S. households used natural gas; however, this percentage varied by region (EIA 2001). Once the CNG reaches public natural gas stations, consumers have a similar experience to typical gasoline or diesel dispensers and have comparable filling times. Figures 4.3 and 4.4 provide visualization of the numbers of fueling stations in each state and a detailed map of fueling stations in the state of Washington.

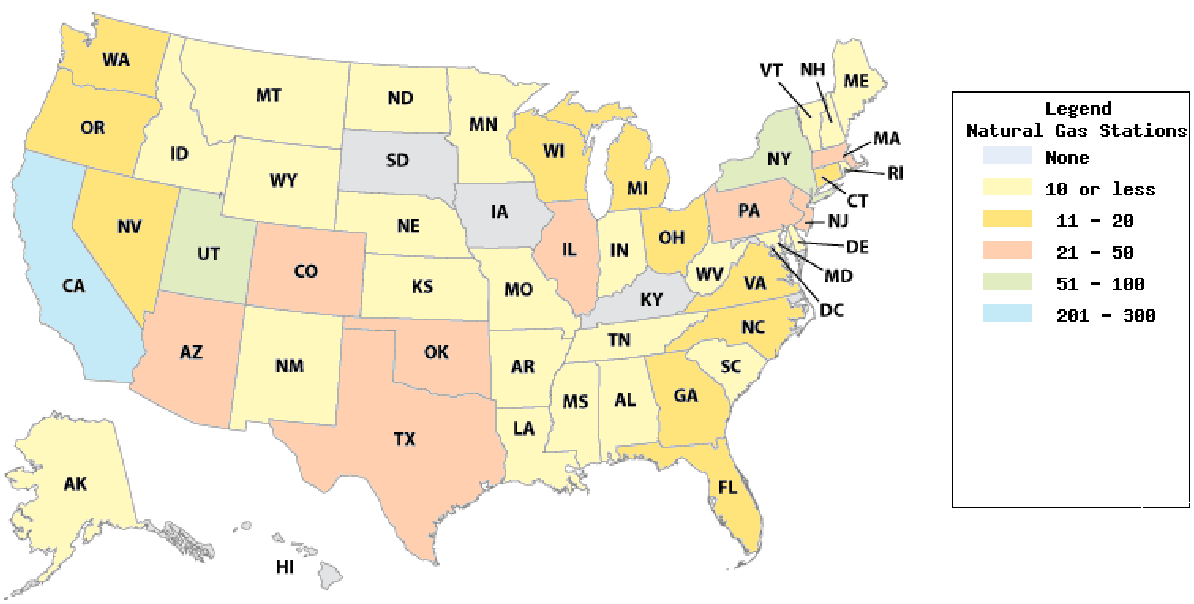


Figure 4.3 Natural Gas Fueling Station Counts

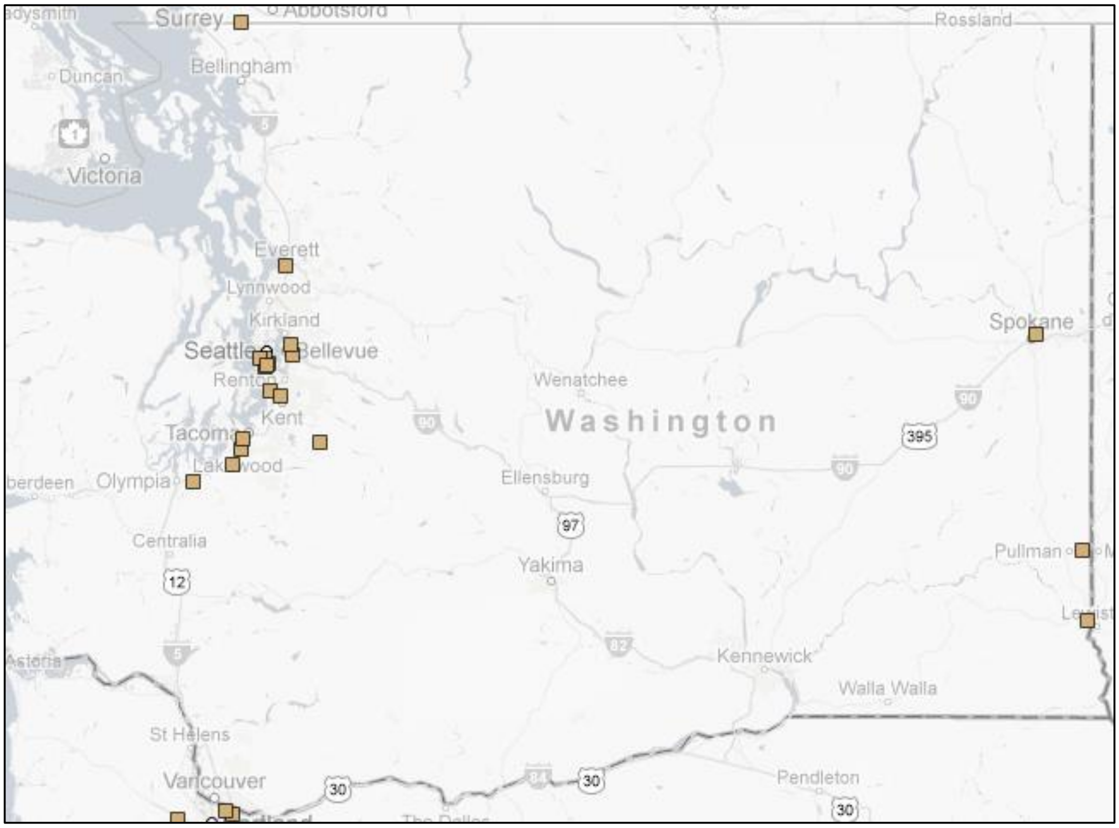


Figure 4.4 Natural Gas Fueling Locations in Washington State

4.6 Incentivizing Natural Gas Vehicles

There are easily identifiable clusters of natural gas stations around the country. The three most aggressive states for natural gas vehicles are California, Oklahoma, and Utah as shown in Figure 4.5. Utah has a unique opportunity to develop a natural gas corridor along Interstate-15 due to an abundance of domestic resources. This links Utah to California through southern Nevada. Such a project reduces one of the major drawbacks of natural gas resulting from a limited vehicle range compared with the traditional gasoline engine as well as limited existing fueling stations through much of the U.S. Table 4.5 provides incentives that have been put into a statute at the federal level in order to incentivize natural gas vehicles.

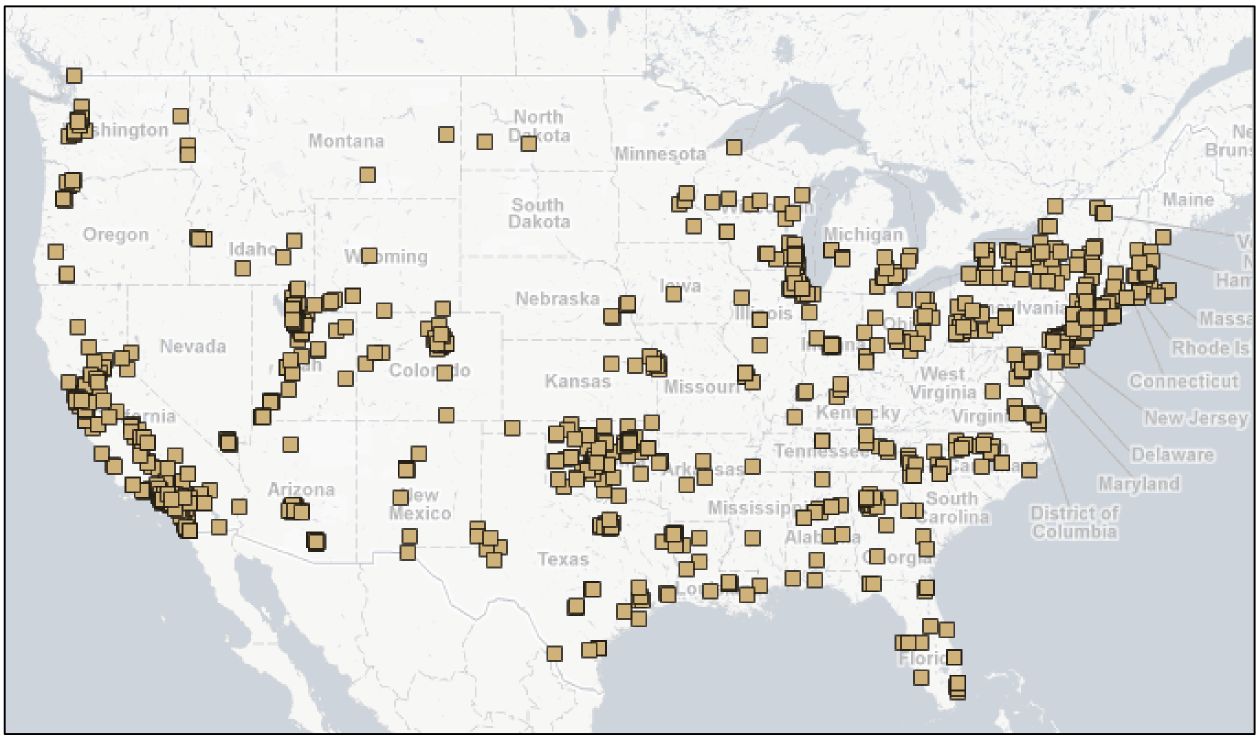


Figure 4.5 Map of U.S. Compressed Natural Gas Fueling Facilities

Table 4.5 Federal Laws with Incentives for Natural Gas Fuel, Vehicles, and Infrastructure

Incentive Type	Federal Law	Provision
Fuel	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users, P.L. 109-59 (8/10/05) (SAFETEA-LU)	An excise tax credit is available for alternative fuel sold to operate a motor vehicle. The credit is $0.50 per GGE of CNG and $0.50 per liquid gallon of liquefied petroleum gas, LNG, and liquefied hydrogen. The entity eligible for the credit is the one that reports and pays the federal excise tax on the fuel. The tax credit is also available to nonprofit tax-exempt entities that fuel on-site. The excise tax credit, paid from the General Revenue Fund, is partially offset by an increase in the motor fuel excise tax rate for CNG/LNG, which is now on parity with that for other motor fuels. Section 204 of the Emergency Economic Stabilization Act/Energy Improvement and Extension Act of 2008 (P.L. 110-343, passed 10/3/08) amended the expiration date for the alternative fuel excise tax credit from 9/30/09 to 12/31/09.
Vehicle	Energy Policy Act of 2005, P.L. 109-58 (8/8/05)	A "qualified alternative fuel motor vehicle" tax credit is available for the purchase of a new, dedicated, or repowered AFV. It is for 50% of the incremental cost of the vehicle, plus an additional 30% if the vehicle meets certain tighter emission standards. These credits range from $2,500 to $32,000, depending on the size of the vehicle. The credit is effective on purchases made after 12/31/05 and expires 12/31/10. The vehicle must be acquired for use or lease by the taxpayer claiming the credit. (a) The credit is only available to the original purchaser of a qualifying vehicle. If a qualifying vehicle is leased to a consumer, the leasing company may claim the credit. (b) For qualifying vehicles used by a tax-exempt entity, the person who sold the qualifying vehicle to the person or entity is eligible to claim the credit, but only if the seller clearly discloses in a document to the tax-exempt entity the amount of credit. The seller may pass along any savings of the tax credit but is not required to do so. The Internal Revenue Service does not set limits on the amount of credits claimed by any one entity.
Infrastructure	Energy Policy Act of 2005, P.L. 109-58 (8/8/05)	An income tax credit is available for 30% of the cost of natural gas refueling equipment, up to $30,000 in the case of large stations and $1,000 for home refueling appliances. The credit is effective on purchases placed in service after 12/31/05 and expires 12/31/10 (due to passage of the Emergency Economic Stabilization Act, P.L. 110-343). The American Recovery & Reinvestment Act of 2009 (P.L. 111-5, passed 2/17/09) amended the value of this credit for the purchase of equipment used to store and dispense qualified alternative fuels placed in service during 2009 and 2010. The credit for these years is $50,000 or 50% of the cost, whichever is smaller, for business property and $2,000 or 50% of the cost, whichever is smaller, for home refueling.

Sources: AFDC; NGVAmerica

4.7 Example of State Incentives for Natural Gas Vehicles

Utah offers a clean fuel vehicle tax credit providing for 35% of the incremental cost (up to $2,500) of a clean fuel vehicle manufactured by an OEM or an income tax credit for 50% of the cost (up to $2,500) of a conversion made from January 1, 2009, to December 31, 2014.

An important aspect of Utah's success with NGV is the Public Service Commission's authority to approve requests by gas utilities for a special NGV rate that is less than full cost and can allocate these additional costs to remaining rate payers. This authority effectively serves as a subsidy that has kept the cost of CNG for transportation fuel lower than the national average in Utah. There are more fueling stations in Utah than in any other state, mainly due to the rather large deposits of natural gas. This is a benefit to both fleet and private CNG car owners. The fueling infrastructure is clustered around what is known as the I-15 corridor, running from the northern border with Idaho southward to the Arizona border.[1] Utah is a good example of a state that is investing in natural gas to help mitigate the rising cost of transportation in the short run. Implications from this investment are informative for other states interested in providing their citizens with more options in transportation.

However, Utah does have one major advantage that might not be shared by other states. Providing infrastructure for AFVs is less of a problem due to the population concentration along the northern portion of the I-15 corridor. For other states, the decision will be to invest in similarly concentrated corridors, like the "West Cost Electric Highway" spanning 585 miles of Interstate 5 in Washington and Oregon. These investments represent significant commitments by state and federal stakeholders for particular alternative energy investment.

Utah's commitment to natural gas is largely fueled by the vast resource deposits in the state. Utah has access to many natural gas fields, but the largest cluster of resources is in a shale gas field in the eastern-central portion of the state near Price, UT. In Utah, the incentives of using natural gas are two-fold: the benefits of domestic production and the low cost of transporting the fuel to consumers. Figure 4.6 shows the concentration of natural gas deposits in the Uinta-Piceance Basin.

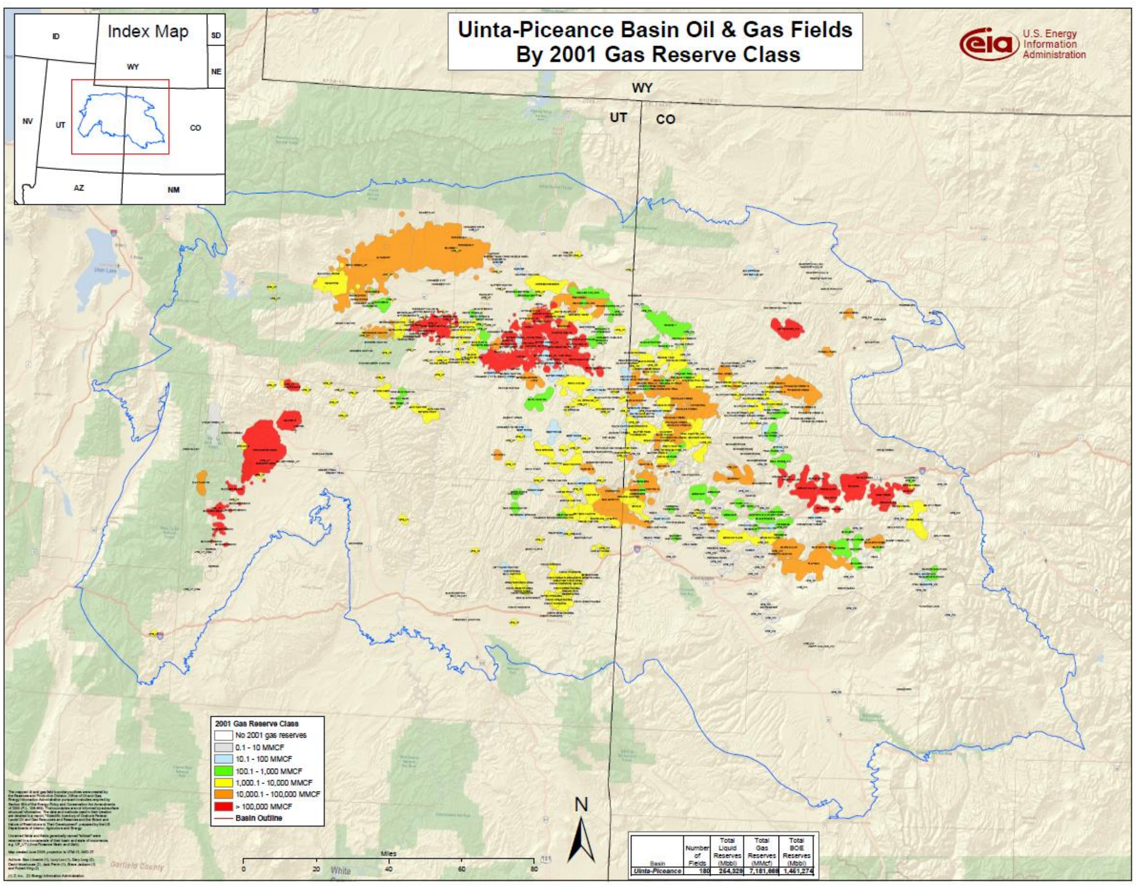


Figure 4.6 Map of the Uinta-Piceance Basin (Source: U.S. EIA)

[1] "Governor Huntsman, Questar announce Natural Gas Corridor." *questar.com*. Questar Corporation, 12 Feb 2009. Web. 21 Sep 2012.

In the past seven years, Utah has renewed focus on conserving energy and finding alternative sources for transportation energy. Both the state's fleet vehicles and the private consumer vehicles are taking advantage of locally extracted natural gas.

The federal tax per gasoline gallon equivalent (GGE) for gasoline, diesel, and CNG are $0.184, $0.244, and $0.183, respectively, while state taxes vary for each fuel (IRS 2010). The current official source of funding for the Federal Highway Administration is the Highway Trust Fund generated through motor fuel taxes. In addition to this, each state levies taxes to fund their own transportation projects; these taxes average $0.305 per gallon of gasoline and $0.244 per gallon of diesel. They vary quite a bit; for example, the state of Utah charges $0.245 per gallon of gasoline and diesel collecting a total of $350 million in 2009, while the state of Washington charges $0.375 per gallon of both fuel types collecting a total of $1.18 billion in 2009 (American Petroleum Institute, 2012). These revenue sources are under pressure as vehicles become more fuel-efficient and VMT increase much faster than revenue.

The new class of fuel-efficient vehicles exacerbates this trend. These cars are particularly popular with consumers because they are often the target of a substantial subsidy. For example, from 2006 until 2010, purchasers of hybrid cars could be rebated a maximum of $2,400 for a fuel economy credit plus $1,000 for a conservation credit. Other programs existed (notably one for natural gas) over the same time period. The Energy Improvement and Extension Act of 2008 replaced the existing programs with provisions for plug-in electric vehicles starting in 2009. These provisions included a $2,500 credit plus $417 for each kwh of battery pack capacity in excess of 4 kwh to a maximum of $15,000 (for heavy vehicles) and of $7,500 for passenger cars (less than 8,500 lbs.) with over 12 kwh**.**

5. CNG PRICE RESPONSE MODELING PROCEDURES

In order to model CNG vehicle adoption as a financial decision, it is necessary to make several simplifying assumptions. Assumptions specific to this model are discussed in detail below; however, the most important assumption underlying this analysis is that a CNG vehicle is actually an available option for consumers. Currently, CNG fueling infrastructure is extremely limited in many areas of the United States and in the State of Washington. This lack of infrastructure renders CNG impracticable for many, if not most, consumers. Moreover, CNG vehicle choices are extremely limited. Consumers may not be able to choose a CNG vehicle that fits their needs, even if such a vehicle would be cost effective, because it is not available. With this assumption in mind, the predictions of this model represent what is possible with expanded CNG infrastructure and expanded CNG vehicle selection, rather than what is probable under current conditions. Although this model is developed from the perspective of a consumer, it is similar to the decision that a business looking to purchase a vehicle may face. See Deal (2012) for a similar approach specific to heavy-duty trucks.

The analysis in this report is based on current technological possibilities. Given current technology and prices, CNG adoption represents a cost-effective decision for some consumers. This is because CNG vehicles enjoy a fuel cost advantage over similar gasoline-powered vehicles. This cost advantage may be undermined by new technological developments in other areas. For example, most auto manufacturers have dramatically improved the efficiency of their gasoline engines via more widespread adoption of direct injection technology (SAE International, 2012). Hybrid electric and electric vehicles are also becoming more popular and technology improvements may further reduce the cost of producing these vehicles. The fuel cost advantage enjoyed by CNG vehicles may not lead to increased adoption rates if new technologies offer consumers more cost-effective travel options via new technological improvements.

Recognizing that there are significant barriers to increased vehicle development and infrastructure and recognizing that technological changes may undermine the fuel cost advantage associated with CNG vehicles, the estimates of our model are best viewed as an upper bound on CNG adoption rates.

5.1 A Model of Consumer Demand for CNG Passenger Vehicles

Consider an individual choosing between two vehicles that differ only in initial purchase price and fuel system. If the vehicles are otherwise identical and the individual does not have preferences that depend directly on the type of fuel system in the vehicle, the choice can be characterized as a pure financial cost-minimization decision. Basic financial economic theory suggests that the individual will choose the vehicle with the lowest cost, where cost is measured by the net present discounted value of all cash flows associated with the choice. Because the vehicles are assumed otherwise identical, the only relevant costs are the initial purchase price, depreciation costs, and the cost of fuel. Basic maintenance costs, registration fees, and other costs associated with vehicle ownership are assumed to be the same across vehicles and are therefore irrelevant to the model. We discuss the implications of these simplifying assumptions below. With these assumptions, however, the total cost associated with the gasoline powered vehicle can be expressed as:

Equation 1

$$TC_g = V_{g0} + f_{g0} + f_{g1}(1+r)^{-1} + f_{g2}(1+r)^{-2} + ... + f_{gT}(1+r)^{-T} - V_{g0}\left(1+\delta\right)^{-T}(1+r)^{-T}$$

Where TC_g is the total present discounted value of all costs associated with the gasoline-powered vehicle, V_{g0} is the value or purchase price of the gasoline vehicle in the initial time period, f_{gt} is fuel costs in year t, and r represents the individual's rate of discount. T is the terminal period at which point the individual sells or scraps the vehicle. The parameter δ measures the annual rate of depreciation and the last term in the expression therefore captures the sales or scrap value of the vehicle at time T. Assuming fuel costs are the same in each period, such that $f_{gt} = f_g$ for all t, this expression can be simplified and written as:

Equation 2

$$TC_g = \left[V_{g0} - V_{g0} \left[(1+\delta)(1+r) \right]^{-T} \right] + \sum_{t=0}^{T} (1+r)^t f_g$$

Note that the expression $\left[V_{g0} - V_{g0} \left[(1+\delta)(1+r) \right]^{-T} \right]$ is the vehicle purchase cost less the present discounted value of the terminal value of the vehicle. This term, therefore, represents the cost to the consumer of owning the vehicle for T periods independent of fuel costs. Let V_{g0}^{*} represent this expression and rewrite the above equation as:

Equation 3

$$TC_g = V_{g0}^{*} + \sum_{t=0}^{T} (1+r)^t f_g$$

The same framework is applied to the CNG vehicle by simply replacing the g subscripts with c subscripts. Because the gasoline and CNG vehicles are assumed otherwise identical, the consumer's choice will then be driven by the *difference* in total costs between the two vehicles. The individual will choose the CNG powered vehicle if $\Delta TC = TC_g - TC_c > 0$:

Equation 4

$$\Delta TC = TC_g - TC_c = \left(V_{g0}^{*} - V_{c0}^{*} \right) + \left(\sum_{t=0}^{T} (1+r)^t f_g - \sum_{t=0}^{T} (1+r)^t f_c \right)$$

This can be written more simply as:

Equation 5

$$\Delta TC = \left(V_{g0}^{*} - V_{c0}^{*} \right) + \sum_{t=0}^{T} (1+r)^t \left(f_g - f_c \right)$$

If time T is far enough in the future that both vehicles will have a near zero scrap or resale value, the above expression can then be written:

Equation 6

$$\Delta TC = \left(V_{g0} - V_{c0} \right) + \sum_{t=0}^{T} (1+r)^t \left(f_g - f_c \right)$$

Note that this expression depends simply on the difference in initial purchase price, the difference in yearly fuel costs, and a discount rate.

Conversely, the above choice is to consider the alternative fuel system as an investment that pays a yearly rate of return (in the form of lower fuel costs) until time T. The individual requires that the investment pays a high enough rate of return to cover the reservation rate, represented by the discount rate. Using the framework above, the initial investment can be thought of as the difference in initial purchase price (the extra amount paid for the alternative fuel vehicle) and the dividend as the yearly fuel savings.

5.2 Other Model Assumptions

An important consideration is the effect that various simplifying assumptions, implicit or explicit in this model, may have on consumer vehicle adoption decisions. As directed by WSDOT, this model was developed under the assumption of consumer cost minimization. However, it is important to recognize that consumer behavior may be influenced by a number of other factors, not all of which are directly consistent with cost minimization. Some simplifying assumptions have also been made, which may not hold for all consumers or vehicles. For example, this model assumes that after choosing a fuel system, the consumer's nominal yearly fuel cost is the same in each year. However, fuel prices may fluctuate and consumer fuel usage may also vary due to variation in yearly miles driven. While this assumption is necessary to develop a tractable model, the actual effect of violation of this assumption on predicted CNG adoption rates will depend on many factors such as consumer expectations regarding future fuel prices. Additionally, it has been assumed that both types of vehicles depreciate at the same rate. However, this assumption may not be true in practice. For passenger vehicles, it is assumed that miles per gallon will be the same for both CNG and gasoline powered vehicles. While this assumption may be approximately accurate for passenger vehicles, it may not be for all vehicles. For example, both the CNG-powered Honda Civic and its gasoline-powered counterpart are EPA-rated at 31 MPG. However, heavy-duty trucks powered by CNG typically have lower MPG figures than comparable diesel-powered trucks. See Deal (2012) for more information on mileage for CNG-powered heavy-duty trucks.

5.3 Using the Model to Predict Demand for CNG Passenger Vehicles

In order to predict vehicle fuel system choice for a given consumer, the model requires estimates of V_{g0}, V_{c0}, f_g, f_c, *T*, *r*, and δ. Estimates of the distribution of some of these variables in the population are available from the National Household Travel Survey (NHTS). These data are used to calculate the travel cost savings from switching to a CNG vehicle under given market conditions and what percentage of the vehicle fleet would incur the greatest savings. Note that calculating the fuel savings that would result from a switch to a CNG vehicle requires knowledge of both miles per gallon (MPG) and vehicle miles traveled (VMT).

Suppose that any gasoline-powered vehicle could be replaced by an equivalent CNG-powered vehicle for a given price. This replacement could occur either by paying to convert or retro-fit the vehicle to run on CNG or by selling the vehicle and replacing it with a CNG-powered equivalent vehicle. This additional cost is the difference between V_{g0} and V_{c0} in the model. This quantity is referred to as the CNG vehicle price differential. It is simple to calculate the present discounted value of switching to a CNG vehicle if a consumer knows the vehicle price differential as well as fuel prices, the expected VMT, MGP, and time of ownership, along with the appropriate discount and vehicle depreciation rates.
To begin, a model was used to calculate the expected fuel cost saving under current values for various VMT/MPG combinations. Then, using a set of estimated baseline parameter values, simulation of potential consumers finding this switch advantageous could be found. Assessing the sensitivity of this simulated proportion to changes in market conditions, particularly the vehicle price differential and the fuel price differential (the difference between the gallon-equivalent price of CNG and the price of gasoline), is then conducted. These simulation estimates are provided for the entire United States and for the State of Washington.

These simulation estimates are derived under the assumption of consumer travel cost minimization and, importantly, under the assumption that vehicle supply and infrastructure are generally available. Currently, vehicle supply is substantially restricted. Moreover, fueling station infrastructure is not well developed in most areas. Very few models of vehicles are available to consumers with factory-installed CNG systems and conversion kits are not available for all vehicles.

5.4 CNG Passenger Vehicle Price Differential

To calculate the appropriate vehicle price differential, CNG passenger vehicles typically have three disadvantages relative to gasoline powered cars: 1) smaller fuel tank capacity reducing vehicle range and increased fueling frequency, 2) reduced trunk space due to the placement of fuel tanks, and 3) reduced power output due to differences in energy content or engineering limitations (Werpy et al., 2010; Whyatt, 2010). For example, the 2012 Honda Civic CNG is rated at 110 hp and 106 lb-ft of torque and weighs 2,848 pounds. All gasoline-powered Civic models are rated at 140 hp and 128 lb-ft of torque and weigh about 2,600 pounds. However, both types of vehicle are rated at 31 MPG (combined city/highway). This power loss and increase in weight may make the CNG vehicle less pleasant to drive and therefore a less attractive option for some customers.

Moreover, fueling stations with CNG capabilities are less common and are more likely to be inconveniently located. In an extreme case, no CNG stations may be available in the area and the consumer would also be required to purchase a home CNG filling station. Walls (1996) estimated that consumer loss in utility due to these considerations is about $1,100-$3,200 in 1996 dollar terms. This additional loss in utility due to the inherent disadvantages of CNG vehicles is an important component of the vehicle price differential.

These disadvantages may not be relevant for some consumers but they will be a major limitation for others. However, these disadvantages may be much less relevant for industrial, service, or fleet vehicles that have access to convenient on-site refueling stations, suggesting that CNG adoption may be much more likely for these sectors of the transportation economy (Whyatt, 2010).

In addition to the loss in consumer utility associated with CNG vehicle disadvantages, there is typically a substantial price differential for CNG vehicles. For example, the Honda Civic CNG has an MSRP that is about $4,000 higher than the Honda Civic EX, and about $7,000 higher than the Honda Civic LX (Werpy, et al., 2010).

5.5 Baseline Model Parameters

Developing model baseline estimates of parameter values are necessary to properly simulate the passenger vehicle fleet share that would consider it advantageous to switch to CNG vehicles. These estimates are based on various sources and the results based on these estimates are subjected to sensitivity analysis for each parameter. These simulations are based on the joint distribution of household VMT and MPG in the NHTS (2009). Histograms for the distribution of these variables are shown in Figure 5.1.

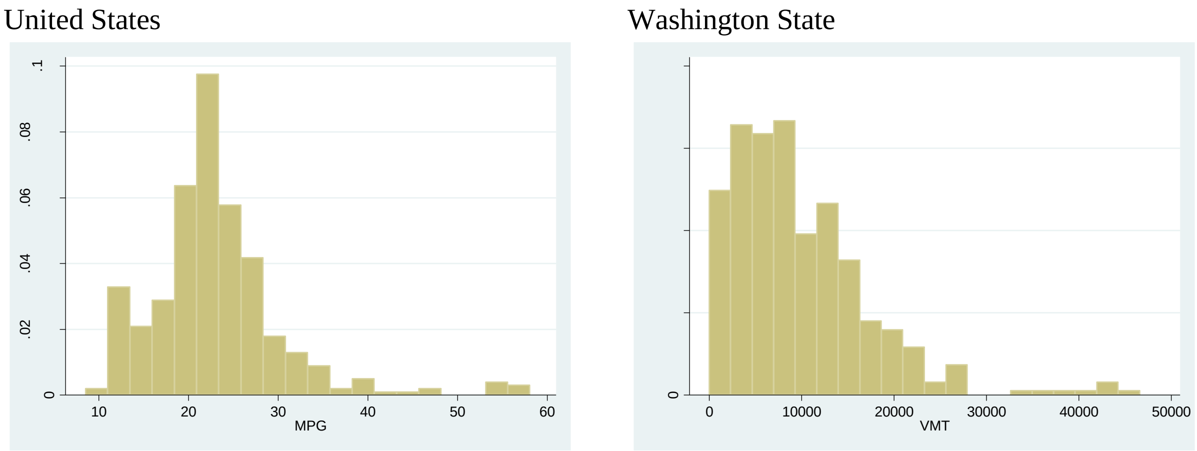


Figure 5.1 Distributions of VMT for U.S. and Washington State

This baseline model uses a fuel price differential of $1.50. This differential is based on the gasoline-CNG price differential in downtown Seattle on March 29, 2013. A vehicle price differential of $7,000 was used in this calculation. This differential is based on the difference between a Honda Civic CNG and a Honda Civic EX plus a $3,000 “inconvenience premium” based on an inflation adjustment to the estimate of consumer welfare loss by Wall (1996). Additionally, a baseline depreciation rate of 15% (Feng, Fullerton, & Gan, 2005), a baseline discount rate of 6%, and a baseline estimate of expected length of vehicle ownership of 60 months was used as indicated by Kelly Blue Book to be the current average. These estimates are based on the sources indicated and market prices observed by the researchers. These baseline model parameters are summarized in Table 5.1.

Table 5.1 Baseline Model Parameters

Purchase Price Differential	$7,000
Fuel Price Differential	$1.50
Length of Ownership	60 Months
Discount Rate	6%
Depreciation Rate	15%

5.6 Simulation Results

5.6.1 Baseline Results

Table 5.2 shows how the present discounted value of expected fuel savings varies with VMT and MPG under these baseline parameters. The fuel savings are much larger for high VMT vehicle and low MPG vehicles. This result is intuitive: more miles traveled means more fuel burned, and therefore higher potential savings. Lower MPG likewise suggests high fuel consumption and greater potential savings. Interestingly, this result suggests that high mileage, low MPG vehicles are the most likely to adopt CNG. This prediction is confirmed by market experience; CNG adoption is more likely for high mileage, low MPG vehicles like buses and fleet vehicles.

Table 5.2 PDV of Expected Fuel Savings at $1.50 Fuel Price Differential

	VMT per year							
MPG	8000	10000	12000	14000	16000	18000	20000	22000
14	$3,695	$4,618	$5,542	$6,466	$7,389	$8,313	$9,237	$10,160
16	$3,233	$4,041	$4,849	$5,657	$6,466	$7,274	$8,082	$8,890
18	$2,874	$3,592	$4,310	$5,029	$5,747	$6,466	$7,184	$7,903
20	$2,586	$3,233	$3,879	$4,526	$5,173	$5,819	$6,466	$7,112
22	$2,351	$2,939	$3,527	$4,115	$4,702	$5,290	$5,878	$6,466
24	$2,155	$2,694	$3,233	$3,772	$4,310	$4,849	$5,388	$5,927
26	$1,989	$2,487	$2,984	$3,482	$3,979	$4,476	$4,974	$5,471
28	$1,847	$2,309	$2,771	$3,233	$3,695	$4,157	$4,618	$5,080
30	$1,724	$2,155	$2,586	$3,017	$3,448	$3,879	$4,310	$4,742
32	$1,616	$2,021	$2,425	$2,829	$3,233	$3,637	$4,041	$4,445
34	$1,521	$1,902	$2,282	$2,662	$3,043	$3,423	$3,803	$4,184
36	$1,437	$1,796	$2,155	$2,514	$2,874	$3,233	$3,592	$3,951
38	$1,361	$1,701	$2,042	$2,382	$2,722	$3,063	$3,403	$3,743
40	$1,293	$1,616	$1,940	$2,263	$2,586	$2,910	$3,233	$3,556

The next step, using the joint distribution of vehicle MPG and VMT from the NHTS of 2009, is to calculate the share of the vehicle fleet that would consider it advantageous to switch to CNG vehicles under these baseline model parameters. Table 5.3 shows variation in this predicted proportion with respect to the fuel price differential and the vehicle price differential for Washington State. Table 5.4 shows analogous information for the United States.

Table 5.3 Proportion of Passenger Vehicle Fleet with Positive PDV for CNG (Washington State)*

		Purchase Price Differential							
		$3,000	$4,000	$5,000	$6,000	**$7,000**	$8,000	$9,000	$10,000
Gas Price Differential	$1.20	12.9%	2.2%	0.8%	0.3%	**0.0%**	0.0%	0.0%	0.0%
	$1.30	19.9%	6.2%	1.3%	0.5%	**0.0%**	0.0%	0.0%	0.0%
	$1.40	25.9%	8.9%	1.6%	0.8%	**0.3%**	0.0%	0.0%	0.0%
	$1.50	**28.6%**	**12.1%**	**2.2%**	**0.8%**	**0.3%**	**0.0%**	**0.0%**	**0.0%**
	$1.60	31.0%	12.9%	4.6%	1.3%	**0.5%**	0.3%	0.0%	0.0%
	$1.70	35.3%	17.3%	7.3%	1.6%	**0.8%**	0.3%	0.3%	0.0%
	$1.80	38.3%	23.5%	10.2%	2.2%	**1.1%**	0.5%	0.3%	0.0%
	$1.90	42.6%	25.9%	12.1%	4.3%	**1.6%**	0.8%	0.3%	0.3%
	$2.00	46.1%	28.6%	12.9%	6.5%	**1.6%**	0.8%	0.5%	0.3%
	$2.10	50.4%	30.5%	16.4%	8.9%	**2.2%**	1.3%	0.8%	0.3%
	$2.20	52.0%	33.4%	19.9%	10.8%	**4.3%**	1.6%	0.8%	0.5%
	$2.30	55.8%	37.5%	23.5%	12.1%	**6.5%**	1.6%	0.8%	0.5%
	$2.40	57.4%	38.3%	26.4%	12.9%	**7.8%**	2.2%	1.3%	0.8%
	$2.50	59.3%	41.8%	28.6%	16.2%	**10.2%**	3.0%	1.6%	0.8%

*Model assumes extensive CNG fueling infrastructure and vehicle availability

Table 5.4 Proportion of Passenger Vehicle Fleet with Positive PDV for CNG (United States)*

Gas Price Differential	Purchase Price Differential							
	$3,000	$4,000	$5,000	$6,000	**$7,000**	$8,000	$9,000	$10,000
$1.20	10.0%	1.0%	0.1%	0.0%	**0.0%**	0.0%	0.0%	0.0%
$1.30	14.4%	2.5%	0.2%	0.1%	**0.0%**	0.0%	0.0%	0.0%
$1.40	19.0%	4.7%	0.5%	0.1%	**0.0%**	0.0%	0.0%	0.0%
$1.50	22.3%	7.2%	1.0%	0.2%	**0.1%**	0.0%	0.0%	0.0%
$1.60	26.4%	10.0%	2.2%	0.2%	**0.1%**	0.0%	0.0%	0.0%
$1.70	**30.1%**	**13.0%**	**3.8%**	**0.6%**	0.1%	**0.1%**	**0.0%**	**0.0%**
$1.80	34.2%	16.6%	5.7%	1.0%	**0.2%**	0.1%	0.0%	0.0%
$1.90	37.8%	19.0%	7.8%	2.0%	**0.3%**	0.1%	0.1%	0.0%
$2.00	40.7%	22.3%	10.0%	3.0%	**0.6%**	0.2%	0.1%	0.0%
$2.10	45.1%	25.2%	12.5%	4.7%	**1.0%**	0.2%	0.1%	0.1%
$2.20	47.6%	28.7%	14.7%	6.3%	**2.0%**	0.3%	0.1%	0.1%
$2.30	50.1%	31.2%	16.8%	8.4%	**2.7%**	0.6%	0.2%	0.1%
$2.40	52.6%	34.2%	19.5%	10.0%	**4.2%**	1.0%	0.2%	0.1%
$2.50	54.9%	36.7%	22.3%	12.1%	**5.6%**	1.5%	0.3%	0.2%

*Model assumes extensive CNG fueling infrastructure and vehicle availability

Tables 5.3 and 5.4 show the proportion of the passenger vehicle fleet that would find CNG adoption financially advantageous over a range of vehicle price premiums and fuel price differentials for, respectively, the State of Washington and the United States. The baseline estimates of a $7,000 vehicle price premium and a $1.50 fuel price differential are shown in bold. A variation in predicted adoption rates for a range of plausible prices, given current market conditions, is also shown. Although the fuel price differential is about $1.50 at press time, this gap has been as large as $2.20 in downtown Seattle as recently as November 2012. At a fuel price differential of $1.50 and a vehicle price differential of $7,000, this model predicts that only about 0.3% of the vehicle fleet in Washington State would find CNG financially beneficial, if CNG vehicles and fueling infrastructure were widely available. Only 0.1% of the U.S. population would find CNG advantageous under the same circumstances. This small fraction of the population suggests that, at current prices, CNG vehicles would not be financially beneficial to most consumers, even if they were widely available and fueling networks were ubiquitous. However, the tables also show that there is substantial potential for more widespread CNG adoption if vehicle price premiums drop and fuel price differentials increase.

5.7 The Relative Importance of Fuel and Vehicle Price Differentials

An important feature of Tables 5.3 and 5.4 is that they show the relative importance of fuel price differential changes and vehicle price differential changes on the proportion of vehicles that would find a switch to CNG advantageous. Note that at our baseline estimate of $7,000 for the vehicle price differential, no more than 10.2% of Washington State vehicles (and no more than 5.6% of United States vehicles) would find a switch to CNG advantageous even at the very large CNG price differential of $2.50. However, technological improvements that result in a reduction in the vehicle price premium from $7,000 to $4,000 would boost the predicted CNG adoption rate to 12.1% for Washington State and 13.0% for the United States at current fuel prices. Additionally, even with extremely high fuel price differentials, this would not induce high adoption rates if the vehicle price differential is as high as or higher than current estimates (around $7,000). However, if the vehicle price differential drops below $4,000, relatively large portions of the population may find CNG cost effective even at current fuel price differentials. At current vehicle price differentials, however, widespread CNG adoption is unlikely even if infrastructure expands and vehicles are available. For example, at a vehicle price differential of about $7,000, the fuel price differential necessary for the model to predict a 50% CNG adoption rate is over $5. Although fuel price differentials of $2.50 are beyond the edge of what have historically been observed, recent dramatic changes in natural gas markets suggest that past fuel price differentials may not be reliable indicators of future changes.

It should be noted, however, that a $3,000-$4,000 price differential is not unrealistic if the “inconvenience cost” of owning a CNG vehicle (Wall 1996) is not considered. Given that these costs are likely less important for fleet and service vehicles, this model suggests that adoption is more likely in these sectors.

5.8 Other Model Parameters: Sensitivity Analysis

It has also been investigated how sensitive these simulation results are to variation in the other baseline parameters: ownership time, discount rate, and depreciation rate. This has been done by varying each attribute, holding all other attributes constant at the baseline. Full results from these sensitivity analyses are available from the authors. As expected, longer vehicle ownership times are associated with higher predicted rates of CNG adoption, as are lower discount rates and lower depreciation rates. However, even relatively large changes in these variables are associated with only modest changes in the adoption rates predicted by the model.

5.9 Looking Forward

This model of predicted CNG adoption rates is based on the joint distribution of VMT and MPG in the vehicle fleet as reported in the 2009 NHTS. As market conditions change, consumers are expected to respond to these changes by altering the number of miles driven and by changing vehicle choices. As previously stated, an increase in the fuel price differential between gasoline and CNG increases the incentive for consumers to switch to CNG, ceteris paribus. However, an increase in the fuel price differential due to increasing gasoline prices can also be expected to change the distribution of vehicle miles traveled and the vehicle fleet composition as consumers react to these changes.

Research suggests that consumers reduce miles traveled in response to gasoline price changes. However, VMT response to changes in gasoline prices (i.e., the “rebound effect”) appears to be relatively small and declining over time. (Gillingham, 2010; Greene, 1992; Greene, Kahn, & Gibson, 1999; Jones, 1993; Small & Van Dender, 2007). This decline suggests that changes in fleet fuel economy in response to higher gasoline prices may be a relatively more important factor than VMT changes for CNG vehicle adoption rates. For example, Small and Van Dender (2007) find the long-run rebound effect to be only 2.2% for the time period 1997-2001. Interestingly, Burger & Kaffine (2007) find that Los Angeles freeway speeds do not decline in response to higher fuel prices, suggesting that fuel prices are not a large consideration for most drivers. There is also evidence that vehicle scrappage decisions are influenced by gasoline prices. Li, Timmins, and von Haefen (2009) show that a 10% increase in gasoline prices is associated with a 0.22% increase in fleet fuel economy in the short run and a 2.04% increase in the long run.

Given that consumers can be expected to reduce vehicle miles traveled and to purchase more fuel-efficient vehicles, it is natural to ask what expected impact these changes would have on CNG adoption rates. Both types of expected reactions to increased gasoline prices (reduced VMT and more fuel efficient gasoline vehicles) predict lower CNG adoption rates. This is because the expected fuel cost savings associated with CNG will be lower if the consumer drives fewer miles or has a more fuel-efficient vehicle. This is easily shown by observing that the derivative of the present discount value of total cost savings associated with switching to CNG with respect to vehicle miles traveled is positive, while the derivative associated with MPG is negative, as shown below.

The present discount value of total cost savings associated with switching to CNG expressed in Equation 6 can be rearranged as:

Equation 7

$$\Delta TC = \left(V_{g0}^{*} - V_{c0}^{*}\right) + \sum_{t=0}^{T} (1+r)^{t} \left(p_g - p_c\right)\left(\frac{VMT}{MPG}\right)$$

where $\left(p_g - p_c\right)$ is the fuel price differential, which we assume is positive. The derivatives of this expression with respect to *VMT* and *MPG*, therefore, are:

Equation 8

$$\frac{\partial \Delta TC}{\partial VMT} = \frac{1}{MPG} \sum_{t=0}^{T} (1+r)^{t} \left(p_g - p_c\right) > 0$$

Equation 9

$$\frac{\partial \Delta TC}{\partial MPG} = -\left(\frac{VMT}{MPG^2}\right) \sum_{t=0}^{T} (1+r)^{t} \left(p_g - p_c\right) < 0$$

These expressions indicate that, as the vehicle fleet becomes more fuel efficient and consumers drive less in response to rising gasoline costs, these changes actually undermine the incentive for consumers to adopt CNG vehicles. This effect is due to the fact that consumers face many substitute alternatives to dealing with higher gasoline prices. CNG adoption is one alternative; however, other alternatives include changing driving patterns and adopting more fuel efficient vehicles.

5.9.1 Discussion

The predicted proportion of the passenger vehicle fleet that would adopt CNG vehicles is found to be small using the baseline parameters established for this model. Given that the actual proportion of CNG vehicles in the fleet is small, this prediction reflects the reality of the current market. Simulations suggest that a substantial decrease in the vehicle price differential for CNG vehicles is necessary to induce CNG vehicle adoption for a significant portion of the vehicle fleet. Moreover, the model predicts that, even if technology improvements allow for very low conversion costs or manufacturer vehicle price differentials, CNG vehicles are likely to remain a minority in the vehicle fleet.

The fuel price differential necessary to predict CNG adoption for more than 50% of the vehicle fleet is more than $5.00—roughly twice the largest historically observed price differential and about 50 standard deviations larger than the mean of the historical distribution. Within the range of historically observed fuel price differentials, predicted CNG adoption rates are low. Little variation was found in predicted CNG adoption rates with respect to the other model parameters.

While the model predicts that overall CNG adoption rates will be low, a few caveats are in order. First, even at current prices, a non-negligible proportion of the vehicle fleet is predicted to adopt CNG. This proportion is likely to grow as infrastructure becomes available and especially if CNG vehicle prices fall. CNG vehicles make sense for consumers who drive many miles and are willing to live with the inconveniences associated with CNG vehicles. Second, this model is based on the current vehicle fleet. Changes in the vehicle fleet composition and changes in driving habits will affect the analysis. However, as gasoline prices continue to rise and consumers respond by driving less and purchasing more fuel-efficient vehicles, the potential gains from CNG vehicle adoption become smaller. Finally, these models suggest that CNG is most likely to be cost effective for high mileage, low MPG vehicles like service trucks, buses, and delivery vehicles. Moreover, these vehicles are also less likely to be negatively affected by the inconvenience of more frequent refueling.

To summarize, in order for CNG vehicles to become a significant portion of the passenger vehicle fleet, several conditions must be met and are detailed as follows:

5.9.2 Decreased Vehicle Price Differential

First, the vehicle price differential between CNG vehicles and gasoline vehicles would need to be reduced. There is potential for this price differential to shrink if manufacturers scale up production and conversion kits become more widely available and cheaper to install. However, even as costs fall due to economies of scale, there will likely continue to be a substantial vehicle price premium due to the technological requirements associated with a compressed gas fuel system.

5.9.3 Increased Fuel Price Differential

Second, the CNG-gasoline fuel price differential would need to increase. This increase is possible given that supply and demand factors for CNG are more regionally based than for gasoline. However, natural gas and petroleum are substitutes in some markets and growing price differentials would serve to increase relative demand for natural gas, thus limiting the extent to which price differentials could grow.

5.9.4 Limited Transportation Technological Improvements

Another condition that must be met for widespread CNG adoption would be the absence or limited impact of any other technological improvements to vehicle efficiency. For example, a substantial improvement in battery technology could make electric-hybrid vehicles relatively more fuel-cost-effective than CNG vehicles, even if the gasoline-CNG price differential is large. An alternative interpretation of this condition is that technological improvements in CNG vehicle technology would need to at least keep pace with vehicle technological improvements in general.

5.9.5 Expanded Fueling Infrastructure and Vehicle Availability

Under current conditions, CNG vehicles are not a viable option for many consumers. In the absence of a widely available fueling network, CNG vehicle adoption will be limited to specific geographic areas where CNG fueling stations exist. Likewise, without greatly expanded vehicle supply, CNG vehicles will remain a tiny fraction of the overall fleet.

6. NGV EFFECT ON VEHICLE MILES TRAVELLED

In order to identify the effectiveness of substituting natural gas for petroleum in the transportation sector, it is important to understand exactly how consumer demand for travel responds to changes in fuel price. Vehicle miles traveled (VMT) is the most common measure for estimating this demand. The purpose of this section is to forecast VMT in Washington State and to analyze the potential effect of increasing natural gas vehicle adoption on VMT projections. Time series data provided by the State of Washington Department of Transportation (WSDOT) were used for the period 1965-2011. The model predicts VMT as a function of the number of registered vehicles, statewide employment, and fuel prices and is a modified version of the statewide VMT model created by WSDOT that accounts for alternative fuel prices.

In addition to aggregate VMT forecasts, per-capita VMT was also modeled. This model abstracts from the effects of population growth and provides an individual level estimate of the rebound effect.

6.1 Methodological Background

VMT is sensitive to fuel prices, and this sensitivity is traditionally measured with fuel price elasticities. Fuel price elasticities can be determined for long, medium, and short-run periods.

Blair et al. (1984) estimated VMT and miles per gallon as a two-equation recursive system using data collected monthly in the State of Florida between January and December 1967. They estimated linear equations without considering elasticity. Green (1992) estimated their elasticity between -0.25 and -0.4. Gately (1990) used the double logarithmic form model to estimate an equation for VMT of both cars and light trucks using data from between 1966-1988. Gately used the total number of population to account for demographic effects on travel demand. He emphasized the impact of the Baby Boomer generation as well as the increase from 75% to 90% of adults holding a license. Dahl and Sterner (1991) found typical short-run fuel price elasticities of VMT to be -0.26.

Goodwin (1992) explored the effect that the treatment of time and a particular methodological approach can have on these magnitudes. In the time series category, he found estimates of -0.27, -0.71, and -0.53 for short-term, long-term, and ambiguous, respectively. For the cross-section category, he estimated -0.28, -0.84, and -0.18 in short-term, long-term, and ambiguous subcategories, respectively. Goodwin also considered the effect of gasoline price on traffic levels. These effects were smaller than the gasoline consumption effects.

Small and Van Dender (2007) found a short-run fuel price elasticity of VMT of -0.45 on average from 1966-2001 using aggregated macro-data from pooled cross-sections and state-level time-series data. Mabe (2007) estimated the influence of gasoline prices on travel demand, finding income elasticity of 1.16 and a price elasticity of -0.06. Liddle (2009) examined the effect of different factors on VMT using data from 1936-2004. He found that the travel demand increased with income while higher fuel prices decreased consumption. Moreover, he argued that gasoline prices influence vehicle-type decisions, but only in the long-run.

Ficklin (2010) estimated the elasticity of VMT with respect to gas price. He found gas prices have no significant effect on the decision to take a trip. However, those that take at least one trip have an elasticity of -0.0777 with respect to the previous month’s average price, and -0.445 with respect to the current month’s average price.

WSDOT developed a VMT model as a function of Washington motorized registration, statewide employment, and fuel prices using an ARMA(1,1) model. The elasticity of VMT with respect to employment is 0.70, the elasticity with respect to motorized registrations is 0.47, and the fuel price elasticity is -0.072.

6.1 VMT Modeling Methodology

A logarithmic form model, which is standard in the literature, has been estimated. Aggregated time series data for the State of Washington between 1965-2011 were utilized. The primary goal is to estimate the statistical significance and magnitude of the elasticity of VMT with respect to different explanatory variables, especially fuel prices. Elasticity provides a measure of how a percentage change in one variable results in a percentage change in the dependent variable (VMT). For example, an elasticity of VMT with respect to gas price of -0.5 would imply that a 1% increase in gas price will result in a 0.5% decrease in VMT. The gas price elasticity of VMT is described as:

Equation 10

$$elasticity = \frac{\partial VMT}{\partial gasprice} * \frac{gasprice}{VMT} = \frac{\partial \log(VMT)}{\partial \log(gasprice)} = \alpha_{gasprice}$$

where the elasticity is the $\alpha_{gasprice}$ as the estimated coefficient in the model. The logarithmic transformation does not change the relative significance of the results compared to a linear formulation but does allow for an easier interpretation of the elasticity coefficients.

6.2 VMT Data Description

Annual data on VMT for the State of Washington from 1965-2011 were gathered from the Washington State Department of Transportation. Several key types of influences on VMT are considered, such as economic factors, transportation price, and socio-demographic factors during this time frame. VMT is modeled as a function of the number of registered vehicles, employment, and gas price.
Figure 6.1 shows the positive growth of VMT during the analysis period. The rate of VMT growth in recent years has been declining. Much of the decrease in the rate of VMT growth since 1998 can be attributed to increased gasoline prices. The growth rate dipped in 2008 and was likely due to the economic recession. Figure 6.2 shows changes in gasoline prices over the same timeframe.

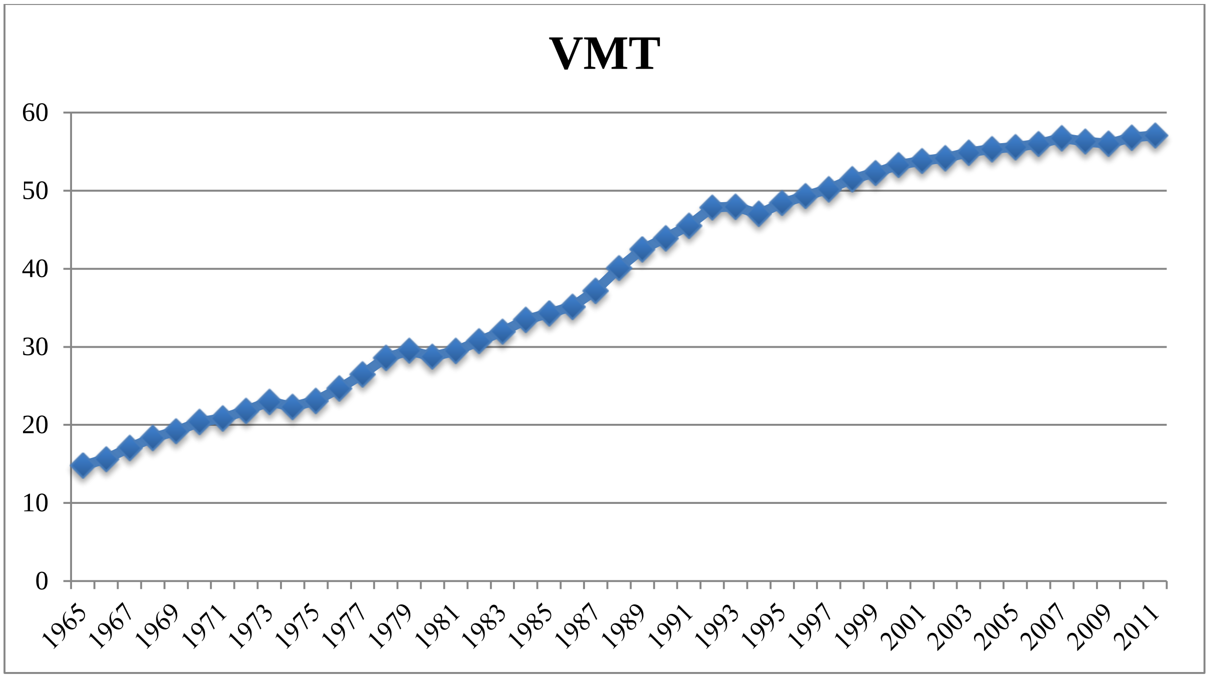


Figure 6.1 Trend of VMT 1965-2011

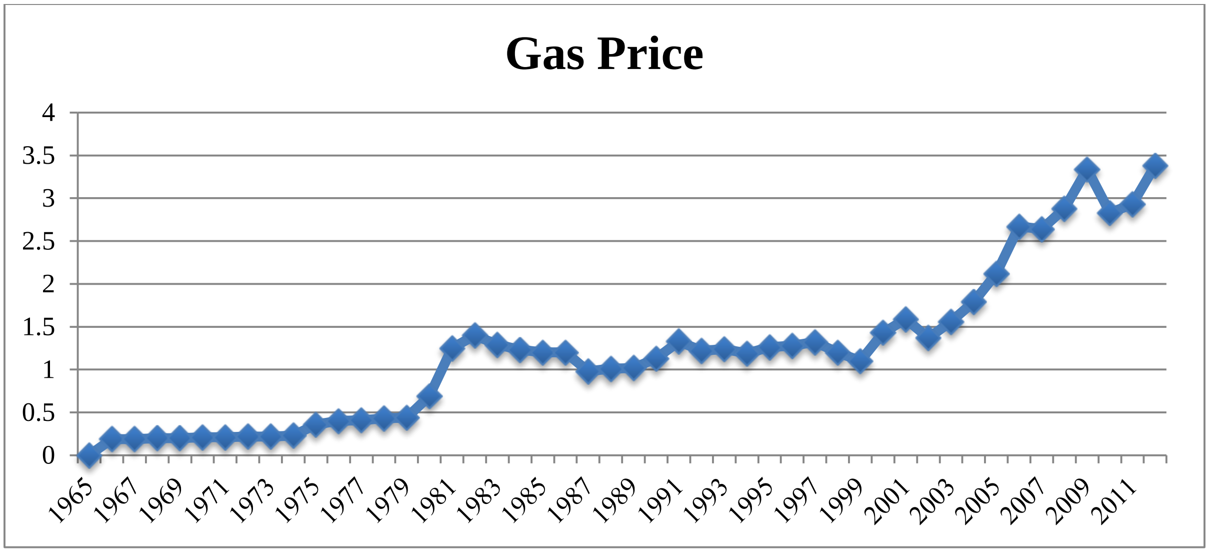


Figure 6.2 Trend of Gas Prices 1965-2011

The number of registered vehicles has steadily increased during the period of study. Figure 6.3 shows that the number of registered vehicles dropped in 2008 at the time of the economic downturn. This effect continued until 2010. However, since 2010, the number of registered vehicles began to increase.

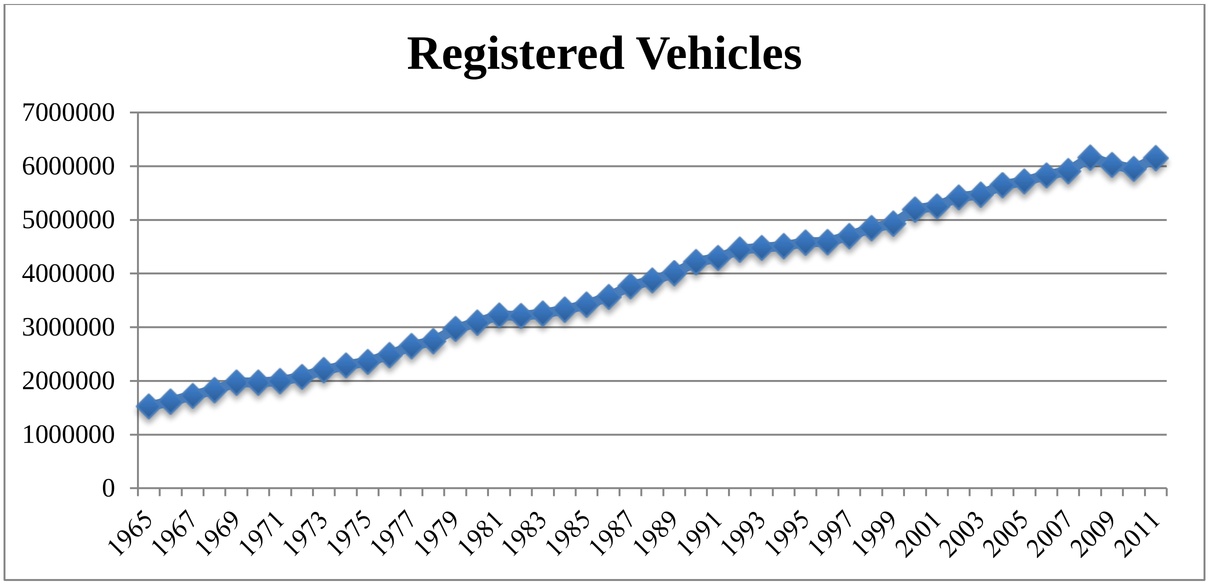


Figure 6.3 Trend of Number of Registered Vehicles 1965-2011

Employment is indicative of the volume of economic activity and has a direct effect on VMT. Therefore, when employment is high, VMT is generally high to accommodate this activity. Figure 6.4 shows employment during the period of study. It is clear that the overall trend is positive, as would be expected with a growing population. However, there is also notable variation in this figure. In particular, employment decreased from 2001 to 2003 as the United States entered into the recession following the burst of the dot-com bubble in 2000 and the events of September 11, 2001. These numbers began to recover in 2003 and increased thinly until the beginning of the Great Recession of 2008. Employment levels continued to fall until 2010 when levels begin to increase slightly.

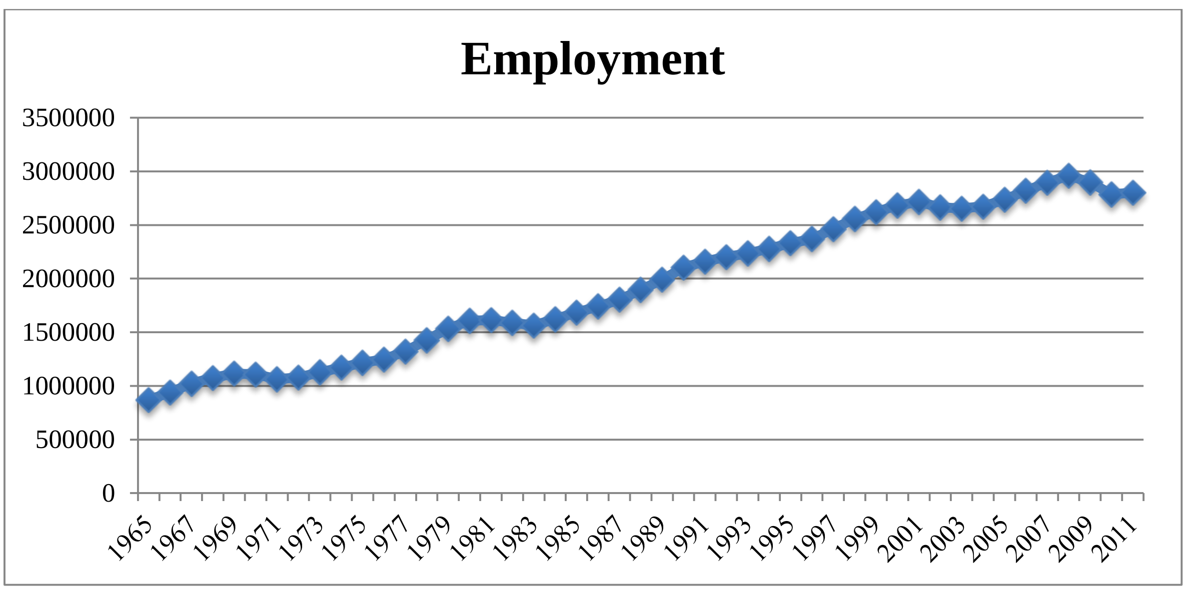


Figure 6.4 Trend of Employment

It was expected that gas prices would negatively affect VMT, while employment for the number of registered vehicles with that had a positive effect on VMT. Figure 6.5 shows population growth over time. Since aggregate VMT is a function of population, Figure 6.6 presents VMT per capita. Aggregate

VMT has been increasing, whereas VMT per capita has been declining, over the past decade. This result indicates that VMT is heavily influenced by population. VMT per capita controls for this effect and should therefore be more sensitive to other dependent variables.

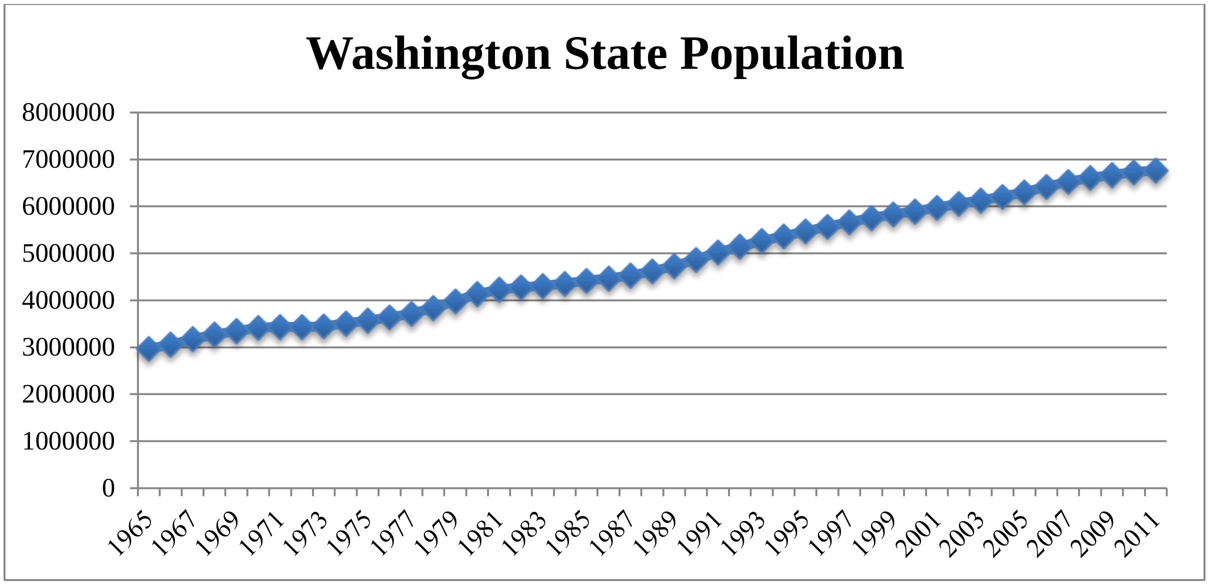


Figure 6.5 Trends of State Population

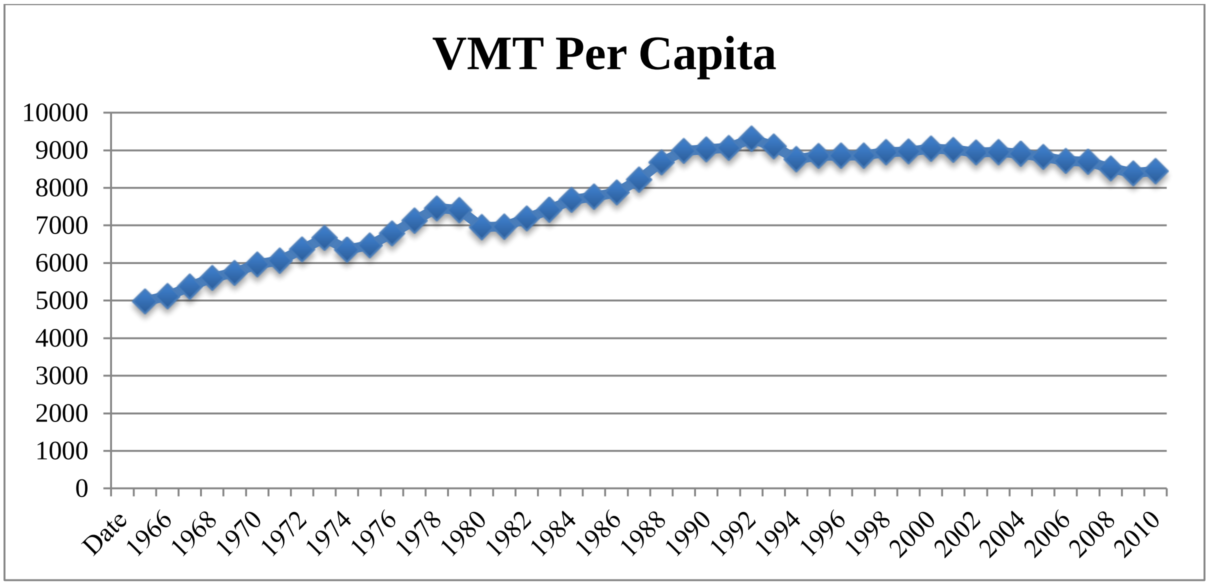


Figure 6.6 VMT Per Capita Trend for Washington State

An observation from Figure 6.6 is that the VMT per population is declining from previous levels. The growth of vehicle miles traveled is not by individual drivers driving more but from increased population and employment demand. The reduction of individual VMT is being seen, especially in millennials who value virtual social interaction over making trips by vehicle.

6.4 Forecasting

In order to estimate the VMT and VMT per capita, the forecasted values of explanatory variables were taken from the WSDOT Economic Analysis, the Washington State Transportation Revenue Forecast Council, and the Washington State Economic and Revenue Forecast Council. The effect of natural gas vehicles on future VMT, the weighted average of fuel price between natural gas vehicles, and conventional vehicles with the adoption rate as weights was used. Average fuel price for forecasting is defined as:

Equation 11

$$\text{Average gas price} = \sum_{i} p_i * k_i$$

where p_i is forecasted unit price of fuel type i and k_i is the percent of vehicles of type i in the fleet. The estimated NGV adoption rate is used to calculate average fuel price for forecasting. The estimates for the adoption rates above present a large range of plausible parameter values. The sensitivity of our forecasts to this parameter has been tested. Nine scenarios are presented as combinations of fuel differential price of $1.50, $2.00, and $2.50 per gallon and purchase price differentials of $3,000, $6,000, and $9,000 to show the effect of NGVs on forecasted VMT and VMT per capita. These scenarios are presented in Table 6.1.

Table 6.1 Different Scenarios to Forecast VMT

Scenario	Fuel Differential Price	Purchase Differential Price	NGV's Percentage of Fleet
1	$1.50	$9000	0%
2	$2.00	$9000	0.5%
3	$2.50	$9000	1.6%
4	$1.50	$6000	0.8%
5	$2.00	$6000	6.5%
6	$2.50	$6000	16.2%
7	$1.50	$3000	28.6%
8	$2.00	$3000	46.1%
9	$2.50	$3000	59.3%

Since the price of natural gas is lower than the price of gasoline, VMT is expected to increase with NGV adoption based on the fuel price elasticity. Scenario 1 is the baseline scenario, as there will be no adoption of NGV. Other scenarios imply that NGV will have an effect on VMT. Table 6.2 presents the forecasted VMT in these different scenarios. The baseline scenario results indicate that VMT will continue to grow even without NGV adoption. Other scenarios, which are influenced by NGVs, all forecast greater VMT. As the portion of NGVs in the fleet increases, there is a corresponding induced increase in VMT.

Table 6.2 Forecasted Change from 2012 VMT (Billion) due to NGV Adoption

Year	Scenario 1 (Baseline)	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9
2013	1.80	(+0.01)	(+0.05)	(+0.02)	(+0.18)	(+0.57)	(+0.61)	(+1.43)	(+2.57)
2014	3.55	(+0.01)	(+0.05)	(+0.02)	(+0.18)	(+0.58)	(+0.62)	(+1.44)	(+2.59)
2015	5.54	(+0.01)	(+0.06)	(+0.02)	(+0.19)	(+0.61)	(+0.65)	(+1.53)	(+2.76)
2016	7.32	(+0.01)	(+0.06)	(+0.02)	(+0.19)	(+0.62)	(+0.66)	(+1.54)	(+2.78)
2017	8.92	(+0.01)	(+0.06)	(+0.02)	(+0.19)	(+0.60)	(+0.64)	(+1.49)	(+2.67)
2018	10.96	(+0.02)	(+0.06)	(+0.02)	(+0.20)	(+0.65)	(+0.69)	(+1.62)	(+2.92)
2019	13.09	(+0.02)	(+0.07)	(+0.02)	(+0.22)	(+0.72)	(+0.77)	(+1.81)	(+3.28)
2020	14.77	(+0.02)	(+0.07)	(+0.02)	(+0.22)	(+0.72)	(+0.77)	(+1.81)	(+3.27)
2021	16.64	(+0.02)	(+0.07)	(+0.02)	(+0.23)	(+0.74)	(+0.79)	(+1.86)	(+3.36)
2022	18.47	(+0.02)	(+0.07)	(+0.02)	(+0.23)	(+0.76)	(+0.80)	(+1.89)	(+3.42)
2023	20.45	(+0.02)	(+0.07)	(+0.02)	(+0.24)	(+0.78)	(+0.83)	(+1.96)	(+3.55)
2024	22.28	(+0.02)	(+0.07)	(+0.02)	(+0.24)	(+0.78)	(+0.83)	(+1.95)	(+3.52)
2025	24.42	(+0.02)	(+0.08)	(+0.02)	(+0.25)	(+0.81)	(+0.87)	(+2.03)	(+3.68)
2026	26.28	(+0.02)	(+0.07)	(+0.02)	(+0.25)	(+0.80)	(+0.85)	(+1.99)	(+3.58)
2027	28.21	(+0.02)	(+0.07)	(+0.02)	(+0.24)	(+0.79)	(+0.84)	(+1.96)	(+3.50)
2028	30.18	(+0.02)	(+0.07)	(+0.02)	(+0.24)	(+0.78)	(+0.83)	(+1.92)	(+3.42)
2029	32.30	(+0.02)	(+0.07)	(+0.02)	(+0.24)	(+0.78)	(+0.83)	(+1.92)	(+3.42)
2030	34.81	(+0.02)	(+0.08)	(+0.02)	(+0.25)	(+0.82)	(+0.87)	(+2.03)	(+3.62)
2031	37.00	(+0.02)	(+0.08)	(+0.02)	(+0.25)	(+0.82)	(+0.87)	(+2.02)	(+3.59)

Table 6.3 Forecasted Change in Per Capita VMT from 2012 Levels due to NGV Adoption

Year	Scenario 1 (Baseline)	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9
2013	150.54	(+2.23)	(+8.95)	(+2.67)	(+29.47)	(+95.88)	(+101.96)	(+238.90)	(+431.16)
2014	286.19	(+2.23)	(+8.94)	(+2.67)	(+29.46)	(+95.76)	(+101.83)	(+238.21)	(+428.82)
2015	448.48	(+2.32)	(+9.33)	(+2.79)	(+30.73)	(+99.99)	(+106.34)	(+249.35)	(+450.56)
2016	571.91	(+2.32)	(+9.31)	(+2.78)	(+30.66)	(+99.70)	(+106.02)	(+248.20)	(+447.35)
2017	661.85	(+2.22)	(+8.94)	(+2.67)	(+29.42)	(+95.44)	(+101.47)	(+236.38)	(+422.76)
2018	817.63	(+2.37)	(+9.53)	(+2.85)	(+31.38)	(+102.04)	(+108.50)	(+253.93)	(+457.41)
2019	984.51	(+2.57)	(+10.35)	(+3.09)	(+34.11)	(+111.24)	(+118.33)	(+278.81)	(+507.72)
2020	1077.44	(+2.55)	(+10.24)	(+3.06)	(+33.75)	(+109.97)	(+116.96)	(+275.00)	(+499.01)
2021	1193.04	(+2.58)	(+10.38)	(+3.10)	(+34.21)	(+111.48)	(+118.57)	(+278.81)	(+506.06)
2022	1301.07	(+2.60)	(+10.43)	(+3.12)	(+34.38)	(+111.97)	(+119.09)	(+279.85)	(+507.39)
2023	1425.93	(+2.66)	(+10.67)	(+3.19)	(+35.17)	(+114.62)	(+121.91)	(+286.77)	(+520.83)
2024	1522.68	(+2.62)	(+10.52)	(+3.14)	(+34.66)	(+112.81)	(+119.97)	(+281.50)	(+509.17)
2025	1659.14	(+2.69)	(+10.80)	(+3.23)	(+35.60)	(+115.97)	(+123.34)	(+289.80)	(+525.34)
2026	1750.30	(+2.62)	(+10.51)	(+3.14)	(+34.61)	(+112.53)	(+119.66)	(+280.10)	(+504.68)
2027	1846.46	(+2.55)	(+10.24)	(+3.06)	(+33.72)	(+109.47)	(+116.39)	(+271.51)	(+486.57)
2028	1944.98	(+2.49)	(+9.99)	(+2.99)	(+32.88)	(+106.59)	(+113.31)	(+263.46)	(+469.81)
2029	2058.61	(+2.46)	(+9.89)	(+2.96)	(+32.55)	(+105.44)	(+112.09)	(+260.13)	(+462.55)
2030	2219.78	(+2.56)	(+10.29)	(+3.07)	(+33.86)	(+109.79)	(+116.71)	(+271.46)	(+484.29)
2031	2333.96	(+2.53)	(+10.15)	(+3.03)	(+33.41)	(+108.21)	(+115.03)	(+266.96)	(+484.29)

The low fuel price elasticity of VMT suggests that introducing natural gas vehicles will not have much effect on future VMT. Scenario 9 is potentially an extreme case, where nearly 60% of vehicles run on natural gas. This portion of natural gas vehicles induces an extra 3.62 billion VMT in 2030 over the baseline scenario of 34.81 billion VMT without natural gas vehicles. Even this rather modest increase is based on an assumption of extremely favorable circumstances for natural gas vehicles: a $3,000 purchase price differential and $2.50 fuel price differential. This scenario would require a concentrated effort from car manufacturers to substantially lower prices for natural gas vehicles as well as a dramatic divergence between the price of gasoline and natural gas. It is unlikely that VMT projection will be radically altered by the introduction of a large proportion of NGV.

VMT per capita is more sensitive to fuel prices than is aggregate VMT. Therefore, it is expected that NGV adoption rates will have a greater effect on VMT per capita. The results of different scenarios are presented in Table 6.3. The baseline (scenario 1) demonstrates that under a no-change scenario, VMT per capita increases by 2,220 vehicles mile traveled in 2030 over 2011 levels. The comparison of the baseline scenario and scenario 9 (the extreme case) are presented for VMT and VMT per capita in Figures 6.7 and 6.8, respectively.

These figures forecast that the effect of NGV adoption on VMT per capita is greater than the effect on VMT. This result is consistent with the observation that VMT per capita is more sensitive to fuel price. Second, projected growth rates of VMT are greater than projected VMT per capita growth rates. This counterintuitive result is based on the effect of population growth.

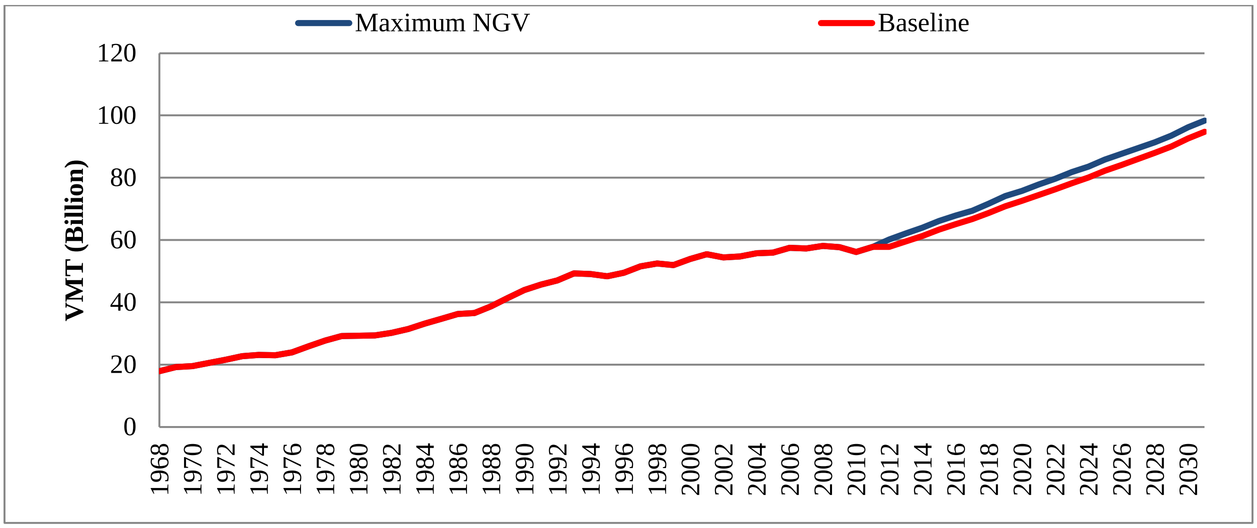


Figure 6.7 Total VMT Comparison of Baseline and Scenario 9

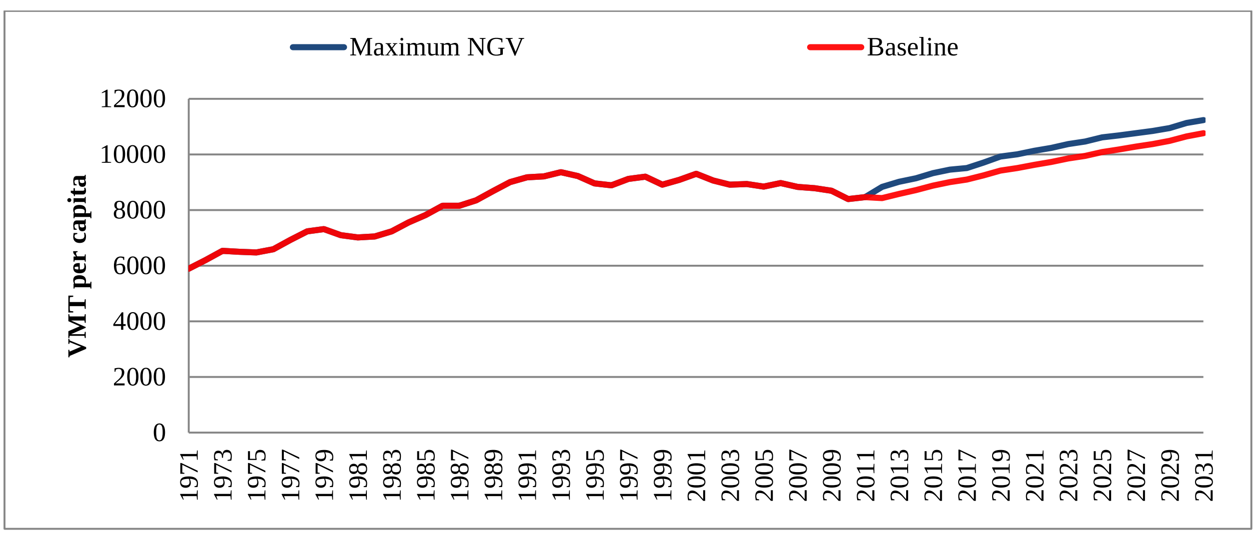


Figure 6.8 VMT Per Capita Comparison of Baseline and Scenario 9

6.5 Sensitivity Analysis

VMT forecasts are sensitive to a number of factors. Fuel price is one of the main explanatory factors in the variation of the VMT models. Fuel prices varied as a weighted average of prices using the predicted adoption rates as weights. The adoption rate was determined based on the purchase price differential and fuel price differential. Therefore, these two variables are the main source of differentiation in these forecasts. In this section, the sensitivity of VMT with respect to these variables has been analyzed. Figures 6.9 and 6.10 depict the sensitivity of VMT and VMT per capita to these variables, respectively. Both VMT and VMT per capita increase when the fuel price differential increases and decrease when the purchase price differential increases. These effects increase the attractiveness of NGVs.

From these figures, it is clear that VMT and VMT per capita are more sensitive to fuel price differential when the vehicle purchase price differential is small. This highlights the large upfront purchase price as the main obstacle associated with adoption of NGVs.

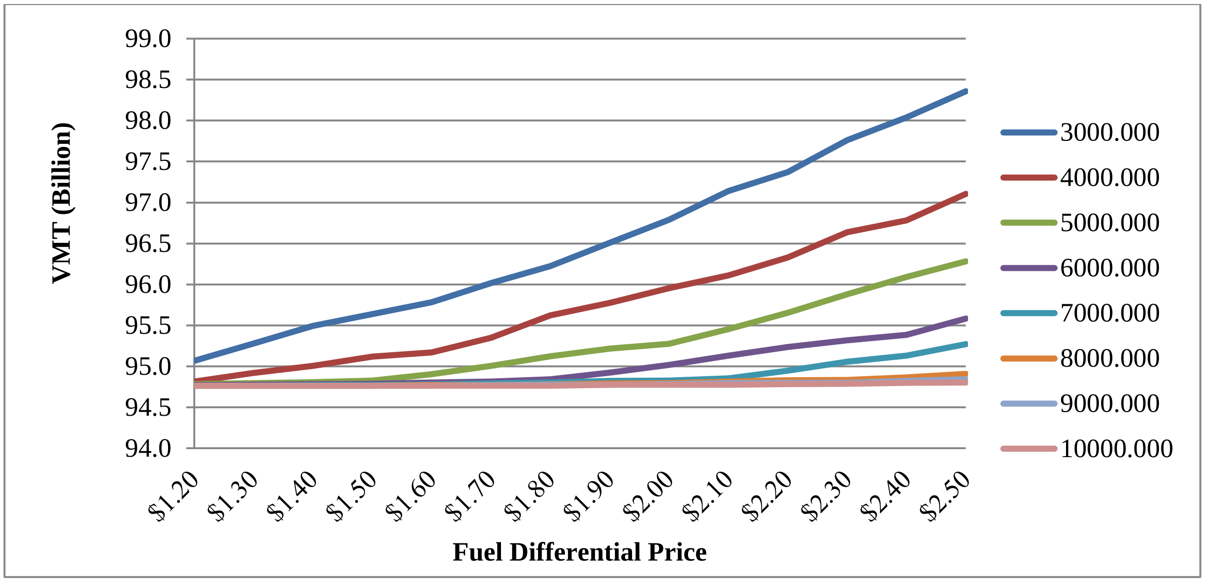


Figure 6.9 2031 Total VMT by Differential of Fuel Cost and Upfront Purchase Price

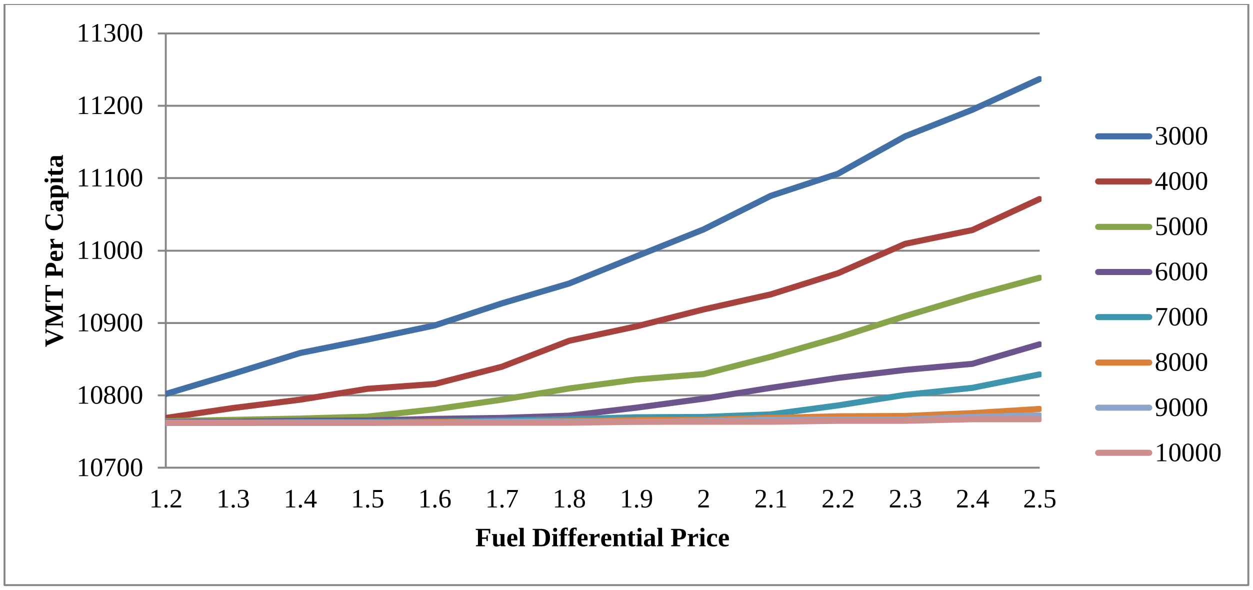


Figure 6.10 2031 Per Capita VMT by Differential of Fuel Cost and Upfront Purchase Price

6.6 Conclusion

This study helps WSDOT assess the impacts of changes in fuel price on travel demand, particularly how NGV adoption affects VMT. The VMT as a measure of travel demand was modeled by using time series data. The data were taken from WSDOT from 1965-2011. VMT was regressed on the number of registered vehicles, employment, and gas price. An ARIMA (0,1,1) model was fit. Based upon this model, estimated elasticity of VMT with respect to number of registered vehicles, employment, and gas price are 0.226, 0.267, and -0.083, respectively. In addition to the VMT model, another model was adapted to exclude population effects. The VMT per capita model was fit using per capita versions of the same explanatory variables. An ARIMA(1,1,1) fit this data best. The estimated coefficient of this model for number of registered vehicles per capita, employment per capita and gas price are 0.286, 0.220, and -0.096, respectively. These estimates imply that VMT per capita is more sensitive to these variables than VMT.

Finally, VMT was forecasted in multiple scenarios by assuming the natural gas price and the associated adoption rate. These adoption rates were calculated using data from the 2009 National Household Travel Survey. The joint distribution of household VMT and MPG, along with assumptions about the purchase price differential and fuel price differential, is used to calculate the proportion of the fleet that would find NGVs to be financially advantageous. These forecasts indicate that the effect of increasing NGV adoption rates is negligible.

7. NGV ADOPTION EFFECT ON EMISSIONS

Adoption of natural gas powered vehicles has the potential to spur reductions in greenhouse gas (GHG) emissions from the transportation sector. The size of these reductions depends on the rate at which consumers and firms adopt natural gas powered vehicles. In this study, estimates for the potential carbon emission reductions from both the light-duty and heavy-duty vehicle fleets are provided. The basic economic decision of whether or not to adopt a compressed natural gas (CNG) vehicle is driven by similar factors (vehicle prices, fuel prices, etc.) for both light- and heavy-duty vehicles. However, the types of available data that describe market conditions for these two sectors of the transportation fleet are different. In particular, much more detailed data are available for the light-duty fleet than for the heavy-duty fleet. For this reason, the techniques used in this report to estimate the impact of CNG adoption on carbon emissions are different for these sectors. Overall, the conclusions of this research are similar in both cases: CNG adoption is likely to produce only a modest reduction in overall carbon emissions from the transportation sector.

This section begins by briefly reviewing the chemistry of emissions that makes carbon emission reductions via CNG adoption possible. Then this information is combined with the framework to predict CNG vehicle adoption rates in the light-duty vehicle sector. This exercise produces a range of estimates of carbon emission reductions from the light-duty vehicle sector. Following these results, the methodology for estimating the potential for carbon emission reductions from the heavy-duty vehicle fleet is explained and discussed. A discussion of the overall potential for carbon emission reductions due to CNG vehicle adoption concludes this section.

7.1 Chemistry of Emissions

Given the stoichiometric formula for the combustion of gasoline (octane),

$$2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O$$

it is known that every 1 mol of fuel that is burned will lead to approximately 8 mol of CO_2. Using this ratio and the atomic weight of each atom in the chemical formula leads to the conclusion that for every pound of fuel burned, 3.08 pounds of carbon dioxide is produced. The specific gravity of gasoline is 0.75g/ml at STP (Mackay, Shiu, Ma, & Li, 2006), or 6.259 lbs./gal, indicating that one gallon of gasoline will produce about 19.3 lbs. of CO_2. Information about the fuel efficiency and the vehicle miles traveled (VMT) of the fleet can then be used to compute the approximate number of gallons that the fleet will consume in a given year.

Similarly, the chemical formula for the combustion of natural gas (methane),

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 \ ,$$

combined with information on the atomic weights of each of the chemicals, allowing calculation that the ratio of CO_2 produced to natural gas burned, by weight, will be 2.743. Finally, according to the National Institute of Standards and Technology (NIST), "1 Gasoline gallon [US] equivalent (GGE) means 2.567 kg (5.660 lbs) of natural gas." (NIST 2008). Therefore, burning one GGE of compressed natural gas would yield 15.5 lbs. of CO_2. These calculations indicate that switching from burning gasoline to burning natural gas could represent a 19.6% reduction in CO_2 emissions. It is noted, therefore, that the absolute upper bound on emission reductions due to CNG adoption alone is around 20%—even with 100%

adoption rates, carbon emissions cannot fall more than 20% without reductions in vehicle usage rates or improvements in fuel economy.

7.2 Light-Duty Vehicle Fleet

As previously discussed, consumers would choose to purchase a natural gas vehicle (NGV) if the costs of operating that vehicle are lower than the costs of operating a comparable conventional fuel vehicle. The primary variables that consumers must account for in this calculation are the purchase price of the vehicle, the price of the fuel, expected VMT, fuel efficiency (MPG), and the expected useful life of the vehicle. Based on estimates of these variables, data on fleet fuel efficiency, and fleet VMT per household, the expected adoption rate of NGVs was calculated.
It will be convenient to define an indicator function for when CNG is financially advantageous to the consumer,

Equation 12

$$\phi_{i,j} = \begin{Bmatrix} 1 \quad if \left(V_{g0}^{*} - V_{c0}^{*}\right) + \sum_{t=0}^{T} (1+r)^{-t} \left(p_g - p_c\right)\left(\frac{VMT_i}{MPG_j}\right) > 0 \\ 0 \qquad\qquad\qquad otherwise \end{Bmatrix} .$$

This equation states that, when a NGV is cost effective for the i[th], j[th] VMT / MPG pair, $\phi_{i,j}$ will take on the value of unity. Otherwise, when an NGV is less cost effective than a conventional gasoline vehicle, $\phi_{i,j}$ will take on the value of zero.

Using data from the 2009 National Household Travel Survey (U.S. Department of Transportation, 2009), the proportion of the fleet that falls into specific MPG/VMT combinations is computed. With assumptions about the purchase price differential and fuel price differential, the proportion of the fleet that would find NGVs to be financially advantageous can be calculated. These predicted adoption rates can be found in Table 6.1 of this report. The portion of the fleet that is most likely to adopt NGVs are the high VMT and low MPG combinations—the *dirtiest* vehicles in terms of carbon output.

Because these high VMT, low MPG vehicles can be considered the *dirtiest* portion of the fleet, these conversions can be expected to be the most helpful in terms of reduced CO_2 emissions. However, the size of these reductions depends crucially on whether or not the proportion of the fleet, as represented by these VMT/MPG combinations that find NGVs cost effective, is sufficiently large.

7.2.1 Calculating Emissions

Knowledge of a vehicle's fuel consumption rate and miles traveled allows for the computation of the number of gallons of fuel being consumed. Specifically, the fuel being consumed by a vehicle is the ratio of VMT to MPG,

Equation 13

$$C = \frac{VMT}{MPG} .$$

This figure, combined with knowledge of the chemistry of emissions for different fuels, allows for the calculation of the level of emissions for each VMT/MPG combination within the fleet. The level of emissions is simply a constant proportion of the fuel consumed by weight,

Equation 14

$$e_{MPG,VMT} = k_i C_{MPG,VMT}$$

where $f_{MPG,VMT}$ and $e_{MPG,VMT}$ is the fuel consumed and level of emissions, respectively, in units of weight for the MPG / VMT pair. The constant k_i is specific to each fuel type: the appropriate k_i for gasoline is given as k_g=3.08 and for natural gas as k_c=2.74. These values are idealized in the sense that the formulae do not account for unreacted fuel, impurities, etc.

The total reduction of emissions due to NGV conversion will be a function of fuel consumed by the fleet, the proportion of the fleet that does convert, and the distribution of fleet VMT and MPG. Therefore, the total level of emissions is modeled by the function,

Equation 15

$$TE = h\sum_i \sum_j [\phi_{i,j} k_c w_c \frac{VMT_i}{MPG_j} p_{i,j} + (1-\phi_{i,j}) k_g w_g \frac{VMT_i}{MPG_j} p_{i,j}] \ .$$

TE is the total emissions from both natural gas and gasoline powered vehicles. k is the emissions to fuel consumed ratio, and the subscripts indicate either natural gas (c) or gasoline (g). w is the conversion factor from a volume-based measure to a weight-based measure for natural gas and gasoline, where the subscripts are the same as above. VMT_i indicates the ith level of VMT. MPG_j indicates the jth MPG level. $p_{i,j}$ is the proportion of the fleet that has the VMT/MPG combination of (VMT_i , MPG_j). Finally, h represents the total fleet size. These data were obtained from WSDOT.

The model requires an estimate of the difference in the cost of the two vehicles in order to compute the value of $\phi_{i,j}$. This calculation depends on estimates for many parameter values. The parameters used in this calculation are summarized in Table 7.1.

Table 7.1 Baseline Parameter Values

Parameter	Value
Length of Ownership	60 months
Purchase Price Differential	$7000
Fuel Price Differential	$1.50
Discount Rate	6%
Depreciation Rate	15%

The total level of emissions based on these assumptions and data for the vehicle fleet are 17.98 and 842.36 million tons of CO_2 for the state of Washington and the entire U.S., respectively. The baseline model's parameters were subjected to a sensitivity analysis. For most parameters in the model, the level of emissions was not very sensitive to changes. They were most sensitive to changes in the purchase price differential and changes in the fuel price differential. Table 7.2 and Table 7.3 show the total level of emissions in Washington and the U.S., respectively.[2] The sensitivity analysis results for the other variables are available from the authors on request.

Table 7.2 Predicted Total Level of Carbon Emissions for Washington State (Light-Duty Vehicles, Millions of Short Tons)

		Purchase Price Differential							
		$3000	$4000	$5000	$6000	$7000	$8000	$9000	$10000
Fuel Price Differential	$1.20	17.87	17.96	17.97	17.98	**17.98**	17.98	17.98	17.98
	$1.30	17.87	17.94	17.97	17.98	**17.98**	17.98	17.98	17.98
	$1.40	17.86	17.93	17.96	17.97	**17.98**	17.98	17.98	17.98
	$1.50	**17.85**	**17.92**	**17.96**	**17.97**	**17.98**	**17.98**	**17.98**	**17.98**
	$1.60	17.83	17.90	17.95	17.97	**17.97**	17.98	17.98	17.98
	$1.70	17.83	17.88	17.93	17.96	**17.97**	17.98	17.98	17.98
	$1.80	17.81	17.87	17.92	17.96	**17.97**	17.97	17.98	17.98
	$1.90	17.80	17.86	17.92	17.95	**17.97**	17.97	17.98	17.98
	$2.00	17.80	17.85	17.90	17.94	**17.96**	17.97	17.97	17.98
	$2.10	17.79	17.83	17.88	17.93	**17.96**	17.97	17.97	17.98
	$2.20	17.78	17.83	17.87	17.92	**17.95**	17.97	17.97	17.97
	$2.30	17.78	17.82	17.87	17.91	**17.94**	17.96	17.97	17.97
	$2.40	17.77	17.81	17.86	17.90	**17.93**	17.96	17.97	17.97
	$2.50	17.77	17.80	17.85	17.89	**17.92**	17.95	17.97	17.97

[2] As a reference point, we note that the Washington State greenhouse gas emissions inventory estimates 21.5 million metric tons of CO_2 emissions from on-road gasoline combustion. Full report available at http://www.ecy.wa.gov/climatechange/ghg_inventory.htm

Table 7.3 Predicted Total Level of Carbon Emissions for United States

(Light-Duty Vehicles, Millions of Short Tons)

		Purchase Price Differential							
		$3000	$4000	$5000	$6000	$7000	$8000	$9000	$10000
Fuel Price Differential	$1.20	839.61	842.02	842.33	842.37	**842.37**	842.37	842.39	842.39
	$1.30	838.67	841.52	842.30	842.36	**842.37**	842.37	842.39	842.39
	$1.40	837.74	840.94	842.20	842.33	**842.37**	842.37	842.39	842.39
	$1.50	**837.14**	**840.31**	**842.02**	**842.31**	**842.36**	**842.37**	**842.39**	**842.39**
	$1.60	836.44	839.61	841.62	842.28	**842.34**	842.37	842.39	842.39
	$1.70	835.86	838.98	841.20	842.16	**842.33**	842.36	842.38	842.39
	$1.80	835.30	838.21	840.68	842.02	**842.30**	842.34	842.37	842.39
	$1.90	834.80	837.74	840.15	841.71	**842.24**	842.33	842.36	842.38
	$2.00	834.45	837.14	839.61	841.42	**842.14**	842.31	842.34	842.37
	$2.10	833.90	836.66	839.09	840.94	**842.02**	842.30	842.33	842.36
	$2.20	833.67	836.09	838.60	840.52	**841.71**	842.24	842.23	842.34
	$2.30	833.38	835.70	838.18	840.02	**841.48**	842.13	842.30	842.34
	$2.40	833.13	835.30	837.66	839.61	**841.08**	842.02	842.28	842.33
	$2.50	832.93	834.93	837.14	839.17	**840.72**	841.83	842.24	842.31

In order for these results to be meaningfully interpreted, it is necessary to establish a benchmark level of emissions. The model's prediction for the emissions level without any conversions to NGVs in the fleet as the benchmark level is used. This level of emissions is calculated by the following formula:

Equation 16

$$TE^* = h\sum_i \sum_j k_g w_g \frac{VMT_i}{MPG_j} p_{i,j}$$

where *TE** is the benchmark level of emissions, and all other values in the formula share the same interpretation as the previous formula.

Finally, the difference between the predicted level of emissions, *TE*, and the benchmark level of emissions, *TE**, is calculated as:

Equation 17

$$\Delta E = TE - TE^* < 0$$

The negative sign on this expression indicates that the change is a reduction of total emissions. Substituting the formulae for *TE* and *TE** in this expression and rearranging yields the following formula:

Equation 18

$$\Delta E = (k_c w_c - k_g w_g)\sum_i \sum_j [\phi_{i,j} p_{i,j} \frac{VMT_i}{MPG_j}]$$

This formula states that the reduction in emissions attributable to NGVs is simply the reduction of emissions from only the vehicles that do convert to NGVs.

The percentage reduction of emissions from the benchmark conditions due to a change in market conditions (fuel and vehicle prices) is given in Table 7.4 and 7.5 for the State of Washington and the United States, respectively.

Table 7.4 Predicted Percentage Carbon Emission Reductions for Washington State (Light-Duty Vehicles)

		Purchase Price Differential							
		$3000	$4000	$5000	$6000	$7000	$8000	$9000	$10000
Fuel Price Differential	**$1.20**	0.62%	0.13%	0.04%	0.01%	**0.00%**	0.00%	0.00%	0.00%
	$1.30	0.60%	0.21%	0.06%	0.02%	**0.01%**	0.00%	0.00%	0.00%
	$1.40	0.68%	0.31%	0.09%	0.04%	**0.01%**	0.00%	0.00%	0.00%
	$1.50	**0.74%**	**0.33%**	**0.13%**	**0.05%**	**0.02%**	**0.01%**	**0.00%**	**0.00%**
	$1.60	0.82%	0.47%	0.20%	0.06%	**0.04%**	0.01%	0.01%	0.00%
	$1.70	0.86%	0.56%	0.26%	0.09%	**0.04%**	0.02%	0.01%	0.00%
	$1.80	0.94%	0.63%	0.31%	0.13%	**0.06%**	0.04%	0.01%	0.01%
	$1.90	1.00%	0.68%	0.35%	0.19%	**0.06%**	0.04%	0.02%	0.01%
	$2.00	1.03%	0.74%	0.47%	0.24%	**0.09%**	0.05%	0.04%	0.01%
	$2.10	1.09%	0.82%	0.54%	0.31%	**0.13%**	0.06%	0.04%	0.02%
	$2.20	1.10%	0.84%	0.61%	0.32%	**0.18%**	0.07%	0.05%	0.04%
	$2.30	1.13%	0.88%	0.63%	0.38%	**0.22%**	0.09%	0.06%	0.04%
	$2.40	1.15%	0.94%	0.68%	0.47%	**0.27%**	0.13%	0.06%	0.04%
	$2.50	1.16%	0.99%	0.74%	0.53%	**0.31%**	0.17%	0.08%	0.05%

Table 7.5 Predicted Percentage Carbon Emission Reductions for U.S. (Light-Duty Vehicles)

		Purchase Price Differential							
		$3000	$4000	$5000	$6000	$7000	$8000	$9000	$10000
Fuel Price Differential	**$1.20**	0.33%	0.04%	0.01%	0.00%	**0.00%**	0.00%	0.00%	0.00%
	$1.30	0.44%	0.10%	0.01%	0.00%	**0.00%**	0.00%	0.00%	0.00%
	$1.40	0.55%	0.17%	0.02%	0.01%	**0.00%**	0.00%	0.00%	0.00%
	$1.50	**0.62%**	**0.25%**	**0.04%**	**0.01%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
	$1.60	0.71%	0.33%	0.09%	0.01%	**0.01%**	0.00%	0.00%	0.00%
	$1.70	0.77%	0.40%	0.14%	0.03%	**0.01%**	0.00%	0.00%	0.00%
	$1.80	0.84%	0.50%	0.20%	0.04%	**0.01%**	0.01%	0.00%	0.00%
	$1.90	0.90%	0.55%	0.27%	0.08%	**0.02%**	0.01%	0.00%	0.00%
	$2.00	0.94%	0.62%	0.33%	0.11%	**0.03%**	0.01%	0.01%	0.00%
	$2.10	1.01%	0.68%	0.39%	0.17%	**0.04%**	0.01%	0.01%	0.00%
	$2.20	1.03%	0.75%	0.45%	0.22%	**0.08%**	0.02%	0.02%	0.01%
	$2.30	1.07%	0.79%	0.50%	0.28%	**0.11%**	0.03%	0.01%	0.01%
	$2.40	1.10%	0.84%	0.56%	0.33%	**0.15%**	0.04%	0.01%	0.01%
	$2.50	1.12%	0.89%	0.62%	0.38%	**0.20%**	0.07%	0.02%	0.01%

7.2.2 Discussion of LDV Results

These results indicate that under the baseline conditions, NGV adoption has the potential to reduce CO_2 emissions from the light-duty vehicle fleet by about 0.025% and 0.0037% in Washington State and the U.S., respectively. These small reductions are primarily due to the small portion of the light-duty vehicle fleet for which NGVs are an economically viable alternative. Sensitivity analysis indicates that with a larger fuel price differential ($2.50) and a substantially smaller vehicle price differential ($3,000), CO_2 emission reductions of about 1.16% (Washington) and 1.12% (U.S.) are plausible for the light-duty vehicle fleet.

Some comparative statics may be helpful in understanding why the potential for GHG emission reductions from converting part of the fleet to NGV is so small. The first comparative static is the change in the reduction of emissions due to a change in VMT.

Equation 19

$$\frac{\partial \Delta E}{\partial VMT_i} = (k_c w_c - k_g w_g) \sum_j \frac{\phi_{i,j} p_{i,j}}{MPG_j} < 0$$

Keeping in mind that ΔE<0, this formula says that the size of the reduction will increase as VMT increases, because $(k_c w_c - k_g w_g) < 0$. Intuitively, this is logical because as VMT increases, so will fuel consumption. Therefore, the reduction in emissions will be amplified for the part of the fleet that converts to NGVs.

The next comparative static result is that lower MPG portions of the fleet will contribute more to the overall reduction:

Equation 20

$$\frac{\partial \Delta E}{\partial MPG_j} = (k_g w_g - k_c w_c)\sum_i [\phi_{i,j} p_{i,j} \frac{VMT_i}{MPG_j^2}] > 0 .$$

This comparative static says that, as fuel economy increases, the reduction in the emissions level will become smaller. These two comparative static results indicate that the greatest reductions in emissions by switching to natural gas will be the part of the fleet with high miles and low fuel economy. In other words, the *dirtiest* part of the fleet would reduce the most per capita emissions by switching to NGVs and the additional benefit of additional adoptions in terms of CO_2 emission reductions will be subject to diminishing returns due to the greater fuel efficiency and lower VMT of later adoptions. It is also important to consider that, while the *dirtiest* part of the fleet is predisposed to adopting NGVs and this part of the fleet would also contribute the most (per vehicle) to the reduction of emissions, this portion of the vehicle fleet is small in absolute terms.

7.3 Heavy-Duty Vehicle Fleet

The methodology used to calculate the emissions from the light-duty vehicle (LDV) fleet cannot be used for the heavy-duty vehicle (HDV) fleet because data on the distribution of VMT and MPG are not readily available for the HDV fleet. Given this limitation, CO_2 emissions are estimated for the HDV fleet by estimating VMT for the entire vehicle fleet and using knowledge of the overall fuel efficiency of different classes of HDVs. HDVs account for approximately 10% of all VMT (Jackson, 2001). Corporate average fuel efficiency (CAFE) standards for HDVs give a lower numerical bound, meaning that the fuel efficiency of these vehicles can be no worse than these standards. This lower bound on fuel efficiency would therefore imply an upper numerical bound on emissions, meaning that emissions from these vehicles will be no larger than these estimates.

In 2011, the last year for which there are data, total VMT for the State of Washington was about 57 billion miles. As mentioned above, the HDV fleet accounts for approximately 10% of these miles. Therefore, the HDV fleet in the state currently has an annual VMT of about 5.7 billion miles.

Average fuel efficiency for these vehicles is needed to calculate fuel consumption of the HDV fleet. The CAFE standards for each class of HDV are reported in Table 7.6. Jackson (2001) provides the distribution of fuel efficiency in the HDV fleet by class for the U.S., as well as the proportion of vehicles that fall into each class. (Unfortunately, these proportions are not available specifically for the State of Washington. These estimates are therefore based on the HDV fleet mix for the United States.) These two pieces of information allow for the calculation of an estimate of fuel efficiency for the HDV fleet, weighted by the proportion of vehicles in each vehicle class. It is important to note that because of data limitations we are implicitly assuming that total VMT in each class is proportional to the fraction of the fleet in each class. This assumption is unlikely to be true in practice—some classes of vehicles tend to be used more intensely than others. These numbers are intended as a rough estimate only. Our estimate calculates the weighted fuel efficiency to be about 4.48 MPG.

Table 7.6 CAFE Fuel Efficiency Standards[3] for HDVs by Class: United States

Class	Fuel Efficiency (MPG)	% of HDV Fleet
2b	14.28	50.20%
3	11.62	4.44%
4	11.73	3.29%
5	9.09	2.93%
6	8.63	9.15%
7	6.02	9.65%
8a	6.64	4.96%
8b	6.62	11.43%

The level of fuel consumption is given by:

Equation 21

$$C_{t,\pi} = \frac{VMT_{t,\pi}}{MPG} \ .$$

This expression calculates how fuel consumption changes with VMT, holding the fuel efficiency of the HDV fleet constant.

The level of CO_2 emissions is:

Equation 22

$$e_{t,\pi} = C_{t,\pi}[(1-\pi)k_g w_g + \pi k_c w_c],$$

Where π represents the proportion of the HDV fleet that converts to natural gas, and the other variables are defined as above, although here the baseline comparison is between diesel fuel and natural gas rather than between gasoline and natural gas. By fixing π to zero, a benchmark level of emissions for the HDV fleet can be calculated using an assumption of 100% use of diesel fuel in the heavy-duty vehicles. This benchmark level of emissions is shown in the first row of Table 7.7. (Table 7.8 shows analogous information assuming a mix of 75% diesel and 25% gasoline in the HDV sector.) Subsequent rows show predicted total emissions and the associated percentage reduction in those emissions, for a given level of CNG adoption in the HDV sector in the State of Washington. We note that these estimates are not strongly sensitive to assumptions about fuel type (gasoline or diesel).

[3]See (*Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles; Final Rule*, 2011) for CAFE standards reported as Gallons per 1000 ton-miles. Fuel efficiencies reported here are based on those. The gross payload weights (GPW) used to calculate comparable measures of fuel efficiency in miles per gallon were the midpoint GPW for each class, except for Class 8A & 8B vehicles, which used the lower bound. The remaining 3.95% of the fleet VMT is accounted for by school and transit buses.

Table 7.7 Predicted HDV Fleet Carbon Emissions (100% diesel)

CNG Adoption Rate	Total HDV Fleet Emissions (millions of short tons)	% HDV Fleet Reduction	Implied Elasticity
0% (Baseline)	**7.78**	**0.00%**	**-**
5%	7.63	1.94%	-0.387
10%	7.48	3.87%	-0.387
15%	7.33	5.81%	-0.387
20%	7.18	7.75%	-0.387
25%	7.03	9.68%	-0.387
30%	6.88	11.62%	-0.387
36%	6.70	13.94	-0.387

Table 7.8 Predicted HDV Fleet Carbon Emissions (75% diesel/25% gasoline)

CNG Adoption Rate	Total HDV Fleet Emissions (millions of short tons)	% HDV Fleet Reduction	Implied Elasticity
0% (Baseline)	**7.32**	**0.00%**	**-**
5%	7.19	1.74%	-0.349
10%	7.06	3.48%	-0.349
15%	6.94	5.23%	-0.349
20%	6.81	6.97%	-0.349
25%	6.68	8.72%	-0.349
30%	6.56	10.46%	-0.349
36%	6.40	12.55%	-0.349

The key source of uncertainty in these calculations is the CNG adoption rate for the HDV fleet. Although it is possible to estimate CNG adoption rates based on economic preferences of consumers for the light-duty vehicle fleet, the data necessary to estimate analogous estimates for the heavy-duty vehicle fleet are not available. Moreover, estimates from published sources are scarce and speculative. For example, the California State Alternative Fuels Plan ("California Energy Commission and California Air Resources Board, *State Alternative Fuels Plan: Commission Report*: Joint Report CEC-600-2007-011-CMF," 2007), suggests that CNG penetration in the HDV sector could be as high as 36% by 2050. (See also Werpy et al. (2010)).

7.3.1 Discussion of HDV Results

The results in the first column of Table 7.8 show estimates of the total level of CO_2 emission from the HDV fleet for a given level of CNG vehicle adoption across all classes of heavy-duty vehicles. The second column shows the percentage reduction from the benchmark and the final column shows the implied elasticity of emissions with respect to NGV adoption for heavy-duty vehicles. These results indicate that if 36% of the HDV fleet adopts natural gas, then emissions from the heavy-duty vehicle fleet could be reduced by about 7.09%. This result implies an elasticity of emissions with respect to NGV adoption rates of approximately -0.1969. This elasticity seems to be fairly stable over all the adoption rates considered.

This result for the elasticity generalizes to an extreme value for the proportion to the HDV fleet switching to natural gas. Increasing the proportion of the HDV fleet that runs on natural gas will reduce emissions. This can be seen by the comparative static result,

Equation 23

$$\frac{\partial e_{\pi,t}}{\partial \pi} = C_{\pi,t}[k_c w_c - k_g w_g] < 0 \ .$$

The result can be signed because $k_g w_g > k_c w_c$. Using this comparative static, the elasticity of emissions with respect to the proportion of the HDV fleet that switches can be calculated as

Equation 24

$$\varepsilon_e = \frac{\pi[k_c w_c - k_g w_g]}{[(1-\pi)k_g w_g + \pi k_c w_c]} < 0 \ .$$

The elasticity is negative because of the previous comparative static result. Furthermore, this elasticity can be used to derive a condition for when it will be inelastic. That condition is

Equation 25

$$\pi < \frac{k_g w_g}{2(k_g w_g - k_c w_c)} \ .$$

The LHS of this expression is bound by the unit interval. The RHS is a constant that is based on the chemistry of emissions, and is equal to 2.54. The LHS of this expression is always less than the RHS, therefore the elasticity of emissions with respect to the proportion of the HDV fleet converting to natural gas is always inelastic. The inelastic nature of emissions with respect to the adoption rates suggests that converting even a relatively large proportion of the HDV fleet to natural gas is unlikely to dramatically reduce GHG emissions.

7.4 Total Emission Reductions: Light-Duty and Heavy-Duty Estimates Combined

In this section, estimates of the potential for CO_2 emissions reductions from both the LDV fleet and the HDV fleet are combined to estimate the potential for total CO_2 emissions reductions from the on-road transportation sector. Although the HDV fleet accounts for only about 10% of VMT, the HDV fleet accounts for approximately 40.6% of total on-road transportation CO_2 emissions. Moreover, there is some evidence to suggest that CNG adoption may be relatively more attractive in the HDV sector (Werpy, et al., 2010), suggesting that a large share of CO_2 emission reductions from CNG conversions may be attributable to the HDV sector.

Figure 7.1 shows an estimate of the percentage reduction of emissions for the total vehicle fleet in Washington State for various levels of the adoption rate in the HDV fleet. The figure shows that even in the extreme case of a 36% adoption rate in the HDV fleet, only a 2.88% reduction in overall transportation sector emissions and be expected—that is a reduction of 872,017 tons of CO_2.

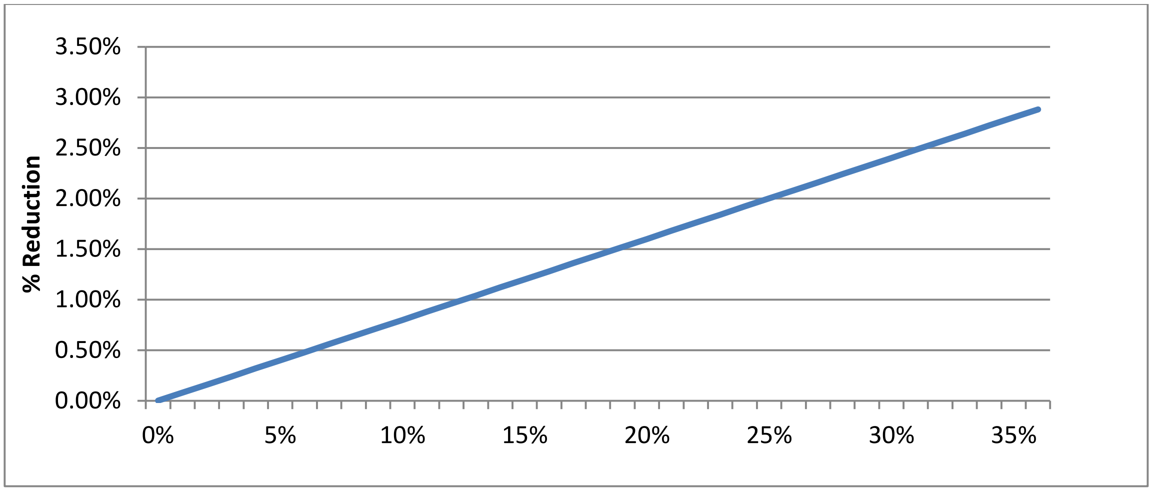


Figure 7.1 Effect of HDV Adoption on Total Transportation Sector Carbon Emissions

It is estimated that HDV adoption could contribute no more than about a 2.88% reduction in aggregate on-road transportation sector CO_2 emission to the State of Washington. From the light-duty vehicle sector, it is estimated that CNG adoption, even under the extreme conditions of a fuel price differential of \$2.50 and a \$3,000 purchase price differential, is likely to contribute no more than a 0.70% reduction in aggregate on-road transportation sector CO_2 emissions. In the absence of dramatic price or technology changes, the maximum reduction in total on-road transportation sector CO_2 emissions due to adoption of NGVs that could be expected would be about 3.58% for the State of Washington. For the United States, the analogous figures would be about 2.89% reductions from the HDV fleet and 0.67% reductions in the LDV fleet, for a combined total reduction of about 3.56%.

The combustion of natural gas produces about 20% less CO_2 per unit of energy than the combustion of gasoline, suggesting that the complete replacement of gasoline powered vehicles with CNG powered vehicles could reduce transportation sector CO_2 emissions by around 20%. However, it is estimated that the actual level of greenhouse gas emission reductions from the transportation sector due to adoption of CNG vehicles is likely to be relatively modest. Under current price conditions, only a small minority of light-duty vehicle owners would find CNG adoption to be economically viable. These estimates suggest that CNG adoption in the light-duty vehicle fleet will result in CO_2 emission reductions of about 0.025% in Washington State and about 0.0037% in the United States.

Higher levels of adoption in the heavy-duty vehicle fleet are possible, although current information on HDV CNG adoption rates is rare and generally speculative. It is speculated that in the case of 36% CNG adoption rates, CO_2 emissions from this sector could fall by about 7%. However, CO_2 reductions from the overall transportation sector due to CNG adoption, even under conditions of aggressive adoption in the HDV fleet and favorable conditions for light duty vehicles, are likely to be less than 4%. These relatively modest reductions in GHG emission are due primarily to current price conditions and technological limitations. Under current price conditions, CNG vehicles do not make economic sense for most consumers. Although economic conditions are relatively more favorable for many heavy-duty vehicles, widespread adoption still faces many logistical and technological barriers.

8. EFFECT OF NGV VEHICLES ON FUEL TAX REVENUE

Transportation is one of the major energy consuming sectors in the U.S. The continued growth in fuel consumption not only increases dependency on foreign oil but also causes environmental issues due to the emissions of greenhouse gas (GHG). Improvement in automobile fuel economy has been proven to be one of the most effective tools in controlling oil demand and GHG emissions in the transportation sector around the world (An and Sauer, 2004). Conversely, fuel efficiency improvement also raises some concerns about potential negative effects on fuel tax revenue.

Over the past 60 years, the fuel tax has been the primary funding source for building and maintaining highway infrastructure in the U.S. Similar to other parts of the country, Washington State is concerned about rising construction and maintenance costs and declining fuel tax revenue. The increase of fuel-efficient vehicles poses challenges for transportation finance since motorists consume less fuel per mile traveled and thus pay fewer tax dollars for the same amount of road use. While this trend is favorable for the environment and energy security, it has direct negative impact on fuel consumption. Therefore, to estimate future fuel tax revenue and GHG emissions, the behavior and elasticity of fuel consumption under the context of increasing fuel efficiency should be considered.

The presence of two offsetting effects that fuel efficiency has on gasoline consumption complicates the elasticity of fuel consumption. Improvement of fuel efficiency is expected to reduce gasoline consumption per mile traveled. However, improved fuel efficiency reduces the marginal and average cost of travel, thereby encouraging drivers to drive more, which in turn increases gasoline consumption. The efficiency improvement offsets some of the energy-saving benefit and creates the rebound effect. Therefore, it is imperative to take the rebound effect into consideration when estimating the future fuel tax revenue and GHG emissions.

The goal of this portion of the study is to estimate the potential loss of fuel tax revenue and GHG emissions that result from increasing fuel efficiency. Models of vehicle miles traveled (VMT) and fuel efficiency (i.e., miles per gallon [MPG]) will be developed. The elasticity of VMT with respect to travel cost and the elasticity of MPG with respect to fuel price will be generated from these models. Annual time series data from 1976 to 2011 provided by Washington State are used for model estimation.

8.1 Modeling Methodology

There is currently ongoing debate on how improving fuel efficiency reduces fuel consumption. The Transportation Revenue Forecast Council developed a fuel consumption model as a linear regression model that does not consider the dynamic effect of VMT and fuel efficiency on fuel consumption. The demand for gasoline is a derived demand that is completely related to demand for travel services and it contains certain behavioral and technological components. These components are actually related to how much individuals travel (VMT) and the size and fuel efficiency of the vehicle fleet (MPG). Therefore, to catch these components' effect, fuel consumption is defined as a combination of VMT and MPG and will be estimated as system of equation. The following equations define gasoline consumption (g) and travel cost per mile (c):

Equation 26

$$g = m/e$$

and

Equation 27

$$c = p/e$$

where m is the miles traveled, e is the realized fuel efficiency in mile per gallon and p is fuel price per gallon. VMT and fuel efficiency models are required to derive a fuel consumption model. Numerous factors may influence the amount of miles traveled and fuel efficiency tendency.

Aggregate time series data were used to estimate parameters of VMT and MPG models in this study. Annual data for the State of Washington from 1976-2011 were gathered from Washington State Department of Transportation (WSDOT). Several key types of influences are considered in the model, such as economic factors, transportation costs, and socio-demographic factors. Variables that can be extracted from the dataset include: the quantity of gasoline consumed, the price of gasoline, VMT, employment, and number of registered vehicles. Trends in gas prices, number of registered vehicles, and employment rates were outlined further in part six of this report. Figure 8.1 shows the trend of MPG during the study period. MPG has been increasing over time and can be primarily explained by technology development in the auto industry. To combat increasing fuel consumption, USDOT established policies for auto manufacturers to improve fuel efficiency in vehicles.

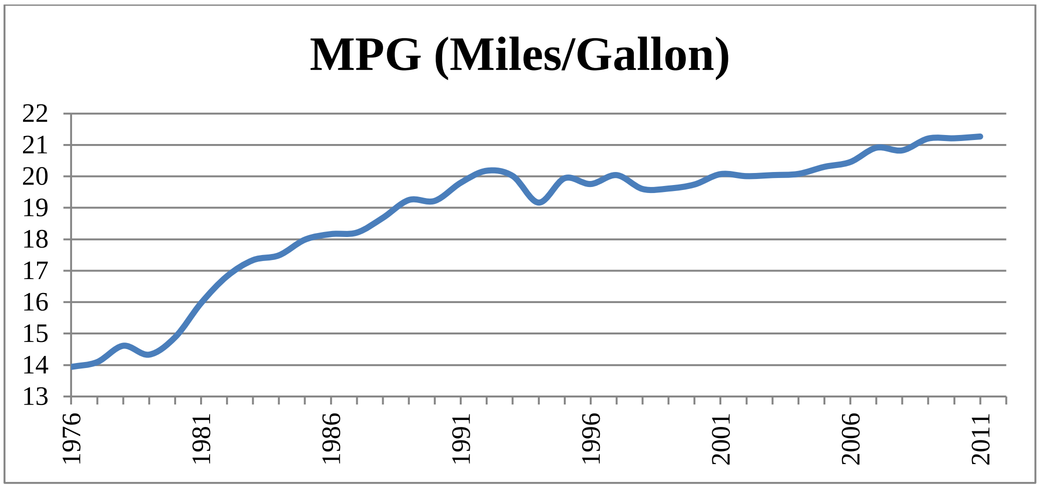


Figure 8.1 MPG of the Vehicle Fleet Over Time

The model assumes that aggregate VMT depends on the per-mile fuel cost of driving along with demographics, economic conditions, and the lagged value of VMT. Fuel efficiency is under the influence of fuel price, the expected amount of driving, and the lagged value of fuel efficiency. Fuel efficiency variation results from manufacturers' adjustment of the relative price of various models, consumers' adjustments via purchase of various models, consumers' decisions about vehicle repair and services, and driving habits (Small and Van Dender, 2005).

Changes in gas prices and fuel efficiency influence VMT through the fluctuation in fuel cost per mile. Fuel efficiency is an exogenous variable in the VMT model, however, other factors may also impact it. Increasing fuel price and/or amount of travel may lead to higher fuel efficiency since users may choose to drive more fuel-efficient vehicles to reduce their travel costs. Therefore, it is also imperative to treat fuel efficiency as an endogenous variable. Considering fuel efficiency as an exogenous variable would overestimate the rebound effect (Binswanger 2001, Small and Van Dender, 2005). As a result, the model is considered as a system of equations with VMT and MPG as two endogenous variables.

Finally, the system of equation model that includes transformed VMT and MPG equations are estimated with the 3SLS method. The estimated ρ for the VMT equation is 0.573. The 3SLS model with first order of autocorrelation has been used in studies done by Small and Van Dender (2005) and Babula and Corey (2004) for the whole system of equation without testing serial correlation.

In Table 8.1, coefficient, standard error, and t-statistic value for each variable are presented. To test whether an equation is adequately specified, the stationarity of each estimated equation's residuals is considered as a goodness-of-fit alternative besides the adjusted R^2 value (Babula, 1997). Granger and Newbold (1986) pointed out that stationary equations should generate stationary residuals with no unit root. The results of the Augmented Dickey-Fuller test on each of the equation's residuals indicate that both equations' residuals are stationary at 5% significance level and the system of equation model has been specified adequately.

Table 8.1 Model Estimation Results of the 3SLS Method

		VMT AR(1)-MPG AR(0)			Adjusted R^2
Endogenous	Exogenous	Coefficient	Standard Error	t-statistic	
$lnVMT_t$	$lntercept$	2.928768	0.310551	9.43	0.96
	$lnEmp_t$	0.248456	0.168454	1.47	
	$lnregveh_t$	0.892899	0.173962	5.13	
	$lncost_t$	-0.14637	0.025503	-5.74	
$lnMPG_t$	$lntercept$	1.060077	0.763644	1.39	0.97
	$lnGasprice_t$	0.024924	0.010222	2.44	
	$lnMPG_{t-1}$	0.910531	0.077908	11.69	
	$lnVMT_t$	-0.03248	0.039105	-0.83	

Overall, the results lend strong support to the model. All coefficients have the expected signs and are significant in t-statistic except for the coefficient associated with the employment variable in the VMT model. Also, the employment coefficient is almost significant and the estimated model is based on a relatively small sample size. The sign of employment is logical, since it is expected that the VMT goes up when the number of employment and economic activities increases. The number of registered vehicles represents the demographic situation. It is expected that more vehicles lead to more trips. Thus, the registered vehicle coefficient, which represents the direct relation between the number of registered vehicles and VMT, shows a positive sign. The driving cost change per mile can be explained by changes in gas prices and fuel efficiency. Rising gas prices increase driving cost, which has a negative effect on the VMT. In contrast, improving fuel efficiency decreases driving cost thereby increasing the VMT. Therefore, considering the effects of both gas prices and fuel efficiency on driving cost, the sign of cost coefficient in the VMT model is logical. The elasticity of VMT with respect to cost per mile is -0.146.

The lagged VMT variable was dropped from the model, because it was not statistically significant and had negative side effects. The inclusion of the lagged dependent variable had an undesirable side effect on the employment coefficient (Green, 1992). The coefficient associated with the employment variable, which was expected to be positively related to the VMT, would be negative and insignificant if the lagged VMT variable was included.

The MPG model also can be well explained by selected independent variables. The gas price coefficient in this model is positive and significant. It clearly implies that users try to increase fuel efficiency by purchasing more fuel-efficient vehicles or repairing their cars when the gas price increases. The MPG is elastic with respect to gas prices by a coefficient of 0.025. Based on the logged VMT coefficient, there is no inertia effect of VMT on fuel efficiency.

Based on equations 35 and 37, the short-run elasticities of gasoline consumption with respect to fuel efficiency and gasoline price are estimated to be -0.854 and -0.167, respectively. A one-unit increase of fuel efficiency decreases fuel consumption by 0.854 units and a one-unit increase of gas price decreases consumption by 0.167 units. A possible inference is that the gas price effect on gas consumption is not tangible. The short-run rebound effect of improving fuel efficiency is approximately 14.6%, which implies that 14.6% of the efficiency improvement is retrieved in the form of increased vehicle travel. Given the insignificance of the lagged dependent variable in the VMT equation, long-run elasticities are similar to the short-run estimates. The estimated rebound effect is in line with the results of previous studies in literature (Greene, 1992, Jones, 1993, Haungton and Sarkar, 1996 and Wirl, 1997).

8.2 Model Results and Analysis

Both the fuel tax revenue and GHG emissions are the outcomes of fuel consumption. Therefore, the precise estimation and forecasting of fuel consumption is vital in policy and decision making for the government. A fuel consumption analysis is conducted before estimations of fuel tax revenue and GHG emissions are completed. When fuel efficiency goes up, people consume less fuel for their trips. A small rebound effect is expected, indicating more travel demand and a minor increase in fuel consumption due to higher fuel efficiency. The outcome of these interactions results in less reduction in fuel consumption, which was previously estimated as the elasticity of gasoline consumption with respect to fuel efficiency. The potential change of fuel consumption if fuel efficiency is improved by a single percent is defined as below:

Equation 28

$$\Delta g = g . g_e . a$$

where:
g: Fuel consumption
Δg: Fuel consumption loss
g_e: Fuel consumption elasticity with respect to fuel efficiency
e: Fuel efficiency
a: $\frac{\Delta e}{e}$

The fuel consumption reduction resulting from different levels of fuel efficiency improvement is presented in Figure 8.2. The rebound effect at different levels of fuel efficiency improvement is also shown. It can be observed that the rebound effect is prominent when fuel efficiency improvement is more significant. For example, if fuel efficiency is increased by 60%, which means that fuel consumption is expected to be reduced by 60%, the rebound effect increases fuel consumption by 8.78%. The figure only considers fuel efficiency as a variable of fuel consumption. Other factors, such as population, economic conditions, and gasoline prices also have influence on fuel consumption through VMT.

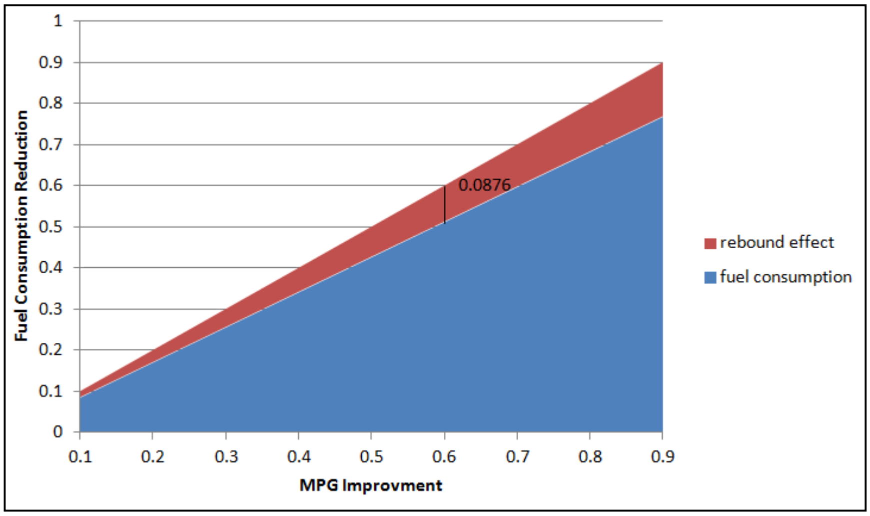


Figure 8.2 Effect of Fuel Efficiency Improvement on Fuel Consumption

Figure 8.3 presents fuel consumption forecasted using the estimated model (VMT/MPG) under different scenarios. The real scenario is where all variables are used as their future values. In all other scenarios, the value of the corresponding variable is assumed to be fixed after 2011. Comparison of the forecasted fuel consumption in each scenario indicates its relative importance and the effect of exogenous variables on fuel consumption. It should be noted that the forecasted values of employment, number of registered vehicles, and gasoline prices are treated as exogenous variables, and their values are provided by WSDOT. The forecasted values of VMT and MPG are estimated from the model developed.

Consumption in the future will be greater without improving fuel efficiency. Therefore, improving fuel efficiency could be a significant factor in controlling future fuel consumption. The increasing gas prices may also reduce future fuel consumption but to a lesser extent than fuel efficiency. As a result, fixing gasoline prices leads to more fuel consumption. In the estimated model, the increase of gasoline price increases fuel efficiency as well as trip cost per mile. These two effects are conflicting, but the magnitude of trip cost per mile coefficient in the VMT model is larger. Therefore, the positive effect of gas price on fuel consumption through VMT dominates its negative effect on fuel consumption through MPG. Increasing employment and the number of registered vehicles lead to more VMT and fuel consumption. Fixing the value of the number of registered vehicles leads to the highest reduction in fuel consumption; therefore, it could be the most influential variable in fuel consumption forecasting. The forecasting of the number of registered vehicles should be treated with caution due to its relative importance in forecasting fuel tax revenue and GHG emissions.

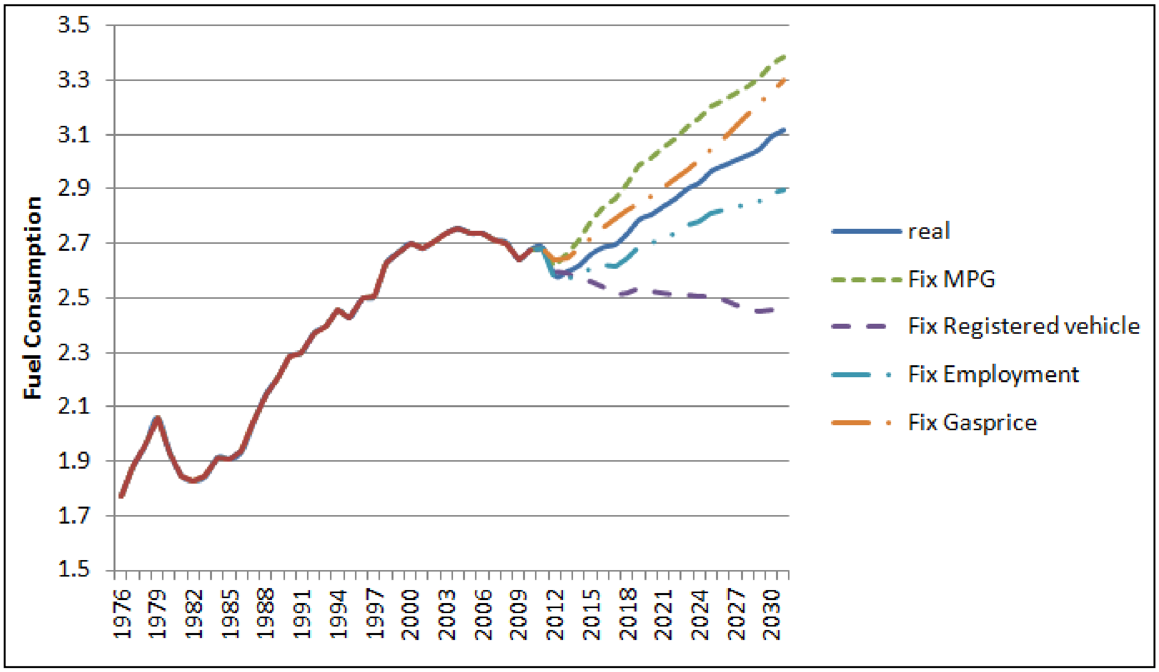


Figure 8.3 Fuel Consumption Forecast in Different Scenarios

8.3 Revenue Forecast

By improving the fuel efficiency, fuel consumption may decrease. The whole fuel tax revenue reduction due to fuel efficiency improvement based on the fuel tax of 39 cents per gallon is presented in Table 8.2. While fuel consumption will be decreased by fuel efficiency improvement, increase of the number of registered vehicles and employment will cause an increase. The results indicate that in 2031, the State of Washington could have an estimated loss of $106 million due to fuel efficiency improvements.

Table 8.2 Fuel Efficiency Effect on Revenue

Year	Fuel consumption reduction (Million gallons)	Revenue loss in billions of dollars (Million dollars)
2012	34.70	$13.53
2013	66.95	$26.11
2014	96.64	$37.69
2015	122.45	$47.76
2016	145.03	$56.56
2017	166.87	$65.08
2018	185.19	$72.22
2019	197.68	$77.09
2020	206.70	$80.61
2021	215.07	$83.88
2022	222.17	$86.65
2023	227.95	$88.90
2024	232.83	$90.80
2025	237.37	$92.57
2026	241.22	$94.07
2027	246.59	$96.17
2028	253.24	$98.77
2029	260.65	$101.65
2030	267.03	$104.14
2031	271.54	$105.90

9. CONCLUSION

This report evaluates the economic competitiveness of natural gas as a transportation fuel and estimates the extent to which natural gas is likely to substitute for petroleum as a transportation fuel. Additionally, the potential impacts of natural gas vehicle adoption on vehicle miles traveled, greenhouse gas emissions (CO_2), and fuel tax revenue have been assessed.

Natural gas enjoys a per-BTU cost advantage over petroleum, and this price advantage is likely to persist into the foreseeable future. New low-cost extraction technology (hydraulic fracturing or "fracking") has increased the supply of domestic natural gas while petroleum prices have increased. Expert opinion suggests this price difference is likely to persist and that natural gas in the United States will enjoy a price advantage over petroleum for many years.

Despite the per-BTU cost advantage enjoyed by natural gas relative to gasoline, as a transportation fuel natural gas faces some substantial disadvantages. In addition to competition from other alternative fuels, widespread adoption of natural gas vehicles would require substantial investment in fueling infrastructure. Very few natural gas vehicles are available directly to consumers from manufacturers, and those vehicles that are available are more expensive and suffer from several other disadvantages. For example, because natural gas is less energy dense, NGVs are typically less powerful, heavier, have less storage/trunk space, and have more limited range due. Despite the fuel cost savings, these disadvantages and the additional cost tend to make natural gas vehicles an uneconomical choice for most consumers. Models of consumer preference suggest that a substantial decrease in the price of natural gas vehicles would be necessary to induce a notable increase in light-duty NGVs adoption rates. However, natural gas may represent an attractive alternative for a substantial portion of the heavy-duty vehicle fleet, and there is evidence of increasing adoption rates in this sector.

These estimates suggest that natural gas vehicle adoption is unlikely to substantially affect VMT in Washington State. Additionally, VMT is more highly sensitive to variables that are correlated with overall population size (the number of registered vehicles and total employment) than to fuel prices. Although per-capita VMT has been declining in recent years, aggregate VMT in Washington State has been increasing steadily due to increased population. Higher fuel prices do have a negative effect on VMT, although the estimated elasticity is relatively low. Finally, the adoption of natural gas vehicles is unlikely to have a substantial effect on VMT.

Natural gas vehicle adoption has the potential to reduce greenhouse gas emissions because natural gas is about 20% less CO_2 intensive than gasoline. This model of consumer adoption of light-duty NGVs, combined with reasonable assumptions about NGV adoption in the heavy-duty vehicle sector, indicates that under current price conditions only modest reductions in CO_2 emissions due to NGV adoption are expected. Baseline estimates suggest about a 0.02% decrease in CO_2 emissions from the light-duty vehicle sector is possible due to NGV adoption. If price conditions for light-duty vehicles become much more favorable (lower NGV prices and a larger fuel price differential), this figure could rise to 1.16%. Reasonable assumptions suggest that reductions from the heavy duty sector of the fleet are unlikely to exceed 7%, even under conditions of extremely optimistic adoption rates. Overall, transportation sector emissions (light- and heavy-duty fleet combined) are unlikely to be reduced by more than 4% overall, even under conditions of aggressive CNG adoption.

Finally, the report investigated the impact of increased fuel efficiency on future fuel tax revenues. Alternatively fueled vehicles such as natural gas vehicles and electric vehicles have started to erode fuel tax revenues. In addition, automobile manufacturers have started to make all vehicles more fuel efficient. If the current taxing structure continues into the 2020s, then WSDOT will experience significant decreases in revenue generated by the fuel tax.

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