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Essays on the Economics of Energy and Transportation

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ESSAYS ON THE ECONOMICS OF ENERGY AND TRANSPORTATION

by

Ryan N. Barnes

A dissertation submitted in the partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Economics

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UTAH STATE UNIVERSITY
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ABSTRACT

Essays on the Economics of Energy and Transportation

by

Ryan N. Barnes, Doctor of Economics

Utah State University, 2017

Major Professor: Dr. Ryan Bosworth
Department: Applied Economics

Natural gas is a fuel that can be used for transportation. It has many desirable properties, for example, it is generally less expensive and less carbon intensive than conventional fuel. Research was conducted to ascertain the viability of natural gas as a consumer transportation fuel. The extent to which the price of natural gas has decoupled from the price of oil was investigated. The price of natural gas was found to have significantly deviated from the price of oil on an energy parity basis; however, this new regime was found to be unstable. As a counter point to this finding international trade in natural gas was found to be increasing, and the growth of an international market for natural gas appears to be emerging. A model of natural gas vehicle adoption was then developed at the consumer level. Given the baseline parameter values in the model, significant adoption of natural gas vehicles appears to be unlikely. The model was then extended to understand the role that natural gas could play in the abatement of Carbon Dioxide (CO_2). Due to the low predicted adoption of natural gas vehicles the predicted abatement of CO_2 from natural gas vehicles was also low. Furthermore, it was found by simulating various policy regimes that were designed to encourage natural gas vehicle adoption that these policies were a relatively expensive way to abate CO_2 emissions. The main conclusion drawn from this research is that despite the attractiveness of many of the qualities of using natural gas as a transportation fuel, namely lower fuel prices and lower CO_2 emissions policy makers should not encourage the adoption of natural gas as a transportation fuel.

(131 pages)

PUBLIC ABSTRACT

Essays on the Economics of Energy and Transportation

Ryan N. Barnes

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. In recent years the growing uncertainty about oil prices and availability has made long-range transportation planning even more challenging. Rather than relying on trend extrapolation, this study uses market mechanisms to shed light on key long-range transportation planning assumptions. In particular, this study was conducted to help WSDOT assess the likelihood that natural gas will substitute for petroleum fuels and estimate the impacts that changes in fuel prices will have on natural gas vehicle demand, fuel consumption, and Greenhouse Gas emissions.

The main findings of this project were that there is an unstable price difference per unit of energy between natural gas and oil. This price difference accounts for the relative attractiveness of natural gas as a transportation fuel. Furthermore, an international market for natural gas is emerging due to the international trade in liquefied natural gas. Despite these potential benefits the market has created for the use of natural gas as transportation fuel, our model still predicts that consumers will not adopt natural gas vehicles. Due to the low adoption of natural gas vehicles, pollution abatement policies designed around increasing adoption of natural gas vehicles is likely to be very expensive.

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Ryan N. Barnes

DEDICATION

First of all to my wife, Charity, for the love, support, and encouragement that you have given me throughout this project to sit down and slog through, even when I didn’t want to. I really couldn’t have done it without you. And to my son, J.D., without you this dissertation would have been finished six months earlier. But I love you so much; I gladly took every single delay that you caused without regret. To my Dad, for working so hard, and teaching me the value of education. To my Mom, thanks for the love and support. Thanks to both of you, Mom and Dad, for giving me these opportunities. And thank you, Dr. Bosworth, for taking me under your wing, and being my friend.

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CHAPTER 1

INTRODUCTION TO THEMATIC CONTENT

1.1. Introduction

Natural gas is a fuel whose price has fallen relative to other fuels. It is natural to start to think of new uses for this fuel as consumers and energy producers try to substitute to this fuel. Rather than just being used for electricity generation and heating, natural gas is increasingly being used as a transportation fuel in the commercial and consumer vehicle fleets. It raises the question of what role natural gas is going to play long-term in the vehicle fleet.

The main purpose of this dissertation is to ascertain whether or not Natural Gas Vehicles (NGVs) are an economically viable alternative fuel vehicle. The question is motivated by policy questions such as: should policy makers invest in infrastructure to support consumers with NGVs? Will consumers purchase NGVs without financial incentives from policy makers? And, how cost effective is it to use NGVs to abate carbon dioxide (CO_2) emissions?

In the sense that these policy questions are motivated by a lack of coverage in the academic literature, this dissertation seeks to fill those gaps. Often the literature only tangentially addresses these policy questions. The next section expands on this idea and highlights some of the main gaps in the literature that motivate each chapter of the dissertation. Therefore, although this dissertation is mainly motivated by policy questions, it is also motivated by gaps in the literatures that give rise to these questions.

The dissertation is divided into two main sections which are sub-divided into two chapters each. The first section is an empirical investigation into the macro-effects that affect the price of natural gas. The second section analyzes a micro-level model of a consumer making the choice of whether or not to purchase a NGV. Each chapter deals with a unique but related research problem. The first chapter looks at the relationship between the price of natural gas and the price of oil. The second chapter investigates the role that liquefied natural gas (LNG) plays in uniting regional natural gas markets into one global market for natural gas. Using these two studies as a backdrop for the case for using natural gas as a transportation fuel, the following chapter presents the basic consumer model of this dissertation. This model is used to predict current adoption of NGVs under various price scenarios. The final main chapter of this dissertation then uses this model to calculate the marginal abatement costs of NGV technology on CO_2 emissions. Three policy regimes are examined.

1.2. Relationship to Literature

The dissertation fills a small gap in the literature. Specifically, each chapter fills in a different portion of the gap. The first two chapters look at the macro-market for natural gas to provide a backdrop for the next two chapters. The last two chapters specifically answer the main research question of this dissertation.

The first chapter looks into the relationship between the price of oil and natural gas. This relationship has been explored by various researchers attempting to determine if the price of oil and natural gas have become decoupled from each other. Various researchers have found that the price of natural gas is governed by the price of oil (Brown & Yücel, 2008; Mohammadi, 2011; Regnard & Zakoïan, 2011). However, Ramberg and Parsons (2012) show that much of the volatility between the long-run relationship between oil and natural gas can be accounted for by allowing for structural breaks in the cointegration relationship. In a similar vein this chapter looks for structural breaks in the relationship between oil and natural gas by using a recursive Gregory-Hansen test

(Gregory & Hansen, 1996). This chapter of the dissertation fills in a small portion of the literature by using this test to detect structural breaks in the co-integrating relationship between oil and natural gas.

The next chapter looks at the question of whether or not a single global market is emerging for natural gas, or if it will continue to be governed by the oil market. This study fits into the literature concerned with price integration between regional natural gas markets and the role that LNG has played in this integration (Brown & Yücel, 2009; Nuemann 2012; Neumann, Siliverstovs, & von Hirschhausen, 2006; Siliverstovs L'Hégaret, Neumann, & von Hirschhausen, 2005). However, the key difference between the model presented in this chapter and this vein of literature is the novel use of the gravity model to determine the role that LNG plays in the global natrual gas market. This chapter concluded that natural gas markets are becoming less regional and that a separate global natural gas market is emerging (Jensen, 2004) due primarily to trade in LNG.

The next chapter answers the question of what types of adoption rates can be expected for NGV vehicles amongst consumers. This chapter contributes to the set of the literature that deals with the adoption of NGVs. Staub (2013) gives an overview of the use of natural gas in transportation. Deal (2012) studies the conditions under which firms would be willing to adopt NGVs. Walls (1996) values various attributes unique to natural gas. Matic (2005) looks at the opportunities to use natural gas as a transportation fuel. This chapter contributes to this literature by predicting the adoption rate of NGVs by consumers under different price conditions. The main findings of this chapter are that adoption rates are low and will likely continue to be low.

The final chapter examines the question of whether policy makers should encourage the adoption of NGVs to reduce GHG emissions. Specifically, this chapter narrowly focuses on CO2 emissions. It is similar to other studies that estimate the marginal abatement cost of CO2 under various abatement mechanisms. For example, Li, Linn, and Spiller (2013) and Knittel (2009) investigate the marginal abatement cost of cash for clunkers. Kok, Annema, and van Wee (2011) and Kesicki (2012) find the marginal abatement cost for electric vehicles. And Bernesteanu and Li (2011) look at hybrid electric vehicles. This chapter finds that in comparison to these studies NGVs have a marginal abatement cost that are orders of magnitude greater than these studies. This indicates that NGVs are an inefficeint CO2 abatement technology. This chapter adds to this literature by giving an estimate of the marginal abatement costs for NGVs.

This small sampling of the literature is only meant to illustrate how each chapter of this dissertation fits in with the overall theme of the dissertation and highlight the main differences between that chapter and the studies described thus far in those studies. Other portions of the relevant literature will be discussed at length with more detail in the constituent chapters of this dissertation, as well as how that chapter fits in with that literature.

1.3. Data Collection and Methodology

Data were obtained from various sources during the course of this research. The data were obtained in order to answer different research questions. The first two chapters use the different data sets, and the last two chapters use a common third dataset.

The first main chapter of the dissertation makes use of daily spot price data. Time series for oil and natural gas were collected. This data was obtained from the Energy Information Agency (2014). Cushing, OK WTI spot prices are used for oil, and Henry Hub spot prices are used for the natural gas prices. The sample period used in this study is

January 7, 1997 to April 14, 2014. Since natural gas is less energy dense than oil, the price of both commodities is measured in USD per MMBtu (million BTUs). This unit of measure ensures that the prices are being compared on an energy parity basis because the prices of both commodities are using the same unit of measure.

A recursive Gregory-Hansen test (Gregory & Hansen, 1996) was then used on this data to determine the stability of the long-run cointegrating relationship between the price of oil and natural gas. The Gregory-Hansen test looks for a single structural break at an unknown time. By applying the test recursively over a rolling window, I identify multiple structural breaks at various times.

The next chapter utilizes data that were collected from three main sources. First, trade data for natural gas and liquefied natural gas were obtained from the U.N.'s comtrade database in a panel of 92 countries over 20 years. Second source of data that was used came from the World Bank's database of World Development Indicators. This data was used to augment the trade data with national demographic data such as GDP, unemployment rate, percentage of land protected by government, inter alia. The final data source was the latitude and longitudes of each of the capital cities of the 92 countries were obtained. From this data the great circle distance between the any two capital cities were calculated. These three datasets were then merged by using the importing and exporting countries as identifiers for the merging.

The resultant dataset is then analyzed with a gravity model over the panel. Various estimating models are used including a random effects model, a random effects model with an AR(1) process, a pooled model, and a Pseudo-Poisson Maximum Likelihood model (Silva & Tenreyro, 2006, 2011). Each of these estimating models produced results that were consistent with each other. Cross-equation restrictions were tested on the distance variables to see if LNG has had a significant effect on the natural gas market as a whole.

The final dataset used in this dissertation comes from the National Highway Travel Survey of 2009. This data was used to identify the population of vehicles on the road along two variables, miles per gallon (MPG) and vehicle miles travelled per year (VMT). We use a discretized distribution of these two variables to determine the probability that a vehicle will have a particular VMT and MPG. Using this data along with assumption about prices we created a model that could generate the adoption rate of natural gas vehicles.

Using the adoption rates from this model, the CO2 emissions for the vehicle fleet could be estimated. In the last chapter, of the dissertation I show how these emissions can be calculated from this adoption rate model. By substituting different price differences in the model, various policy scenarios can be counterfactually simulated to see what effect these scenarios would have on CO2 emissions.

1.4. Practical Significance

This dissertation is aimed at answering basic policy questions about the adoption of NGVs. Specifically, the questions that it answers are first, what macro-effects might encourage the adoption of NGVs? Second, how will consumers behave individually in response to this price difference?

Therefore, the first half of this dissertation looks at two macro-effects that may contribute to the increased demand for NGVs. First, the price of natural gas is significantly less than oil on an energy parity basis. The first chapter looks into the question of whether or not this price difference is likely to persist. This chapter investigates this question mainly by looking at the stability of the relationship between the prices of the two commodities.

The next chapter investigates whether global demand for natural gas is likely to increase or decrease. This chapter investigates this question through the use of a gravity model. This study is designed to see whether or not the natural gas market is more integrated due to the trade of LNG.

The next two chapters take more of a micro-approach. The model presented in the third chapter and used in the fourth focuses on the financial choice of whether to buy a NGV or not. This model may be able to generalize to other alternative fuel vehicles. This model can be used to estimate the adoption rate of NGVs, and the effect that different policy regimes will have on the adoption rate, and thus emissions as well. Policy makers should be interested in these two chapters, because they show what the adoption rate of NGVs would be with and without their intervention. Furthermore, the final chapter shows what the cost of intervention in terms of abating CO2 emissions would be.

The significance of this study is that it will provide policy makers with a road map that can be used to make decisions about NGVs. In particular, throughout this dissertation I will show that although NGVs have many attractive features, such as low fuel costs that may persist into the future, and an emerging global market, NGVs do not make sense for most consumers. Furthermore, the cost to use NGVs as an abatement technology is much larger than similar programs designed to reduce CO2 emissions. From this exploration of the topic, it is clear that the potential benefits of encouraging adoption rarely outweigh the costs. Thus policy makers may not want to encourage the adoption of NGVs.

1.5. Limitations

Although throughout this dissertation my main argument is that policy makers may not want to incentivize consumers to purchase NGVs, a fully definitive answer to this question is likely impossible. Each of the chapters in this dissertation answers only a small part of this question and one could make a career out of cataloging every aspect of this problem.

The data used to answer these research questions primarily comes from the United States of America, with the notable exception of trade data from multiple countries. It is entirely possible that the conclusions that will be drawn from this dissertation is idiosyncratic to the United States, and will not generalize well to other countries. For example, Iran and Pakistan both have significant adoption of NGVs. Data from the United States which predicts a very low adoption rate obviously does not generalize to these countries.

Another aspect of the data is that it must be viewed within the context of the last few years. Much has changed in terms of what is possible in the extraction of natural gas. Further technological developments may change the nature of the problem. Advances in vehicle technology particularly would have a great impact on the outcomes of these problems.

Furthermore, the research detailed in this dissertation cannot fully circumscribe the research problems. For example, in the course of conducting this research further questions about the role that weather plays on international trade of natural gas were raised. Additionally, the inconvenience premium uses an estimate from Walls (1996) which was adjusted for inflation. The question of what this inconvenience premium is remains an open issue. One could devise further studies into this aspect of the literature and spend considerable effort on estimating the inconvenience premium. Other literatures were drawn upon, and some of the research benefited from these literatures. The literature on the rebound effect was particularly useful; see Sorrell and Dimitropolos (2008) for a review of this literature.

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CHAPTER 2

DETECTING STRUCTURAL BREAKS IN THE COINTEGRATING RELATIONSHIP BETWEEN OIL AND NATURAL GAS PRICES

2.1. Introduction

The relationship between oil and natural gas is of interest to various stakeholders. For example commodity traders may base a trading strategy on this relationship. Businesses in the energy sector may make significant investments in extracting one resource over the other based on the current and projected relationship between oil and natural gas. Policy makers need to understand this relationship to design efficacious energy programs. These stakeholders need to recognize whether changes to this relationship are temporary or permanent. This study identifies that a permanent structural break has occurred from the historical relationship of oil and natural gas. Two pricing regimes are identified, and analyzed separately.

Compared to the old regime, this new regime identified in this study can be characterized by a larger relative price between oil and natural gas. The change in relative price appears to be driven mainly by the recent decline in the price of natural gas. This decline has been attributed to recent developments in the technology to extract natural gas (Rogers, 2011).

Furthermore, the new regime exhibits much less price volatility than in the previous regime. The decline in price volatility is not just limited to one commodity. Both oil and natural gas experience significantly less volatility than in the previous regime. The decrease in price volatility of both goods is likely due to the decrease in volatility of oil prices, based on oil’s role as a mediating good in the natural gas market.

The most prominent similarity between both regimes is the instability of the long-run price relationship between oil and natural gas. The instability of this long-run relationship accounts for the regime switch that occurred. The gradual separation of the natural gas market from the oil market likely contributed to the switch to this new long-run equilibrium. This new long-run equilibrium should not be viewed as a complete decoupling from the oil market. As the independent natural gas market continues to mature, the instability of the new regime is likely to result in the relationship between oil and natural gas to reach different long-run equilibria.

The findings presented in this paper support the hypothesis of a weakly integrated energy market. However, the long-run relative prices and the volatility of prices in this integrated market are unstable. Indeed, a fundamental shift has occurred in the energy market during the period of this study. The analysis in this study has identified verifiable differences between the old price regime and the new one.

2.2. Previous Literature

Policy makers need to have a careful understanding of the price relationships between various energy sources to make informed decisions (Yücel & Guo, 1994). Historically, the relationship between oil and natural gas prices has been dominated mainly by the shocks to the oil market (Mohammadi, 2011) (Regnard & Zakoïan, 2011) (Brown & Yücel, 2008). This relationship persisted despite the fact that oil is an internationally traded good, while natural gas is a regionally traded good although it is rapidly integrating into one world market (Siliverstovs, L’Hégaret, Neumann, & von

Hirschhausen, 2005). The current study examines evidence of a recent change to the long-run relationship between oil and natural gas prices. This change could call into question the idea of an integrated energy market.

Mohammadi (2011) finds evidence that the natural gas market is influenced by the oil market, but that the oil market is not influenced by the natural gas market. He also finds that neither of these commodities influences the coal market. Regnard and Zakoïan (2011) also find that oil and natural gas prices are cointegrated, but that much of the volatility in natural gas prices is determined by outdoor temperature. Brown and Yücel (2008) also find a stable long-term relationship between oil and natural gas. Their results indicate that the tie between natural gas and oil is primarily due to substitution and competition between natural gas and petroleum products. These studies, inter alia, provide the basis for a weakly integrated energy market with limited substitutability between different fuel types.

Recently, the historical stability of the relationship between oil and natural gas prices has been called into question. A process of price decoupling has been observed. Erdős (2012) finds that oil and natural gas prices have decoupled since early 2009. He also finds that oil prices influence natural gas prices only in the pre-2009 period. He fails to find evidence of a recoupling. Ramberg and Parsons (2012) document that although simple cointegrating relationships between oil and natural gas can be useful much of the volatility in these prices is left unexplained by simple formulaic relationships. They show that a modest improvement in the predictive power of these simple formulas can be achieved by allowing for structural breaks in the relationship.

The present study contributes to this literature by using more recent data to identify the date of a regime change from the previous long-term equilibrium to a new one. Separate models for each regime are run to identify key differences between each regime.

Finally, the stability of the new regime is tested to determine whether this new price regime is likely to persist over time.

2.3. Data

The data consists of daily spot prices for oil and natural gas. Cushing, OK West Texas Intermediate Oil (the underlying commodity for oil traded in futures markets on the New York Mercantile Exchange) spot prices are used for oil, and Henry Hub (a distribution hub of the natural gas pipeline system located in Louisiana) spot prices are used for the natural gas prices. The sample period used in this study is January 7, 1997 to April 14, 2014. Prices were obtained from the Energy Information Administration (Energy Information Administration, 2014). Natural gas is less energy dense than oil. In order to make price comparisons between oil and natural gas meaningful, the price of both commodities is measured in USD per MMBtu (million BTUs). This unit of measure ensures that the prices are being compared on an energy parity basis.

Figure 2.1 depicts the historical energy prices. A tight relationship existed between the price of oil and natural gas. From a visual inspection it appears that this tight relationship persisted until the early part of 2009. This tight relationship suggests that there was probably a single market for energy in the United States. After 2009, it appears as though there is a fundamental change in how natural gas is priced relative to oil. This apparent fundamental shift provides the motivation for the analysis that follows.

Table 2.1 provides summary statistics for each of the two price series. Summary statistics for the ratio (oil to natural gas) of the two prices is also reported. The average price of oil over the sample period was $9.60/MMBtu. The average price of natural gas

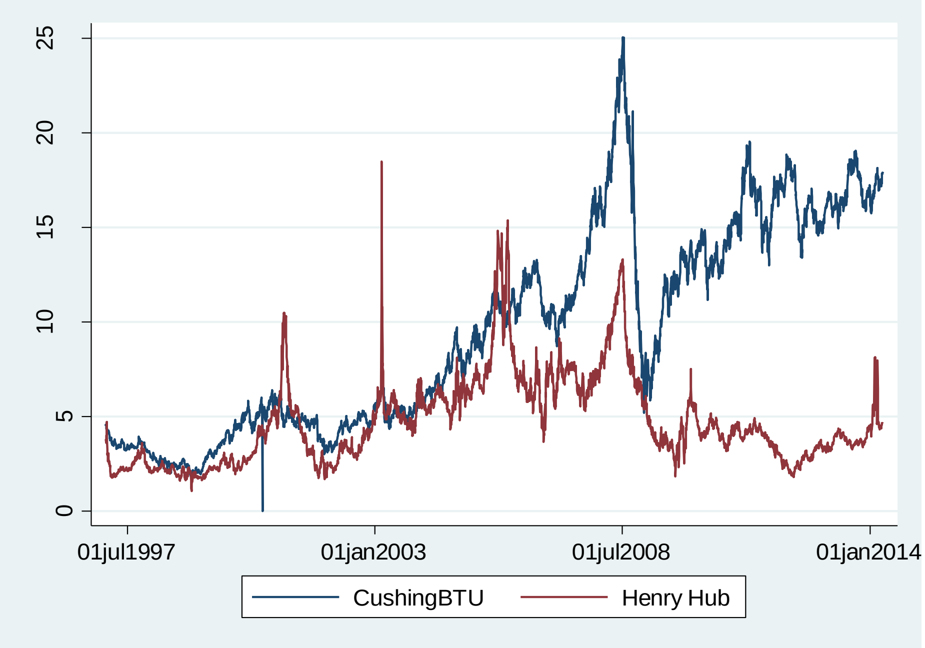

Figure 2.1. Price of oil and natural gas over time

over the sample was slightly above what would be implied by taking the ratio of the averages. The average relative price was 2.26 ($ oil/$ natural gas).

A prerequisite for a cointegration relationship between oil and natural gas is that both time series have unit roots. Although well established in the literature that these price series have unit roots (Brown & Yücel, 2008; Mohammadi, 2011; Ramberg & Parsons, 2012; Siliverstovs et al., 2005), the oil and natural gas price series are tested for unit roots. The results of various tests for unit roots are presented in Table 2.2. The null hypothesis for these tests is that the series contains a unit root. None of the test statistics are significant at the 5% level. However, weak evidence exist that natural gas prices may not have a unit root. The ADF test statistic for natural gas is significant at the 10% level. At the 5% significance level, the null hypothesis that each price series contains a unit roots is accepted. The analysis continues on this basis.

Table 2.1. Energy Price Descriptive Statistics

Variable Name	Description	Mean (Std. Dev)
Cushingbtu	The price of 1 million BTUs of WTI oil as measured at Cushing, OK. ($/MMBtu)	9.60 (5.46)
HenryHub	The price of 1 million BTUs of natural gas as measured at Henry Hub. ($/MMBtu)	4.70 (2.33)
Ratio	The Relative Price of Oil to Natural Gas. This price is calculated as the ratio of the two prices above.	2.26 (1.53)

Table 2.2. Unit-Root Test Results

	Augmented Dickey-Fuller	Phillips-Perron
WTI (Cushing, OK)	-0.011	0.232
Henry Hub	-1.854*	-1.484

*, **, *** indicate significance at 10%, 5% and 1% significance levels respectively.

2.4. Results and Discussion

A Gregory-Hansen (Gregory & Hansen, 1996) test is used to determine whether or not a structural break occurred, and if so, when the break occurred. Table 2.3 presents the results of this test. These results clearly indicate a regime switch occurred between April, 27 2009 and July 6, 2009. Anecdotally, the shift occurred approximately at the same time that horizontal drilling and hydraulic fracturing began to be widely utilized (Rogers, 2011). Furthermore, the decline in the capability to substitute quickly between distillate fuel oil and natural gas may have also played a role (Brown & Yücel, 2008). Any inference that these technological changes were the cause of this disruption would be pure speculation without further data to support this claim.

Table 2.3. Results of Gregory-Hansen Test

	Test Statistic	Break Point (Date)	Break Point (Obs)
ADF	-5.11**	July 6, 2009	3120
Z(t)	-4.81*	April 27, 2009	3072
Z(a)	-60.31***	April 27, 2009	3072

*, **, *** indicate 10% 5% and 1% significance levels respectively.

The standard deviation for both price series decreased significantly after the regime switch. Classical variance ratio tests were conducted on both price series. This test is an F-test, with 3070 and 1252 degrees of freedom for both price series. The test statistic is the ratio of the standard deviation before and after the regime switch. Natural gas prices were 9.32 (p=0.00) times more variable before the regime switch. Oil prices were 4.81 (p=0.00) times more variable before the regime switch.

The relative price of oil to natural gas over the entire period of study was 2.26 ($ oil/$ natural gas). This overall average obscures the important differences between the regimes. Prior to the regime switch the average relative price of oil to natural gas was 1.43 ($ oil/$ natural gas), and 4.29 ($ oil/$ natural gas) afterwards. A standard t-test with unequal variances indicates (t=105.93) that there was a change in the relative price of oil to natural gas due to the structural break.

These classical tests seem to imply that the markets for oil and natural gas have become decoupled since the structural break. They also suggest that since the regime switch the volatility of both oil and natural gas prices has decreased. These classical hypothesis tests do not account for the temporal nature of the data. The conclusions that we can draw from these tests may be spurious.

To confirm these findings, vector error correction models (VECM) were conducted on subsamples of the data (before and after the structural break). The cointegrating vectors for these VECMs are reported in Table 2.4. These cointegrating vectors capture the long-run relative prices of oil to natural gas. They differ from the average values reported above because these vectors account for the time series nature of the data. The average relative prices are also reported in this table for comparison. Before the structural break the long-run relative price of oil to natural gas was 1.59 ($ oil/$ natural gas). This ratio would imply a pricing rule of thumb near the 10:1 (barrels of oil to MMBtus of natural gas) rule. After the regime switch the long-run relative price of oil to natural gas was 4.31 ($ oil/$ natural gas) which would imply a pricing rule closer to 26:1.

These long-run relative prices echo the values found for average relative prices in each period. This result lends further support to the idea that a fundamental shift in the way energy is priced has occurred, namely that the relative price of oil to natural gas has shifted to a new long-run equilibrium. The long-run relative price of oil to natural gas has increased approximately 171% over its previous long-run relative price.

In order to determine whether this new normal constitutes a fundamental shift from the organization of the oil and natural gas markets, the impact parameters are analyzed. The adjustment parameters for the VECMs are reported in Table 2.5. The parameters before the structural break show that shocks in the oil market passed through to the natural gas market. However, shocks to natural gas did not flow through to the oil market. Also it is interesting to note that there is no evidence to support shocks in the natural gas market affecting the natural gas market. These conditions imply that the natural gas market was mediated mainly by the oil market during this period, and that separate markets for natural gas and oil did not exist during this period.

Table 2.4. Cointegrating Vectors

	Before Regime Change	After Regime Change
WTI (Cushing, OK)	1 (--)	1 (--)
Natural Gas (Henry Hub)	-1.60*** (0.124)	-4.31*** (0.442)

Cointegrating vectors are normalized on WTI. *, **, *** indicate 10% 5% and 1% significance levels respectively.

In the second period, the short-run adjustment parameters are significant for shocks in the oil market. These shocks are carried through to the natural gas market, as in the previous period. However, the point estimate for an oil shock's effect on the natural gas market has decreased slightly from the previous period. Shocks to the natural gas market also now have a significant effect on the natural gas market. These shocks still do not have a significant effect on the oil market. These conditions imply that the natural gas market has become disentangled somewhat from the oil market in recent years. It appears that two separate markets have emerged; though, oil prices still mediate natural gas prices.

These findings echo those of Brown and Yücel (2008). They found that oil prices help to determine the price of natural gas. These results do, however, support the conclusion that the market for natural gas has become less dependent on oil over time. This trend of disentangling the two markets is likely to continue over time.

The smaller adjustment parameter values in the second period indicate a decrease in volatility during this period. Smaller adjustment parameters imply that random shocks to the system do not create large swings in prices. This implies a decrease in the volatility

Table 2.5. Impact Parameters

		Before Regime Change	After Regime Change
WTI Crude			
	WTI Shocks	-0.0034** (0.0017)	-0.0029* (0.0016)
	Natural Gas Shocks	0.0055** (0.0027)	0.0125* (0.0071)
Natural Gas			
	WTI Shocks	0.0067*** (0.0020)	0.0022* (0.0012)
	Natural Gas Shocks	-0.0107*** (0.0032)	-0.0094* (0.0051)

*, **, *** indicate 10% 5% and 1% significance levels respectively.

of each of the price series. This decreased volatility of the prices confirms the earlier result from the classical variance ratio test.

The two markets have separated to some degree, but long run relationships still exist between the two commodities. The long run relationship has changed to a new equilibrium recently. This switch implies an inherent instability in the long run relationship. It calls into question the stability of the new long-run equilibrium. Table 2.6 depicts the eigenvalue stability condition for the VECM in the first period, and the eigenvalue stability condition for the second period. This condition states that the long-run relationship between variables is unstable if one of the normalized eigenvalues approaches unity.

The first period is unstable. The largest eigenvalue for this period is 0.99. This large eigenvalue is expected given the regime switch that ended this period. The second period also gives a large eigenvalue of 0.98. Since this eigenvalue is close to unity, the long-run relationship between oil and natural gas reported above is unstable for the second period.

Table 2.6. Results from Eigenvalue Stability Test

Before Regime Shift	After Regime Shift
0.989712	0.991748
0.677437	0.687385
0.677437	0.687385
0.656644	0.675492
0.639364	0.675492
0.639364	0.584230
0.638702	0.546891
0.638702	0.546891
0.616834	0.544420
0.616834	0.544420
0.609490	0.519306
0.609490	0.519306
0.544677	0.497113
0.544677	0.497113
0.072752	0.075623

Normalized eigenvalue omitted.

These findings are confirmed by a recursive Gregory Hansen test. This test differs from the original test in that it allows for the identification of multiple structural breaks at unknown dates, instead of a single structural break. It allows for the examination of the stability of the second period. Figure 2.2 presents the Augmented Dickey-Fuller (ADF) statistic for this test over time, with the 95% and 99% critical values. This test suggests that the structural break which this paper has examined to this point was the result of two separate regime changes. One occurred three months before the structural break that has been examined thus far (June 2008), and the other almost five months later than the structural break previously examined (February 2009).

Figure 2.2 indicates that the long-run relationship may have recently entered into a period of instability. The ADF test statistic is currently significant at the 95% level. This result is tempered by the fact that the test statistic is not significant at the 99% level. These findings seem to agree with the eigenvalue stability condition. The new long-run relationship between the price of natural gas and oil may not persist into the future. The market for these commodities may be in the process of shifting to a new equilibrium. This test does not indicate which direction this new equilibrium will likely take, just that the price difference is unstable.

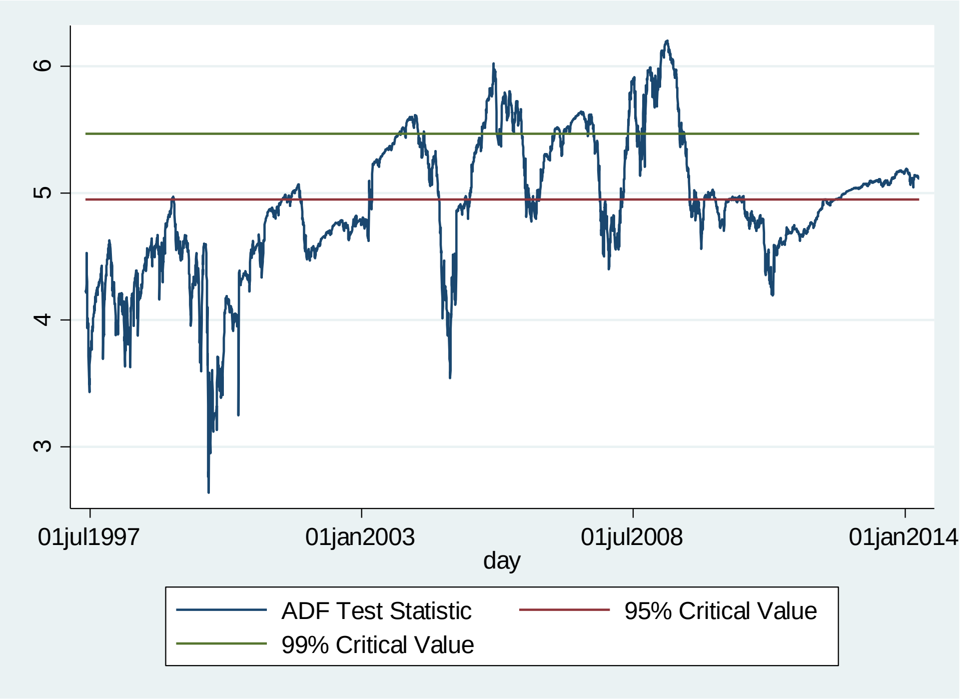

Figure 2.2. Stability of oil and natural gas relationship

As can be seen from Figure 2.2, the long-run equilibrium between the oil and natural gas markets is not characterized by long periods of stability. There are at least 9 periods that can be considered unstable with 95% confidence, and 5 periods of instability with 99% confidence in the sample period. Furthermore, the evidence suggests that the current instability is increasing. In the context of previous long-term relative price instability, the current instability is not surprising. Most likely, the instability is due to the gradual evolution of separate markets for oil and natural gas.

2.5. Conclusion

The link between oil and natural gas has, at times, been very strong. This strong link has given rise to various rule-of-thumb pricing measures in the energy industry, such as the 6:1 and 10:1 rules. The 6:1 rule, for example, simply states that one price exists between oil and natural gas after controlling for thermal parity. The 10:1 rule seems to also recognize this same fact, but it allows for price differences due to the differing production, transportation, and storage costs of these different fuels as well as accounting for the limited substitutability between them.

These measures have been useful in the past, but recently, the price ratio between a barrel of oil and one million BTUs of natural gas has departed from these historical relationships. This departure has called into question the reliability of these rules-of-thumb. When these two prices have decoupled in the past, it appears as though the break was of a temporary nature (Ramberg & Parsons, 2012). The duration of this recent breakaway is rather unprecedented, lasting nearly 5 years at the time of writing.

This study provides evidence that the duration of the current price separation may be due to a revolution in the oil and natural gas industries. Specifically, the date at which the structural break occurred may indicate that technological developments, such as hydraulic fracturing, may have played an important role in this revolution.

However, one limitation of this study is that it only examines simple relationships between prices over time. The analysis can only determine whether a regime switch has occurred, if so when, and what the new equilibrium looks like after it has been reached. It offers no explanation as to the causes of a regime change, nor any prediction as to what new equilibrium will be reached after the regime switch has occurred. Future research should pursue these theoretical concerns to determine the role that hydraulic fracturing and other technologies have played in disrupting these markets, or whether decreased substitutability played a more significant role (Brown & Yücel, 2008).

Whatever the cause, a change occurred that caused the initial decoupling of the two markets, and it appears that the markets may have since recoupled in a new equilibrium. This new equilibrium seems to be characterized by inexpensive natural gas relative to oil, and less price volatility for both commodities. The new equilibrium also appears to be entering a new state of fragility, which may lead to further changes.

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CHAPTER 3

LNG IS LINKING REGIONAL NATURAL GAS MARKETS: EVIDENCE FROM THE GRAVITY MODEL[1]

3.1. Introduction

The technical problems associated with transporting a pressurized gas have historically dictated that natural gas markets be regionally isolated markets, with persistent price differences. However, in recent years, the process of liquefying natural gas to reduce transportation costs has become more common and trade in liquefied natural gas (LNG) has increased (Ruester, 2010). Research has demonstrated that international natural gas market prices are increasingly integrated (Neumann, 2012; Neumann, Siliverstovs, & von Hirschhausen, 2006; Siliverstovs, L'Hégaret, Neumann, & von Hirschhausen, 2005); often the literature has suggested that liquefied natural gas may be a major reason for this integration (Brown & Yücel, 2009; Neumann, 2012). This explanation seems likely because LNG accounts for about 20% of the share of global natural gas trade and that share is expected to increase to 30% (Cornot-Gandolphe, 2005). Figure 3.1 shows the share of LNG exports over the period of this study. This figure shows that over the past nine years the share of LNG trade increased.

LNG plays a critical role in market integration because of its flexibility in terms of delivery. Traditional CNG is transported through pipelines to consumers. The pipelines are fixed in direction of flow and physical location of delivery points. The fixed nature of

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[1] This chapter was co-authored with Ryan Bosworth, and published in Energy Economics Volume 47 Issue 1 pp.11-17.

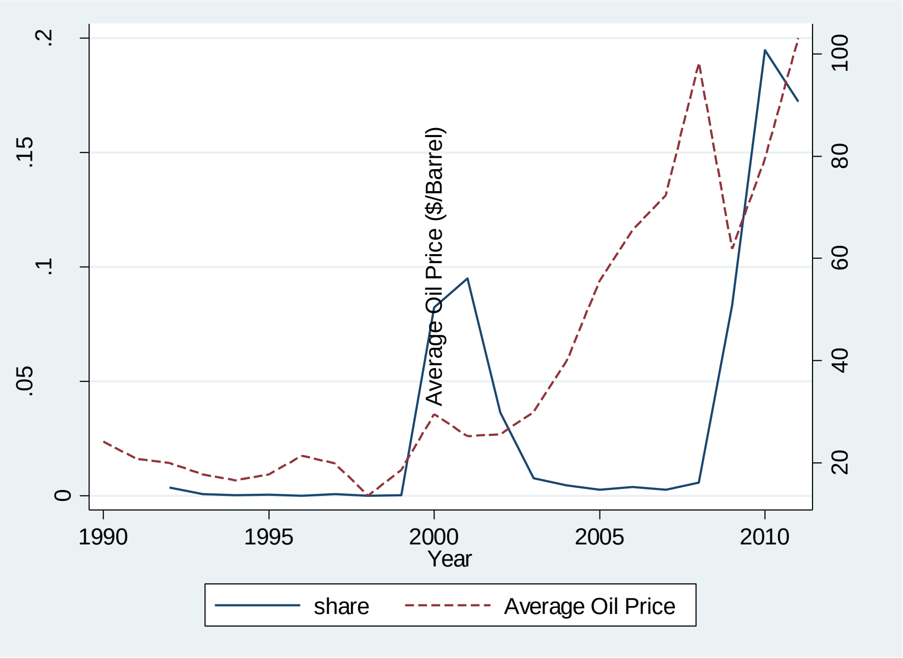

Figure 3-1. Share of LNG exports

CNG greatly reduces the number of delivery points and helps to support regional markets that are not integrated with the international market. LNG may be delivered to multiple, albeit a limited number of points. Furthermore, LNG has been known to be re-routed to delivery points other than the original intended destination (Cornot-Gandolphe, 2005).The flexibility that LNG provides expands the international delivery of natural gas from a pipeline model to one that more closely resembles a traditional commodity. Thus LNG may indeed play a direct role in market integration.

Despite the key role that LNG may play in the integration of these markets, there is little direct evidence that increased LNG trade is in fact the cause of increased natural gas market integration. One exception is Neumann (2012), who examines the cointegration properties of natural gas prices to determine whether LNG is contributing to the integration process of broader natural gas markets. However, this evidence is based on price movements rather than direct observation of trade volumes.

This study directly examines trade volumes to determine the extent to which LNG is a regional commodity. The key contribution of the paper is the use of a gravity model to determine how regional the international LNG market is and the extent to which LNG has affected trade in the total natural gas market. We then compare these results to an analogous analysis of trade in the market for compressed natural gas (CNG).

The main results of this study indicate that while LNG is indeed an international commodity, CNG remains a regional commodity; however, the international natural gas market is less regional overall due to increased trade in LNG. The results of this study may therefore be considered a complement to existing studies of natural gas market integration: while existing studies provide evidence of market integration by considering price movements, we provide evidence of market integration by considering changes in traded quantities of LNG.

The rest of the paper proceeds as follows. The next section reviews the relevant literature. Section three explains the data. The fourth section develops the model. Section five presents and discusses results, and the final section concludes.

3.2. Literature Review

3.2.1. Trade in Natural Gas

Wang and Notteboom (2011) explore global LNG trade, and find that short term trading is increasing globally. Razavi (2009) reports that Asia accounts for 24% of LNG imports, Europe for 24% and North America for about 10%. They also find that to accommodate this trade, and to take advantage of economies of scale, firms have increased the size of their tankers and receiving terminals. Similarly, Ruester (2010) finds that firms that invest in all aspects of the supply chain are better positioned to arbitrage regional prices. Engelen and Dullaert (2010) find that LNG markets, along with other alternative fuel markets, are becoming more efficient. Furthermore, Aune, Rosendahl, and Sagen (2009) suggest that the global natural gas trade will increase substantially in the coming decades, mostly from LNG. With this increase in LNG trade Rosendahl and Sagen (2009) predict that natural gas prices will rise in Europe. Paltsev et al. (2011) find that a globally integrated natural gas market will lead to more U.S. imports. Ghorban (2006) notes that countries with large natural gas deposits invest in the ability to export this commodity.

These previous studies provide an intuitive explanation for studies that suggest that regional natural gas prices are becoming integrated into one global market. Siliverstovs et al. (2005) and Nuemann (2012) both view LNG as a major contributor to global price integration. Brown & Yücel (2009), however, find that oil prices may intermediate the price in different natural gas markets, while LNG plays a smaller role.

Furthermore, simply deregulating natural gas markets may have led to increased integration of regional markets. For example, following deregulation in the United States, Cuddington and Wang (2006) found evidence that the eastern and central markets of the United States became integrated, while the west remained a regional market. Europe’s natural gas markets became deregulated about a decade after U.S. markets. Neumann et al. (2006) and Robinson (2007) both found evidence that national markets in Europe became more integrated after deregulation.

The principal findings of this paper are most similar to Jensen (2004) who concludes that a global market for LNG already exists, but that this market does not necessarily imply a global market for natural gas. Jensen analyzed contracts for natural gas trade, and noted the increase in short-term LNG contracts between countries were evidence of a global market emerging. In contrast, the current study utilizes a gravity model to explain the degree to which CNG, LNG, and total natural gas markets are regionalized.

3.2.2. Using Gravity Models to Analyze Trade Flows

The gravity model has been a popular empirical method for describing bilateral trade flows. See Kepaptsoglou, Karlaftis, and Tsamboulas (2010) for a review of the most recent studies. Other authors have developed the potential theoretical underpinnings of the gravity model (Anderson, 1979, 2010; Bergstrand, 1985). The theoretical basis for the gravity model focuses on its role as measuring transportation costs. Moreover, a steady advancement of empirical methods has led to better fits for the gravity model (Egger & Pfaffermayr, 2003; Martin & Herath, 2008; Mátyás, 1997; Westerlund & Wilhelmsson, 2011). Although theoretical underpinnings of the gravity model may be unclear in some contexts (Deardorff, 1998), the ability to link our dependent variable (trade flows) with distance makes it a natural choice for the purposes of this study. We use the gravity model to describe trade flows in the natural gas market. This approach is most similar to the use of the gravity model to identify regional trading biases. See Greenaway and Milner (2002) for a review of this literature. The inclusion of distance as a regressor within the gravity model helps to identify differences between sub-markets in the natural gas market. A related application of the gravity model is the analysis of the effect of free trade agreements on the level of trade between different countries (Carrere, 2006; Darku, 2009; Stack & Pentecost, 2011).

3.3. Data

We obtain data on exports from the U.N.'s comtrade database. This database consists of self-reports from countries worldwide on exports and imports of various products. A 6 digit harmonized system (HS) of commodity descriptions is used by the database. We utilize data from two HS codes, one for CNG (271121) and the other for LNG (271111).

The data is organized into trading pairs where the exporting country reports the volume of trade with another country. To account for imports as well as exports, each unilateral relationship constitutes a unique pair. For example, if Brazil exports CNG to Argentina, this would be considered to be an observation that is distinct from Argentina exporting CNG to Brazil. Viewing these relationships as distinct allows the dataset to incorporate information on the net exports of each country while using data on total exports.

We use a sample of 92 countries selected by Kellenberg (2012) to be representative of the global income distribution. Table 3.2 lists these 92 countries. Each country's exports in CNG and LNG were reported to the U.N. from 1988 to 2011. The panel follows a potential of 184 unilateral trading pairs across 23 years. As mentioned above each trading pair is considered in two potential observations, one where the first country exports to the second country and another where the roles are reversed. A number of countries never exported CNG or LNG to one or more of the partner countries in any year. Any trading pair that did not trade in any given year was not included in the dataset,

Table 3-1. Summary Statistics

	Mean	SD	Description
Distance (km)	7383.23	4354.50	Distance between capital cities
Exporting countries			
GDP	12912.99	16414.95	Gross Domestic Product per Capita(constant 2005 USD)
Landlocked	0.12	0.32	Dummy indicating whether country is landlocked
Unemployment Rate	8.26	4.29	Unemployment rate in %
Natural Gas	0.95	2.64	% of GDP that comes from production of Natural Gas
Protected Land	12.42	9.52	% of land mass of country that is protected by government
Importing Countries			
GDP	12328.66	16119.44	Gross Domestic Product per Capita(constant 2005 USD)
Landlocked	0.13	0.33	Dummy indicating whether country is landlocked
Unemployment Rate	8.37	4.29	Unemployment rate in %
Natural Gas	0.85	2.50	% of GDP that comes from production of Natural Gas
Protected Land	12.74	9.53	% of land mass of country that is protected by government

leaving an unbalanced panel of 147 unilateral trading pairs. Leaving these pairs out is equivalent to simply analyzing the existent natural gas market.

One feature of the data is that the total international trade of LNG has grown over the sample period. While CNG still accounts for most of natural gas exports worldwide, trade in LNG is increasing. Figure 3.2 shows total trade for both CNG and LNG. Notice the consistent growth in LNG exports (Figure 3.3), while CNG shows a considerable amount of volatility.

The U.N. comtrade dataset was merged with data from the World Bank's World Development Indicators. This data included information about each country's income

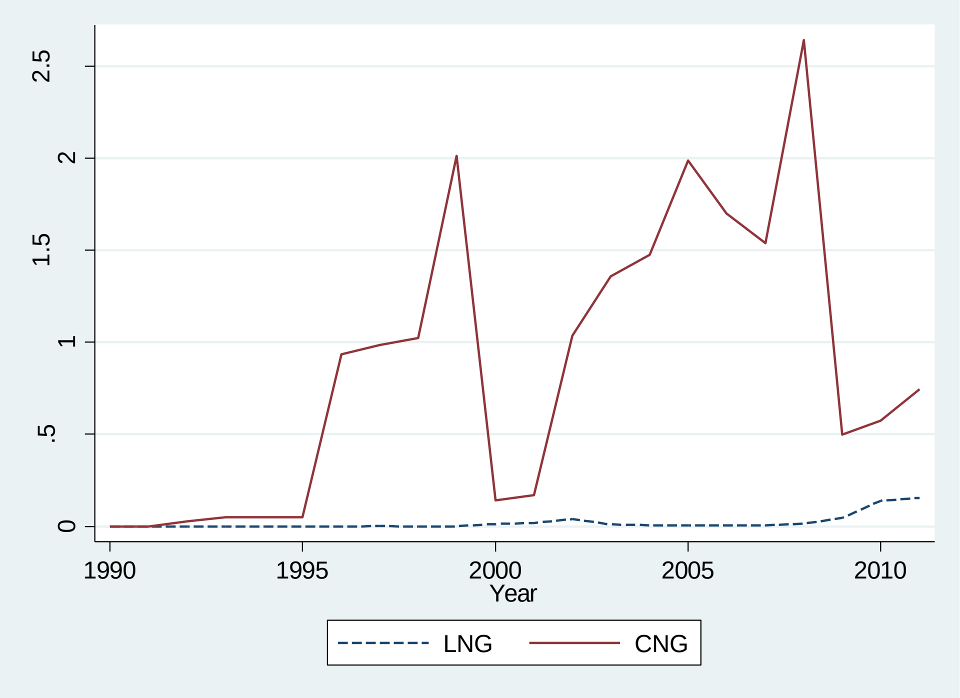

Figure 3-2. Natural gas exports

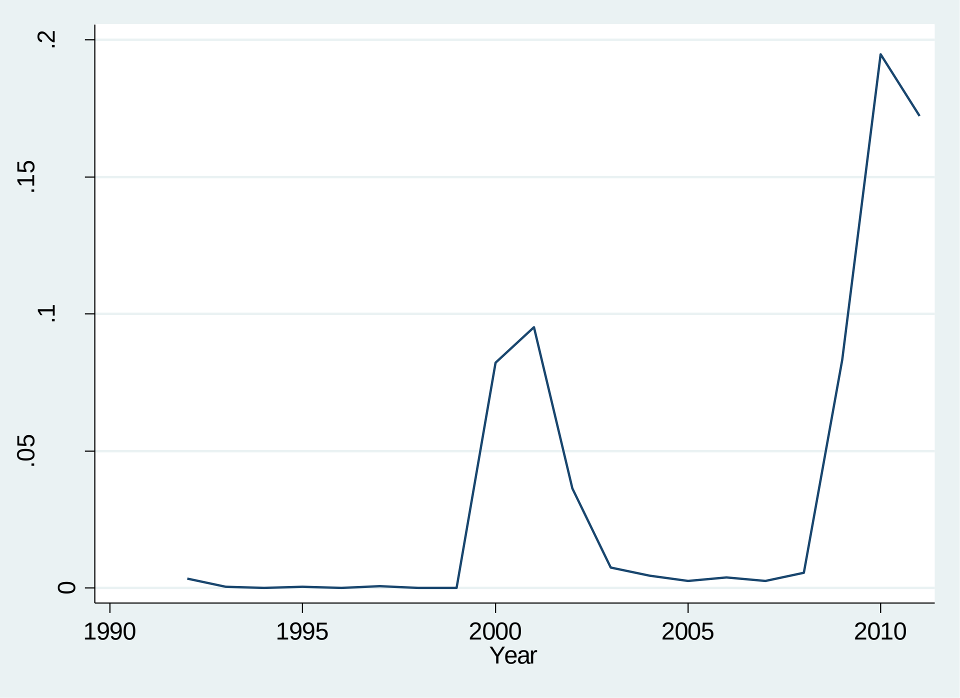

Figure 3-3. Share of natural gas exports

Table 3-2. List of Natural Gas Exporting Countries

Country	Average Distance from Trading Partners (km)	Total Exports (1000 kg)	LNG Exports (1000 kg)	CNG Exports (1000 kg)
Argentina	10154.4	30995.13	0.027	30995.1
Australia	5329.54	361.13	361.13	0.0017
Belgium	5462.87	8159.38	452.32	7707.052
Bolivia	9342.72	115017.4	834.40	114183
Brazil	8609.89	225.78	225.78	0.00019
Canada	7290.54	854893.8	0.16	854893.7
Chile	10517.1	159.00	2.0092	156.99
China	9774.48	8.99	2.096	6.90
Colombia	8411.78	945.75	0	945.75
Czech Republic	5335.85	11.70	0.0023	11.70
Dominican Republic	7668.5	0.0026	0.0012	0.0015
Estonia	5722.93	0.00018	0.00018	0
Finland	5763.04	0.97	0.97	0
Greece	5583.09	0.0032	0	0.0032
Hungary	5368.41	0.0056	0	0.0056
India	8510.91	46.70	45.80	0.91
Israel	6113.57	0.20	0.020	0.18
Italy	5350.74	295.14	295.07	0.067
Jamaica	7971.67	0	0	0
Japan	10664.3	0.31	0.020	0.29
Kenya	7811.78	2.87	2.87	0
South Korea	10224.3	0.025	0.025	0
Luxembourg	5327.54	0.011	0.0040	0.0067
Mexico	9141.89	5757.96	55.63	5702.33
Mali	6448.93	0	0	0
Malta	5485.8	0.0028	0.0028	0
Namibia	8597.54	0.0093	0.0093	0
Nicaragua	8696.09	0	0	0
Norway	5597.72	135158.7	3058.26	132100.5
Pakistan	8030.3	0	0	0
Panama	8458.89	0.00096	0	0.00096
Peru	9511.5	2756.32	2756.32	0.00081
Poland	5460.8	5.73	0.01	5.72
Russia	5960.78	421929	20300.95	401628.1
El Salvador	5310.5	0	0	0
Tunisia	5456.04	0	0	0
Turkey	5841.11	507.78	0.00084	507.78
Uganda	7586.98	0	0	0
Ukraine	5670.96	3455.49	0.01	3455.48
United States	7445.59	111082.1	11875.76	99206.3
Venezuela	7876.93	0.0078	0.0078	0
Vietnam	11165.6	4.76	4.75	0.011

(GDP), unemployment rates, the percentage of GDP that comes from the production of natural gas, the percentage of land area that is protected (i.e. set aside for nature preserves, national parks, etc.) within a country for each time period. The calculated distances between two countries are based on the latitude and longitude of the capital cities.

Naturally, the further apart two countries are, the more costly transportation of goods will be between these two countries. This fact is the main driver behind the results of this paper, namely that LNG is easier to transport over long distances than CNG. Therefore a measure of distance between two countries is required to carry out the empirical modeling. The measure used is the distance between the two capital cities of each country[2]. This distance was calculated based on the great circle distance between the two capital cities.

Traditionally, the gravity model has been estimated with a control for the level of income between the two trading partners. The assumption is that the level of trade between two countries is positively related to their incomes. A related control variable is the unemployment rate. It serves as a control for the general economic conditions within the two countries.

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[2] The distance between capital cities is a common measure of distance between two countries in the gravity model literature (Baldwin & Taglioni, 2006); we follow this practice in the paper. Usually, the capital city is one of the largest population centers for the country, and proxies the distance between the origin of goods and the final destination better than land mass centroids, or nearest border estimates. The correlation coefficient of the distance between the population weighted landmass centroids and the distance between capital cities is 0.9986. With this knowledge the authors were relatively unsurprised to find virtually identical results to those presented in the main text when using population weighted landmass centroids to measure the distance between countries.

Another important control is some measure of the relative abundance of raw natural gas in each country. We use the percentage of the GDP attributable directly to the production of natural gas as a proxy for this variable. Even if a country is relatively abundant in raw natural gas deposits, those deposits may not be available for extraction due to laws and regulations. We control for this fact by also including a variable that measures the proportion of the country's land mass protected in national parks, nature preserves, etc. Landlocked countries may experience difficulty trading because of their lack of natural ports. We include a dummy variable to control for this effect.

3.4. Model

An important econometric consideration is that the key independent variable of interest, the distance between the two countries, does not vary over time. This consideration restricts the number of available econometric models considerably. For example, the fixed effects estimator will not estimate the coefficient for this variable, because the distance variable would be differenced out of the model. Therefore, we use a panel regression model with random effects. This model will allow us to retain the variable of interest while still exploiting the panel nature of the data.

Furthermore, each variable except for the trend and the distance between the two countries is used twice; once for the country from which the export originated, and again for the country of destination. In the reported results, we organize these variables under the subheadings “export” and ‘import” to indicate to which country the variable refers.

Because of the 23 year length of the panel, it may also be appropriate to allow for an autocorrelated error term. Therefore, an AR (1) process is deployed in the model to correct for any possible autocorrelation. The full model is

(1-1) $$\log(T_{it}) = \beta_0 + \beta_{dist}\log(dist_{it}) + \mathbf{X}'\boldsymbol{\beta} + u_{it}$$

$\mathbf{X}$ is a matrix of control variables mentioned above, u is an error term with an AR(1) process. This model was run on the levels of trade for the full natural gas market, CNG, and LNG as the dependent variables respectively. The results of these regressions are reported in Table 3.3, and are discussed below.

As a robustness check, alternative specifications of the model were also estimated. In the second specification of the model, the AR (1) process was dropped from the model. The results for this specification are in Table 3.4. Another specification uses a pooled OLS model with clustered standard errors, clustered on pairs of countries. The results from this regression are also included in Table 3.4. We note that the results of these alternative specifications are similar to the results in Table 3.3, suggesting that our results are not sensitive to choice of error specification.

3.5. Results

3.5.1. Main Results

The results in Table 3.3 show clearly that there is no statistically significant relationship between the distance between two countries and the level of trade of LNG between those countries. On the other hand there is a strong, and statistically significant, relationship between the distance of the two countries and the level of trade in CNG. These results indicate that increasing the distance between two countries by a factor of 2 will decrease trade of CNG between these two countries by a little less than a factor of 9. These results indicate that while CNG is a fuel that is traded only regionally, LNG is a fully international good.

If the international LNG market did not exist, then the international CNG market would be identical to the entire international natural gas market. Thus, trade in LNG greatly expands the international nature of the overall natural gas market.

The final regression in Table 3.3 shows that the natural gas market is less regional than it otherwise would have been, had LNG trading not occurred. A cross-model test was used to check if the coefficients on the distance variable were statistically different in the overall natural gas and CNG models. The test statistic used is a t-statistic. This statistic relies on the sample variance-covariance matrix of the two estimates. The variances and covariances of this matrix were bootstrapped using random subsamples of the full dataset and running regressions on these subsamples. The coefficients of these regressions were saved for each of these subsamples, and the variance and covariance were calculated for each coefficient.

The test statistic was $t=2.399$ with 289 degrees of freedom, which implies a p-value of 0.0085. This statistic is also significant for other specifications of the model. Therefore, the null hypothesis, that the coefficients on distance are the same for both the CNG and natural gas markets, is rejected. This key result suggests that the regional markets for natural gas are becoming less regional because LNG is starting to link these markets.

Furthermore, these results indicate trade in LNG has been increasing at an average rate of 20% per annum. Figure 1a shows the growth in trade of LNG over the past 20 years. As can be seen this growth is nearly exponential in nature, suggesting that LNG trading has been growing at an exceptional rate, especially for the past few years. This growth further suggests that the linkages between regional markets will become stronger in the coming years. Surprisingly, national income, of the importer and exporter, is found to have little effect on the amount of trading in natural gas that occurs. This result suggests

Table 3-3. Panel Regression with AR(1) Process and Random Effects

VARIABLES	(1) Total	(2) CNG	(3) LNG
log(Distance)	-1.258***	-2.880***	0.155
	(0.469)	(0.540)	(0.494)
Export			
log(GDP)	-0.0488	-0.259	0.218
	(0.331)	(0.408)	(0.333)
Landlocked	-3.796	-6.518***	-6.014*
	(2.712)	(2.387)	(3.340)
Unemployment %	-0.0342	-0.0578	-0.199**
	(0.0727)	(0.101)	(0.0810)
Nat. Gas GDP %	0.119*	0.229***	-0.124
	(0.0627)	(0.0623)	(0.115)
Protected Land %	-0.0982	-0.206**	0.0406
	(0.0678)	(0.0915)	(0.0691)
Import			
log(GDP)	0.0193	0.122	-0.0350
	(0.365)	(0.456)	(0.360)
Landlocked	4.194**	2.415	-2.760
	(2.078)	(1.962)	(2.545)
Unemployment %	0.0983	0.148*	-0.00423
	(0.0728)	(0.0787)	(0.107)
Nat. Gas GDP %	-0.149	-0.219	-0.120
	(0.112)	(0.135)	(0.131)
Protected Land %	0.0187	-0.0234	-0.000791
	(0.0497)	(0.0511)	(0.0565)
Time Trend	0.00570	-0.0577	0.189**
	(0.0578)	(0.0658)	(0.0771)
Constant	22.44***	40.12***	5.924
	(6.368)	(8.076)	(6.585)
Observations	507	290	264
Number of pairs	146	75	104
R^2	0.217	0.412	0.133

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.01

Table 3-4. Alternative Specifications

	Panel Regression with Random Effects			Pooled OLS		
VARIABLES	(1) Total	(2) CNG	(3) LNG	(4) Total	(5) CNG	(6) LNG
Logdist	-1.035**	-2.791***	0.175	-1.748**	-3.241***	0.114
	(0.499)	(0.624)	(0.534)	(0.719)	(0.854)	(0.740)
Export						
log(GDP)	-0.202	-0.409	0.237	0.494	0.283	0.447
	(0.351)	(0.467)	(0.355)	(0.378)	(0.506)	(0.418)
Landlocked	-3.124	-5.967**	-5.830	-6.719***	-9.698***	-7.607***
	(2.925)	(2.823)	(3.669)	(2.443)	(2.607)	(2.870)
Unemployment %	0.0830	0.0314	-0.169**	-0.199	-0.287	-0.365***
	(0.067)	(0.085)	(0.079)	(0.136)	(0.175)	(0.107)
Nat. Gas GDP %	0.111**	0.185***	-0.159	0.616***	0.574***	0.184
	(0.0530)	(0.0492)	(0.120)	(0.134)	(0.121)	(0.178)
Protected Land %	-0.0251	-0.0991	0.0540	-0.145	-0.271*	0.145
	(0.0650)	(0.0855)	(0.0721)	(0.0939)	(0.138)	(0.120)
Import						
log(GDP)	0.135	0.0561	0.0633	-0.0337	-0.0992	0.0167
	(0.387)	(0.525)	(0.383)	(0.485)	(0.651)	(0.454)
Landlocked	4.183*	2.616	-2.980	2.420*	-0.784	-3.640
	(2.223)	(2.332)	(2.689)	(1.454)	(1.253)	(2.350)
Unemployment %	0.180***	0.195***	-0.0458	0.0841	-0.0419	-0.110
	(0.065)	(0.064)	(0.109)	(0.123)	(0.125)	(0.156)
Nat. Gas GDP %	-0.185	-0.274*	-0.178	-0.212**	-0.337**	-0.0490
	(0.116)	(0.144)	(0.140)	(0.0922)	(0.142)	(0.113)
Protected Land %	0.0482	-0.0220	0.00388	-0.0216	-0.0294	-0.0533
	(0.050)	(0.056)	(0.059)	(0.0534)	(0.0676)	(0.0502)
Time Trend	-0.0635	-0.0625	0.111*	-0.102	-0.153	0.128
	(0.0438)	(0.0517)	(0.0602)	(0.0869)	(0.114)	(0.112)
Constant	19.37***	39.20***	5.910	26.57***	46.64***	5.998
	(6.668)	(8.851)	(7.035)	(9.507)	(13.92)	(9.635)
Observations	507	290	264	507	290	264
Number of pairs	146	75	104	146	75	104
R^2	0.170	0.360	0.120	0.307	0.514	0.189

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.01

that natural gas deposits are distributed fairly randomly across spatial dimensions, and is neither a primary determinant of income nor is income dependent on natural gas.

The coefficients estimated on ancillary control variables are all plausible. Landlocked countries export less and import more natural gas than their counterparts. Likewise when the unemployment rate is high, CNG exports fall and imports rise. Natural gas exports increase and imports decrease as the proportion of the county's GDP attributable to natural gas increases. The percentage of a country's land mass that is protected has a negative impact on CNG exports, which may be due to the inability to construct pipelines through protected regions.

3.5.2. Robustness of Results

The trade flow variables may be non-stationary. We estimate two cross-sectional models (pre- and post-recession) to verify the robustness of our results. Since Poisson pseudo-maximum likelihood (PMML) estimators are most appropriate for estimating cross-sectional gravity models (Silva & Tenreyo, 2006), we employ this specification. This estimator has the additional benefit of performing well in the presence of large proportions of zero trade flows (Santos Silva and Tenreyo 2010). We take advantage of this benefit and reincorporate zero values back into the dataset. The results of this regression are shown in table 3.5. The cost of using this specification is that the estimates cannot be interpreted in the same way as our previous estimates. This specification requires the use of a log-linear form of the gravity model (where coefficients indicate a percentage change) instead of a log-log specification (where coefficients are interpreted as elasticities) and is therefore not directly comparable. A negative and significant coefficient on the distance variable would indicate that the further two countries are apart the less they will trade. The parameter estimates in this specification are significant as expected, namely distance is significant and negative in the CNG and NG markets, but not in the LNG market for both periods. The positive sign on LNG in the second period is somewhat surprising, as it indicates that the further two countries are from each other the more trade they will engage in. This counterintuitive result could be explained by the post-recession regression being performed on data gathered during the recovery from the recession.

Temperature is an important driver in the natural gas market, and prices are conditioned on weather (Brown & Yücel, 2008). We control for temperature in the importing country using an annual average temperature for that country in a particular year. This data was also collected from the World Bank, but is only available until 2009 as of the time of writing. We did not include this variable in the main results to take advantage of two additional years of data. Table 3.6 presents the same regressions as Table 3.3, except that we include this temperature variable for the importing country. The temperatures variables are not significant in any of the regressions and do not materially affect the other coefficients.

The insignificant result in this regression may be caused by the fact that natural gas may be used both for heating by direct combustion and cooling through electricity generation. Future research may be able to disentangle the effect of extreme temperature variation on patterns of international trade of natural gas.

Oil prices may also be considered an important determinant of the trade of LNG (Brown & Yucel, 2008). We have estimated models that include oil prices as an explanatory variable; however, oil prices were not readily available for every region considered for some time periods. This restriction substantially reduces the number of observations available for analysis (only 52 observations for both the CNG and LNG

Table 3-5. Poisson Pseudo-Maximum Likelihood Estimators

	2007			2010		
VARIABLES	(1) Total	(2) CNG	(3) LNG	(4) Total	(5) CNG	(6) LNG
Logdist	-1.960***	-1.991***	-0.584	-1.319***	-2.205***	1.398**
	(0.385)	(0.407)	(1.330)	(0.421)	(0.567)	(0.605)
Export						
log(GDP)	6.135	6.286	24.46**	3.795***	12.53	1.302*
	(4.838)	(5.060)	(11.57)	(1.385)	(10.68)	(0.699)
Landlocked	-11.09**	-11.32**	-26.02***	-7.789***	-5.952***	
	(4.893)	(5.128)	(8.636)	(1.279)	(1.802)	
Unemployment %	0.690	0.713	-3.148*	0.764***	2.107	0.597***
	(0.921)	(0.979)	(1.756)	(0.222)	(2.515)	(0.202)
Nat. Gas GDP %	1.573	1.613	-3.784*	1.799***	3.805	2.125***
	(1.254)	(1.304)	(2.137)	(0.355)	(4.497)	(0.341)
Protected Land %	-0.995*	-1.018*	-0.798**	-0.540***	-1.435	-0.197***
	(0.603)	(0.617)	(0.398)	(0.181)	(1.105)	(0.0643)
Import						
log(GDP)	1.320***	1.309***	1.560	1.752	1.139	2.442***
	(0.467)	(0.445)	(1.267)	(1.292)	(1.254)	(0.559)
Landlocked	-2.792**	-2.728*		-2.843	-1.757	
	(1.406)	(1.395)		(2.259)	(2.001)	
Unemployment %	-0.237	-0.223	-1.168***	-0.150	-0.316	-0.527**
	(0.266)	(0.263)	(0.291)	(0.136)	(0.263)	(0.217)
Nat. Gas GDP %	-0.229	-0.212	-0.955*	-2.204**	-2.259**	-10.68***
	(0.269)	(0.263)	(0.499)	(0.941)	(0.895)	(3.923)
Protected Land %	-0.00188	-0.00146	0.0892	-0.0811	-0.110	-0.0113
	(0.148)	(0.147)	(0.0673)	(0.102)	(0.113)	(0.0404)
Constant	-39.70	-41.09	-224.8**	-26.94	-107.8	-34.63**
	(52.41)	(55.02)	(108.8)	(18.92)	(111.9)	(16.18)
Observations	1,223	1,223	1,124	575	575	440
R^2	0.903	0.905	0.797	0.375	0.867	0.938

Standard errors in parentheses, *** $p<0.01$, ** $p<0.05$, * $p<0.01$

models). This restriction does not appear to be important to the analysis; we find that the results of regressions that include oil prices are not substantially different from the results of the regressions excluding oil prices. We therefore report only the results of models without oil prices.

3.6. Conclusion

This paper has estimated the relationship between trade volumes and distance between countries in the CNG, LNG, and overall natural gas markets via the gravity model. The results from this analysis offer a confirmation that the recent rise in LNG exports is indeed the major contributing factor to the increasing integration of global natural gas markets.

The use of the gravity model to explore this observed market integration is a novel approach. Much of the work done in this area has focused on tests for mean reversion between two or more prices. The different approach taken in this paper offers strong confirming and complementary evidence that LNG is responsible for de-regionalizing the total natural gas market.

The findings presented in this paper suggest that the LNG trade has made the world market in natural gas less sensitive to distance between trading partners and that trade flows are less restricted by transportation costs than they would have been otherwise. These results suggest that the flexibility to deliver LNG to multiple points plays a crucial role in developing a global market for natural gas.

The main limitation of this approach is that it cannot identify whether or not natural gas prices are statistically integrated, and the strength of that integration. On the other hand, mean reversion tests on observed price data are capable of identifying whether or not markets are becoming more integrated, and the extent of that integration. Another limitation of this study is that the gravity model considers volume of trade, rather than the price at which trade occurs and does not account for the complex pricing clauses in natural gas contracts. This evidence is therefore best viewed as complementary to the findings of studies that use mean reversions techniques to indicate increasing price integration of

Table 3-6. Panel Regression with Temperature Variable

VARIABLES	(1) Total	(2) CNG	(3) LNG
log(Distance)	-1.321***	-2.871***	0.129
	(0.469)	(0.534)	(0.504)
Export			
log(GDP)	-0.163	-0.214	0.112
	(0.330)	(0.400)	(0.334)
Landlocked	-4.719	-8.059***	-4.961
	(2.999)	(2.588)	(3.327)
Unemployment %	-0.0465	-0.0727	-0.197**
	(0.0733)	(0.102)	(0.0815)
Nat. Gas GDP %	0.136*	0.239***	-0.0695
	(0.0631)	(0.0628)	(0.119)
Protected Land %	-0.104	-0.220**	0.0295
	(0.119)	(0.0907)	(0.0694)
Import			
log(GDP)	-0.0178	-0.0658	0.0321
	(0.365)	(0.498)	(0.440)
Landlocked	4.356**	2.247	-1.934
	(2.049)	(1.911)	(2.525)
Unemployment %	0.0977	0.139*	-0.0417
	(0.0733)	(0.0798)	(0.110)
Nat. Gas GDP %	-0.141	-0.256	-0.0501
	(0.118)	(0.140)	(0.141)
Protected Land %	0.0551	-0.00976	0.0438
	(0.0523)	(0.0536)	(0.0601)
Temperature	-0.0178	-0.0544	0.0446
	(0.0654)	(0.0764)	(0.0682)
Time Trend	-0.0553	-0.0451	0.0571
	(0.0603)	(0.0701)	(0.0813)
Constant	25.92***	42.09***	7.173
	(6.710)	(8.110)	(7.046)
Observations	475	278	240
Number of pairs	140	74	98
R^2	0.243	0.432	0.0986

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.01

natural gas markets (Neumann, 2009). Our findings, considered together with evidence provided by studies of the level of integration in prices, provide suggestive evidence that LNG has afforded the global market additional opportunities to engage in price arbitrage of natural gas (Wang & Notteboom, 2011).

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CHAPTER 4

UNDER WHAT PRICE CONDITIONS DO CNG-POWERED PASSENGER VEHICLES MAKE ECONOMIC SENSE?[3]

4.1. Introduction

Natural gas has the potential to be an attractive substitute for petroleum in the market for automotive fuel. New drilling and recovery techniques have resulted in a dramatic increase in the amount of recoverable natural gas consequently creating a decrease in domestic natural gas prices (Paltsev et al., 2011). Natural gas prices in the U.S. have fallen more than sixty percent from their peak in 2008 and proven reserves are approaching all time high levels (Moniz, 2011; Paltsev et al., 2011; Staub, 2013). The increasing price for petroleum and decreasing price for natural gas, at British Thermal Unit (BTU) parity quantities, means there is a growing cost advantage for natural gas. Natural gas also has the desirable property of emitting fewer greenhouse gases, which could increase progress toward climate change goals, as well as less particulate matter. Figure 4.1 shows the divergence in wholesale spot market prices for natural gas and oil between 1994-2012. Figure 4.2 shows an analogous divergence for retail Compressed Natural Gas (CNG) prices compared to gasoline and diesel fuel.

Research suggests that the cost advantage for natural gas may continue in the United States for many years. In part, natural gas markets, unlike the world oil market, lack strong integration and regional price differences can persist for longer periods of time. (Bachmeier & Griffin, 2006; Siliverstovs, L'Hégaret, Neumann, & von Hirschhausen, 2005). Additionally,

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[3] This chapter was co-authored with Ryan Bosworth, Kevin Heaslip, and Ali Soltani-Sobh

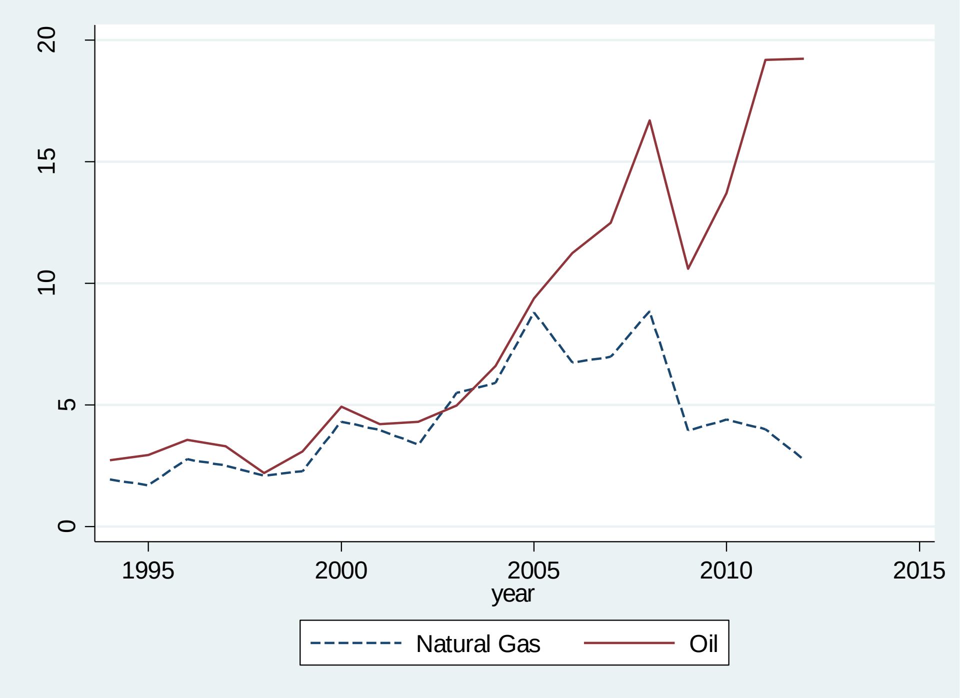

Figure 4-1. Energy prices

Source: U.S. EIA

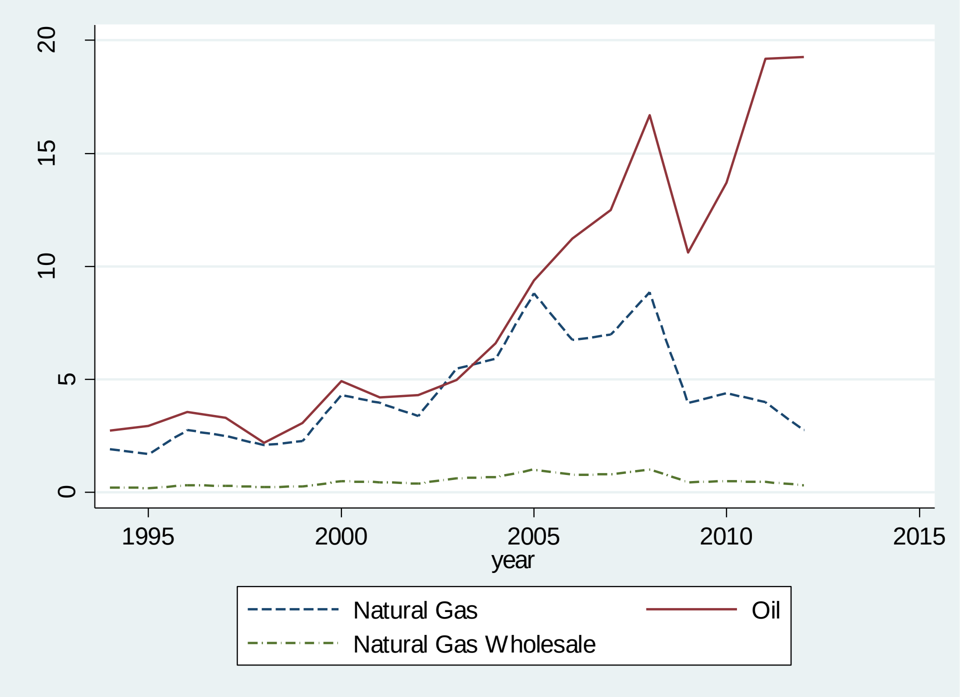

Figure 4-2. Fuel prices

Source: U.S. EIA

Paltsev et al. (2011) find that the supply of natural gas in the United States is projected to grow substantially between now and 2050, with a possible “low-end” estimate suggesting supply growth only through 2030. Summarizing their results, these 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” (p. 1).

Although the low per-BTU cost and reduced pollution associated with natural gas are appealing properties, there are several economic and technical factors preventing widespread adoption of CNG-powered vehicles. CNG vehicles are more expensive than gasoline-powered vehicles, partly due of the cost of building fuel systems capable of handling a compressed gaseous fuel. These added expenses have contributed to a low supply of CNG vehicles. Low vehicle supply has, in turn, contributed to a limited fueling infrastructure. The engineering requirements within a vehicles for CNG fuel tanks result in: reduced vehicle range, increased fueling frequency, increased vehicle weight due to heavy fuel tanks capable of safely storing a compressed fuel, and reduced storage space. Additionally, CNG vehicles are typically less powerful due to the lower energy density of natural gas compared to gasoline vehicles (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 2848 pounds. All gasoline powered Civic models are rated at 140 hp and 128 lb-ft of torque and weigh about 2600 pounds. However, both types of vehicle are rated at 31 MPG (combined city/highway).

A vital component of this study is a consumer decision-making model which considers the annual VMT for the vehicle, the premium paid for the CNG fueled vehicle, the fuel efficiency of the vehicle being replaced, and the price differential between CNG and petroleum gas. This model strives to predict, using various price conditions, what share of the vehicle fleet would find a CNG vehicle more financially worthwhile than an equivalent petroleum vehicle. Analysis is conducted given the assumption of a CNG fueling infrastructure being fully developed and CNG vehicles were widely available for purchase, with the current fuel and vehicle prices. The paper presents a synopsis of the current state of the CNG and NGV markets, the development of the consumer choice model, and analysis of the results of the model for future adoption of CNG vehicle technology, and finishes with summary and conclusions.

4.2. Current State of the Market

According to the Natural Gas Vehicle Association of America there are currently approximately 120,000 natural gas vehicles (NGV) in the U.S. fleet and 15.2 million NGVs worldwide. The Department of Energy reports that there are currently 519 public Compressed Natural Gas (CNG) stations in the United States and a total of 1,107 stations when private stations are included. 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.

There are few CNG passenger vehicles on the market in the United States. This paucity of choice suggests considerable uncertainty regarding the price premium for a CNG vehicle. Honda’s Civic CNG is the only consumer ready vehicle, although some vehicles are available for fleets and special orders. The limited information available suggests that the CNG price premium has not decreased over time and that higher volume manufacturing may not lower costs significantly. For example, Walls (1996) estimates (inflation-adjusted) incremental CNG vehicle costs of less than $5000. Depending on

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 NGV America (2012) (www.ngvc.org)

options, a Honda Civic GX costs about $4000-$7,000 more than its gasoline counterpart (Werpy et al., 2010).

Although this paper focuses on the economic viability of CNG for passenger vehicles, similar limitations exist for CNG-powered heavy-duty trucks. Despite the potentially large fuel-cost savings for large trucks, widespread adoption of heavy-duty CNG vehicles has not yet occurred. As noted by Deal (2012), some factors limiting the application of CNG in heavy-duty vehicles include:

- Limited refueling infrastructure (compared to diesel)
- natural gas trucks are substantially more expensive
- high-capital costs associated with upgrading a maintenance shop to deal with CNG vehicles limited capacity of economical CNG fuel tanks limits operational range and adds weight to the truck,

- LNG (liquid natural gas) use is limited to situations where trucks are re-fueled every 1-2 days
- some fleets are apprehensive about adopting new “high risk” technology

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. Limited availability is due in part to technical limitations associated with CNG. A major consideration is that heavy duty trucks have large power requirements. 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 results in a fuel efficiency penalty of about 10% (Deal, 2012).

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. CNG operating costs are also increased due to the greater weight, more frequent refueling, and reduced range of the vehicles. Finally, the benefits of CNG depend on reduced fuel costs, therefore, price fluctuations of CNG unexpectedly influenced by market forces or governmental policy changes cause CNG to be viewed as a risk.

4.3. Modeling Procedures

The model established for this research has been developed from the perspective of a consumer and the results are specific to the passenger vehicle fleet in the United States. The financial decision of a consumer to adopt a CNG vehicle is similar to the decision a business would make when looking to purchase a vehicle. For additional information on CNG for heavy vehicles, see Deal (2012) and Whyatt (2010), which investigate the cost-effectiveness of Heavy-Duty CNG trucks.

In order to model CNG vehicle adoption as a financial decision, it is necessary to make several simplifying assumptions. Assumptions specific to our 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. This lack of infrastructure renders CNG impracticable for many, if not most, consumers. Moreover, CNG vehicle choices are extremely limited. Consumers in general 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, it is noted that the predictions of our model represent what is *possible* with expanded CNG infrastructure and expanded CNG vehicle selection, rather than what is *probable* under current conditions.

This analysis is based on current technological possibilities. Given current technology and prices, CNG adoption represents a cost-effective decision for some consumers, simply because CNG vehicles enjoy a fuel cost advantage over similar gasoline-powered vehicles. This cost advantage may be undermined by new technological developments in conventional petroleum fueled or other alternatively fueled vehicles.

4.3.1. A Model of Consumer Demand for CNG Passenger Vehicles

The model considers 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 a fuel system preference, the choice can be characterized as a purely 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. The only relevant costs are the initial purchase price, depreciation costs, and the cost of fuel, otherwise the vehicles are assumed identical. Basic maintenance costs, registration fees, and other costs associated with normal vehicle ownership are assumed to be the same across vehicles therefore are irrelevant to the model. Discussions of the implications of these simplifying assumptions are below. With these assumptions, however, the total cost associated with the gasoline-powered vehicle can be expressed as:

$$TC_g = V_{g0} + f_{g0} + f_{g1}(1+r)^{-1} + \cdots + f_{gT}(1+r)^{-T} - V_{g0}(1+\delta)^{-T}(1+r)^{-T}, \tag{4-1}$$

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 period 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 per-period rate of depreciation and the last term in the expression therefore captures the sales or scrap value of the vehicle at time T. If it is assumed that 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:

$$TC_g = \left[V_{g0} + -V_{g0}\{(1+\delta)(1+r)\}^{-T}\right] + \sum_{t=0}^{T}(1+r)^{-t} f_g \tag{4-2}$$

Note that the expression $\left[V_{g0} + -V_{g0}\{(1+\delta)(1+r)\}^{-T}\right]$ is the vehicle purchase cost less the present discounted value of the terminal value (scrap or resale 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:

(4-3) $$TC_g = V_{g0}^{*} + \sum_{t=0}^{T}(1+r)^{-t} f_g.$$

Apply the same framework to the CNG vehicle by simply replacing the *g* subscripts with *c* subscripts. Since 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 $\Delta TC = TC_g - TC_c > 0$:

(4-4) $$\Delta TC = TC_g - TC_c = (V_{g0}^{*} - V_{c0}^{*}) + \left(\sum_{t=0}^{T}(1+r)^{-t} f_g - \sum_{t=0}^{T}(1+r)^{t} f_c\right).$$

This can be written more simply as:

(4-5) $$\Delta TC = (V_{g0}^{*} - V_{c0}^{*}) + \sum_{t=0}^{T}(1+r)^{-t}\left(f_g - f_c\right).$$

An alternative way of thinking about 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 TT. 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 per-period fuel savings.

4.3.2. 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. This model has been 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.

For example, the model assumes that after choosing a fuel system, the consumer's nominal yearly fuel cost is the same in each period. 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.

The assumption has also been made that both types of vehicles depreciate at the same rate. 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.

4.4. 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). This data is used to calculate estimated travel cost savings (for the current vehicle fleet) that would result from a switch to a CNG vehicle. Calculating these cost savings requires knowledge of both miles per gallon (MPG) and vehicle miles traveled (VMT) for a given vehicle and that these variables are available from the NHTS.

Suppose that an equivalent CNG powered vehicle for a given price could replace any gasoline-powered vehicle. This replacement could occur either by paying to convert or retrofit 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. If a consumer knows the vehicle price differential as well as fuel prices, expected VMT, expected MPG, expected time of ownership, the appropriate discount rate and vehicle depreciation rate, it is straightforward to calculate the present discounted value of the decision to switch to CNG.

Using these estimates of the present discounted value of the switch to CNG for each vehicle in the (sample) fleet, the model simulates the proportion of the population that would find this switch advantageous under a set of estimated baseline parameter values. Next, it assesses 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).

It should be noted that the simulation estimates shown below are derived under assumptions of consumer travel cost minimization (as discussed above) and, importantly, under the assumption that vehicle supply and infrastructure are generally available.

4.4.1. CNG Passenger Vehicle Price Differential

Some customers may find the loss in power and increased weight of CNG vehicles less desirable to drive therefore this should be factored in the calculation of the appropriate vehicle price differential. Lack of fueling stations and smaller fuel tank capacity will result in more frequent, less convenient fill-ups. Consumer loss in utility due to these factors is approximately $1100-$3200 in 1996 dollar terms according to Walls (1996). This loss in utility due to the inherent disadvantages of CNG vehicles is an imperative component of the vehicle price differential. These disadvantages may not be relevant for some consumers but they may be major limitations for others. Conversely, 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).

4.4.2. Baseline Model Parameters

In order to simulate the proportion of the passenger vehicle fleet that would find it advantageous to switch to CNG vehicles, it is necessary to choose baseline estimates of the value of the parameters of the model. 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).

This baseline model uses a fuel price differential of $1.50, based on a rough estimate of the national gasoline-CNG price differential in the United States in April 2013. A vehicle price differential of $7000 was used. This differential is based on the difference between a Honda Civic CNG and a Honda Civic EX plus a $3000 “inconvenience premium” based on an inflation adjustment to the estimate of consumer welfare loss by Walls (1996, p. 8). A baseline depreciation rate of 15% (Feng et al. 2013), a baseline discount rate of 6%, and a baseline estimate of expected length of vehicle ownership of 60 months, indicated by Kelly Blue Book to be the current average was also used. These estimates are based on the sources indicated and market prices observed by the researchers. These baseline model parameters are summarized in below.

Purchase Price Differential - $7000
Fuel Price Differential - $1.50
Length of Ownership - 60 Months
Discount Rate - 6%
Depreciation Rate - 15%

Table 4.2 below shows how the present discounted value of expected fuel savings varies with VMT and MPG under these baseline parameters. The most obvious feature of the table is that 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 therefore higher potential savings. Lower MPG likewise suggests high fuel consumption and greater potential savings. 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 4-2. PDV of Expected Fuel Savings at $1.50 Fuel Price Differential

MPG	VMT per year							
	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

4.4.3. Simulation Results

Using the joint distribution of vehicle MPG and VMT from the NHTS of 2009 and calculating the proportion of consumers that would find a switch to CNG financially advantageous using these baseline model parameters, Table 4.3 shows variation in this predicted proportion with respect to the fuel price differential and the vehicle price differential for the United States.

Table 4.3 shows 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 the U.S. These baseline estimates of a $7000 vehicle price premium and a $1.50 fuel price differential are shown in bold. Variation in predicted adoption rates for a range of prices that may be viewed as plausible given current market conditions is also shown. Although the fuel price differential is about $1.50 at the time of this writing, a gap

Table 4-3. Proportion of Passenger Vehicle Fleet with Positive PDV for CNG Adoption (United States)

		Purchase Price Differential							
		$3,000	*$4,000*	*$5,000*	*$6,000*	*$7,000*	*$8,000*	*$9,000*	*$10,000*
Gas Price Differential	*$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 CNG fueling infrastructure and vehicle availability

as large as $2.20 occurred 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 0.1% of the vehicle fleet in the United States would find CNG financially beneficial if CNG vehicles and fueling infrastructure were widely available. This small fraction of the population suggests that, at current prices, CNG vehicles would not be financially beneficial to most consumers, regardless if fueling stations were ubiquitous. However, the table also indicates that there is substantial potential for more widespread CNG adoption if vehicle price premiums drop and fuel price differentials increase.

4.4.4. The Relative Importance of Fuel and Vehicle Price Differentials

A crucial feature of Table 4.3 is that it shows the relative importance of fuel price differential changes and vehicle price differential changes on the proportion of the vehicle fleet that would find a switch to CNG advantageous. Note that at the baseline estimate of $7,000 for the vehicle price differential, 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 resulting in a reduction in the vehicle price premium from $7,000 to $4,000 would boost the predicted CNG adoption rate to 7.2% at current fuel prices. Extremely high fuel price differentials would not be enough to induce high adoption rates while 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 despite current fuel price differentials. At current vehicle price differentials, however, widespread CNG adoption is unlikely even if infrastructure expands and vehicles become available. For example, at a vehicle price differential of about $7000, the fuel price differential necessary for the model to predict a 50% CNG adoption rate is over $5. A fuel price differential of even $2.50 surpasses what has been seen historically; therefore, a fuel price differential of $5 may be viewed as an extremely unlikely event.

It is noteworthy, however, that if the "inconvenience cost" of owning a CNG vehicle (*8*) is not considered, then it is realistic to obtain a price differential of $3000-$4000.These costs are likely less important for fleet and service vehicles consequently the model suggests that adoption is more likely within these sectors.

4.4.5. Other Model Parameters: Sensitivity Analysis

The authors have also investigated how sensitive the simulation results are to variation in the other baseline parameters: ownership time, discount rate, and depreciation rate. This has been accomplished by varying each attribute, holding all other attributes constant at the baseline. Full results from these sensitivity analyses are omitted because of space limitations. As expected, longer vehicle ownership times are associated with higher predicted rates of CNG adoption, as are lower discount rates and lower depreciation rates. Nevertheless, this model predicts that only modest changes in adoption rates will occur even with relatively large changes in these variables.

4.5. Looking Forward

The 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 can be expected to respond to these changes by altering the number of miles driven and by changing vehicle choices. As shown above, an increase in the fuel price differential between gasoline and CNG increases the incentive for consumers to switch to CNG, *ceteris paribus*. Increasing gasoline prices directly affects the fuel price differential, which is expected to alter the distribution of vehicle miles traveled, and the vehicle fleet composition as consumers react to these changes.

Research suggests that consumers do indeed 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, 2011; Greene, 1992; Greene, Kahn, & Gibson, 1999; Jones, 1993; Small & Van Dender, 2007). 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 (2009) 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. For example, 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 predicted 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. Interestingly, both types of anticipated reactions to increased gasoline prices (reduced VMT and more fuel efficient gasoline vehicles) predict lower CNG adoption rates. Intuitively, 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. Observing that 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 easily shows this.

Recall that the present discount value of total cost savings associated with switching to CNG can be expressed as:

$$\Delta TC = (V_{g0}^{*} - V_{c0}^{*}) + \sum_{t=0}^{T}(1+r)^{-t}\left(f_g - f_c\right). \tag{4-6}$$

This can be rearranged as:

$$\Delta TC = \left(V_{g0}^{*} - V_{c0}^{*}\right) + \sum_{t=0}^{T}(1+r)^{-t}\left(p_g - p_c\right)\left(\frac{VMT}{MPG}\right), \tag{4-7}$$

where $(p_g - P_c)$ is the fuel price differential which is assumed positive. The derivatives of this expression with respect to VMT and MPG, therefore, are:

(4-8) $$\frac{\partial \Delta TC}{\partial VMT} = \frac{1}{MPG} \sum_{t=0}^{T} (1 + r)^{-t} \left(p_g - p_c\right) > 0$$

(4-9) $$\frac{\partial \Delta TC}{\partial MPG} = -\left(\frac{VMT}{MPG^2}\right) \sum_{t=0}^{T} (1 + r)^{-t} \left(p_g - p_c\right) < 0.$$

Interestingly, 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 gasoline vehicles.

4.6. Summary and Conclusions

Using the baseline parameters, the research indicates that the proportion of the vehicle fleet that would find a CNG fuel system economically advantageous 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 lower conversion costs or manufacturer vehicle price differentials, CNG vehicle are likely to remain a minority in the vehicle fleet. Importantly, the research found that 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 fifty 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 is 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-zero proportion of the vehicle fleet is predicted to adopt CNG. This proportion is likely to grow as infrastructure becomes available, particularly 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, the 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 are smaller than otherwise. Finally, the model suggests 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:

4.6.1. Decreased Vehicle Price Differential

First, the vehicle price differential between CNG vehicle 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 becomes 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.

4.6.2. 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.

4.6.3. Limited Transportation Technological Improvements

Third, 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.

4.6.4. Expanded Fueling Infrastructure and Vehicle Availability

Finally, 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.

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CHAPTER 5

THE EFFECT OF NATURAL GAS VEHICLE ADOPTION ON EMISSIONS OF CARBON DIOXIDE IN THE LIGHT DUTY VEHICLE FLEET[4]

5.1. Introduction

Natural gas competes with oil as an energy fuel. Historically, on energy parity basis, natural gas and oil have been fairly price competitive. Figure 5.1 depicts this historical relationship. However, due to technological constraints of using a pressurized gas as a fuel source natural gas has not competed with gasoline as a transportation fuel. In recent years the price of natural gas fell relative to oil. The decrease in price of natural gas relative to oil makes natural gas more attractive as a transportation fuel (Dondero & Goldemberg, 2005; Gwilliam, 2000; Janssen, Lienin, Gassmann, & Wokaun, 2006; Matic, 2005). Yeh (2007) finds that for wide spread adoption retail natural gas needs to be priced at least 40%-50% less than conventional gasoline.

Natural Gas is also less carbon intensive than gasoline or diesel fuel, and therefore the adoption of natural gas powered vehicles has the potential to reduce greenhouse gas (GHG) emissions from the transportation sector. However, these reductions depend on the rate at which consumers and firms adopt natural gas powered vehicles. In this study, we provide estimates of the potential for carbon emission reductions from the light-duty fleet in the United States. In addition, we compare the costs of carbon emission reductions via subsidies for natural gas vehicle adoption with the costs of carbon abatement from other strategies. Overall, we conclude that CNG adoption is unlikely to produce

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[4] This chapter was co-authored with Ryan Bosworth, Kevin Heaslip, and Ali Soltani-Sobh.

substantial reductions in carbon emissions at current fuel and vehicle prices and that fuel and vehicle subsidies spur further adoption represent a relatively costly form of carbon abatement.

We begin by briefly reviewing the chemistry of emissions that makes carbon emission reductions via CNG adoption possible. This information is then combined with an economic model designed to predict compressed natural gas (CNG) vehicle adoption rates in the light-duty vehicle sector. Our model produces a range of estimates of carbon emission reductions from the light-duty vehicle sector for given CNG vehicle and fuel price conditions. We conclude with a discussion of the overall potential for carbon emission reductions due to CNG vehicle adoption.

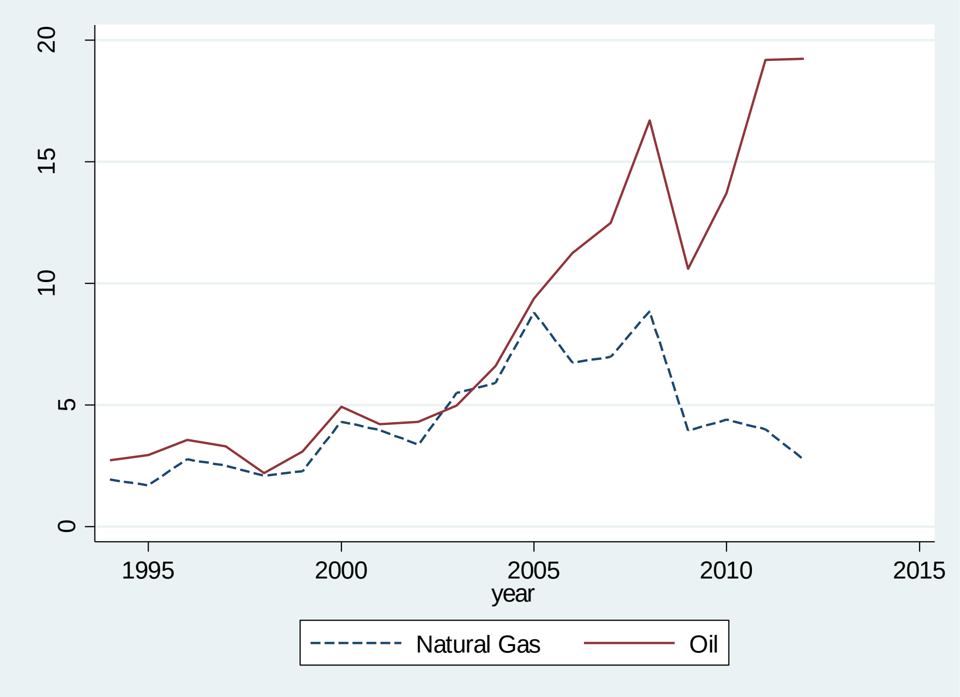

Figure 5-1. The Growing price advantage of natural gas relative to oil

5.2. Chemistry of Emissions

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

(5-1) $$2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O$$

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 et. al. 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),

(5-2) $$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$$

combined with the information on the atomic weights of each of the elements allows for the 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 lb.) of natural gas.” (National Institute of Standards and Technology, 2007). 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.

It is important to note that these reactions are idealized. We assume throughout the paper perfect combustion of the fuel. There is no unreacted or partially reacted fuel, nor contaminants in the fuel. These types of imperfections create other types of emissions such as volatile organic compounds (VOCs), sulfur dioxide (SO_2), Nitrogen Oxides (NO_x), Carbonyl Compounds (e.g. formaldehyde, acetaldehyde, acrolein) and particulate matter (pm10 and pm2.5) (Hesterberg, Lapin, & Bunn, 2008; Karavalakis, Durbin, Villela, & Miller, 2012). Natural gas produces less of these emissions than gasoline (Evans & Blaszczyk, 1997), and the co-benefits of eliminating these criteria pollutants could contribute to the decision to implement policies designed to increase adoption of natural gas vehicles. Muller and Mendelsohn (2009) estimate the marginal social damages for a number of these criteria pollutants.

5.3. Light-Duty Vehicle Fleet

The basic economic decision of whether or not to convert an existing vehicle to a compressed natural gas (CNG) vehicle is driven by simple factors (conversion costs, fuel prices, etc.) for the light-duty vehicle fleet. We assume consumers would choose to convert an existing vehicle to a natural gas vehicle (NGV) if the costs of converting and operating that vehicle are lower than the costs of purchasing and operating a comparable conventional fuel vehicle. This approach leads to a consumer choice model that depends on the option value of converting the vehicle.

A rich literature exists on real option values in the vehicle market. Rust (1987) develops a model of the optimal replacement of bus engines. Moretto (2000) models the decision to participate in a vehicle scrappage program with uncertain future benefits and costs. Camargo et al. (2010) use a real option model to describe the choice between purchasing a flex-fuel vehicle over a gasoline vehicle in the Brazilian auto market. Bastian-Pinto, Brandão, & de Lemos Alves (2010) also examine the utility benefits that Brazilian consumers gain from flex-fuel vehicles under fuel price uncertainty. Avadikyan and Llerena (2010) investigate the automotive industry's incentives to invest in hybrid vehicles using a real options approach. García and Miguel (2012) use a real options approach to investigate whether or not electric vehicles are an attractive option to Spanish consumers.

The individual will choose the vehicle with the lowest present discounted cost of all monetary flows. The model for NGV conversion can be envisioned as an individual choosing between two identical vehicles that differ only in their fuel system and initial purchase price, because we can capitalize the conversion costs into the purchase price. At first glance, this assumption appears to ignore important work done on vehicle choice modelling[5], where consumers receive utility from other attributes of the vehicle other than strictly monetary costs. However, the strictly monetary model presented in this paper describes the purely financial choice of whether or not the consumer should convert an existing vehicle to run on natural gas.

We also assume that all associated costs of ownership such as maintenance, registration fees, property taxes, etc. are identical across both vehicle types. The primary variables that consumers must account for in this calculation are the purchase price of the vehicle, the price of the fuel, expected vehicle miles traveled (VMT), fuel efficiency (MPG), and the expected useful life of the vehicle.

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[5] Brownstone, Bunch, and Train (2000), for example, illustrate the importance of combining revealed preference data with stated preference data to control and obtain realistic values for various vehicle attributes. Our approach does not account for these various attributes because we assume that the stock vehicle and the converted vehicle will share these attributes, and therefore the value of these attributes will be lost when the stock vehicle is differenced with the converted vehicle. These values are therefore irrelevant to our calculations.

(5-3) $TC_g = V_{g0} + f_{g0} + f_{g1}(1+r)^{-1} + \cdots + f_{gT}(1+r)^{-T} - V_{g0}(1+\delta)^{-T}(1+r)^{-T}.$

This equation simply states that the total cost of ownership of a gasoline vehicle is the original purchase price of the vehicle less any residual value discounted to the present, plus the discounted value of a flow of fuel costs. A comparable relationship can be stated for an NGV. Recognizing that fuel costs are a linear transformation of fuel consumption, specifically:

(5-4) $f_{it} = p_{it}\frac{VMT_t}{MPG_t}$

We further assume that fuel consumption is equal in each period and that fuel prices are constant. The assumption of constant fuel consumption comes from the assumption that driver habits are stable across time, and that fuel efficiency will be unaffected by conversion. Finally, we assume that future fuel prices are constant under the assumption that the best predictor of future fuel prices is the current fuel price therefore consumers are assumed to use the current fuel price to estimate future fuel costs. Substituting the expression for fuel costs in Equation 2 into Equation 1, collecting the terms containing the original purchase price into one term, and rearranging the formula gives the following result:

(5-5) $TC_g = V_{g0}^{*} + \sum_{t=0}^{T}(1+r)^{-t} f_g.$

Subtracting this equation from the comparable equation for NGVs and substituting the expressions for fuel costs into the model gives the basis for the consumer's decision. V_{g0}^{*} is the difference between the current value and the discounted residual value of the vehicle at period $T.$ Specifically, the consumer will decide to convert if the option value of conversion is positive. It is convenient to define the consumer’s choice problem as an indicator function for when CNG is provides a positive option value to the consumer.

(5-6) $$\phi_{i,j} = \begin{cases} 1 \quad \text{if} \quad \left(V_{g0}^{*} - V_{c0}^{*}\right) + \sum_{t=0}^{T}(1+r)^{-t}\left(p_g - p_c\right)\left(\frac{VMT_i}{MPG_j}\right) > 0 \\ \quad 0 \quad \text{otherwise} \end{cases}$$

This equation states that, when a NGV is cost effective (has a positive option value) for the ith, jth VMT / MPG pair, $\phi_{i,j}$ will take on the value of unity. Otherwise, when an NGV is less cost effective (has a negative option value of conversion) than a conventional gasoline vehicle, $\phi_{i,j}$ will take on the value of zero. Essentially, the decision criterion measures the option value of purchasing a natural gas vehicle. For positive option values, the consumer switches to natural gas.

Using data from the 2009 National Household Travel Survey (United States 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 4.3 of this dissertation. 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.

5.4. 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,

$$C = \frac{VMT}{MPG} \quad \text{(5-7)}$$

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,

$$e_{MPG,VMT} = k_i C_{MPG,VMT}, \quad \text{(5-8)}$$

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 does 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,

$$TE = h \sum_i \sum_j \left[\phi_{i,j} k_c w_c \frac{VMT_i}{MPG_j} p_{i,j} + \left(1 - \phi_{i,j}\right) k_g w_g \frac{VMT_i}{MPG_j} p_{i,j} \right], \quad \text{(5-9)}$$

where 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 i^{th} level of VMT. Consumers are also assumed to have a well-known behavioral response in the number of miles driven after converting to CNG due to the lower fuel price. This behavioral response is a phenomenon known as the rebound effect (Greene, 2012; Small & Van Dender, 2007; Sorrell, Dimitropoulos, & Sommerville, 2009). The rebound effect is an income effect that occurs due to the lower price per mile driven (Sorrell & Dimitropoulos, 2008). MPG_j indicates the j^{th} 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.

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 5.1. The total level of emissions based on these assumptions, and data for the vehicle fleet is 842.36 million tons of CO_2. The baseline model's parameters were subjected to a sensitivity analysis. The length of ownership was based on the estimated average length of vehicle ownership by Kelly Blue Book to be 60 months. The model above, therefore assumes a payback period of five years. This assumption is immediately suspect because of studies that look at the payback periods for fuel savings find that the typical consumer only considers the first three years of fuel savings (Greene, Patterson, Singh, & Li, 2005). This study may, therefore, overestimate the financial benefit of converting a vehicle to natural gas. The overestimate of these benefits will imply that the reduction in CO_2 emissions will also be overestimated. The authors find that any overestimation in the reduction of the CO_2 emissions cannot qualitatively change the conclusions drawn.

Table 5-1. 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%
Rebound Effect Elasticity	0.22

Furthermore, correcting this overestimation can only strengthen the final conclusions the authors draw, and therefore reducing the payback period from 5 years to 3 years is moot.

The baseline purchase price differential reflects two important aspects of the car. The first is the actual cost of conversion. The cost of conversion can be affected by the cost of materials and labor. These conversions can cost between $2000 and $4000. The $4000 cost of conversion is most likely an overestimate. It is based primarily on the price difference between a Honda Civic GX (the natural gas version of the civic) and a Honda Civic EX (the most comparably equipped version of a Civic) (Werpy, Santini, Burnham, & Mintz, 2009). Under the Alternative Motor Fuels Act, manufactures of CNG vehicles may receive special fuel economy credits. Therefore, the $4000 premium on this OEM vehicle may be more of a marketing strategy than actual cost of production. We, therefore, take the $4000 as the first part of this baseline purchase price premium as an upper-bound on the cost of retrofitting a vehicle to use CNG. The second part of this premium includes an “inconvenience premium” due to switching to a natural gas fuel. The inconvenience premium accounts for the lack of infrastructure (Kirk, Bristow, & Zanni, 2014), reduced power (Evans & Blaszczyk, 1997), reduced trunk space due to safety requirements of placing the fuel tank in the trunk of the vehicle, and making the vehicle heavier to reinforce valves and other components to handle a pressurized gas instead of a liquid fuel. This inconvenience premium is based on the work of Walls (1996) and adjusted for inflation, approximately \$3000. Combining the estimates of the cost to convert a vehicle with the inconvenience premium yields an estimated purchase price premium of \$7000. We allow this parameter to vary significantly in the sensitivity analysis due to the high uncertainty associated with our baseline figure. We allow this figure to range between \$3000 and \$10,000.

The baseline fuel price differential was based on a rough estimate of the national gasoline-CNG price differential in the United States in April 2013. Due to the inherent volatility of both of these price series, we allow the price differential to vary in our sensitivity analysis. We allow the price differential to range between \$1.20 and \$2.50 per gallon.

A baseline depreciation rate of 15% was used for this analysis (Feng, Fullerton, & Gan, 2005), and a baseline discount rate of 6% was used. For these parameters, 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 5.2 shows the total level of emissions in the U.S.

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:

(5-10) $$TE^* = h\sum_i \sum_j k_g w_g \frac{VMT_i}{MPG_j}\, p_{i,j},$$

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

Table 5-2. 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

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

(5-11) $$\Delta E = TE - TE^* < 0$$

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

(5-12) $$\Delta E = (k_c w_c - k_g w_g) \sum_i \sum_j \left[\phi_{i,j} p_{i,j} \frac{VMT_i}{MPG_j}\right].$$

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.

Table 5-3. Predicted Percentage Carbon Emission Reductions for United States (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%

The percentage reduction of emissions from the benchmark conditions due to a change in market conditions (fuel and vehicle prices) is given in Table 5.3.

5.5. 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 0.0037%. 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 an extremely large fuel price differential ($2.50) and a substantially smaller vehicle price differential ($3000), 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.

$$\text{(5-13)} \qquad \frac{\partial \Delta E}{\partial VMT_i} = \left(k_c w_c - k_g w_g\right) \sum_j \frac{\phi_{i,j} p_{i,j}}{MPG_j} < 0.$$

Keeping in mind that $\Delta E < 0$, this formula says that the size of the reduction will increase as VMT increases, because $\left(k_c w_c - k_g w_g\right) < 0$. 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:

$$\text{(5-14)} \qquad \frac{\partial \Delta E}{\partial MPG_j} = \left(k_g w_g - k_c w_c\right) \sum_i \left[\phi_{i,j} p_{i,j} \frac{VMT_i}{MPG_j^2}\right] > 0.$$

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.

These results imply an elasticity of emissions with respect to NGV adoption rates of approximately -0.1969. This elasticity is fairly constant due primarily to the chemistry of emissions. Natural gas (methane), when combusted, emits about 19.7% less carbon dioxide than gasoline (octane). The stability of this ratio allows for a generalization to extreme values of the adoption rates. Increasing the proportion of the NGV fleet will reduce emissions. This can be seen by the comparative static result,

$$\frac{\partial e_{\pi,t}}{\partial \pi} = C_{\pi,t}\left(k_c w_c - k_g w_g\right) < 0. \tag{5-15}$$

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 NGVs in the fleet that switches can be calculated as

$$\varepsilon_e = \frac{\pi\left(k_c w_c - k_g w_g\right)}{\left[(1-\pi)k_g w_g + \pi k_c w_c\right]} < 0. \tag{5-16}$$

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

$$\pi < \frac{k_g w_g}{2\left(k_g w_g - k_c w_c\right)}. \tag{5-17}$$

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 adoption rates is always inelastic.

The inelastic nature of emissions with respect to the adoption rates suggests that converting even a relative large proportion of the fleet to natural gas is unlikely to dramatically reduce GHG emissions.

5.6. Policy Implications

The model developed thus far has three main policy levers which can be used to achieve additional abatement. The first of these policy levers is a subsidy on the purchase of a NGV. The second policy lever that this model provides is a tax on gasoline consumption. In practice the reasons for implementing gasoline taxes are generally the maintenance of infrastructure. Pollution control is a secondary concern. Furthermore, our model already accounts for the current gasoline tax in the gasoline fuel prices used. Therefore, the analysis that follows assumes an increase in the gasoline tax as an abatement technology. The final policy lever that is available in this model is a subsidy on natural gas paid at the pump. This policy would lower NGV's operation costs and thus make the conversion to a NGV more attractive.

Each of these policy levers operates by reducing the relative cost of owning a NGV relative to a conventional vehicle. These policy levers then give rise to substitution and income effects. For the cases of subsidizing natural gas as a fuel and subsidizing NGVs, the substitution, or adoption effect, lowers GHG emissions, while the income effect erodes the abatement from the adoption effect. Whereas for an increase in the gasoline tax the opposite is true, the income effect reduces emissions, and the adoption effect erodes the reductions in emissions gained from the income effect.

5.6.1. Subsidizing NGVs

Figure 2 depicts the estimated marginal abatement cost curve for the subsidizing NGVs. Each point on the figure indicates a $1000 increment to the subsidy. The estimated marginal abatement costs increase from $1,274/ton CO2 to $5,750/ton CO2. Over this range of prices the amount of CO2 abated increases from essentially zero tons to over 40 million tons.

The curve is upward sloping, which is the theoretically expected relationship. The upward sloping nature of this curve satisfies the necessary condition for finding the socially optimal level of abatement. However, the large starting price on this curve, namely $1,274/ton CO2, suggests that the sufficient conditions probably will not be satisfied since other abatement programs with smaller marginal abatement costs, like the Cash for Clunkers program of 2009, are considered environmentally inefficient (Knittel, 2009; Li, Linn, & Spiller, 2013). A socially optimal subsidy using this policy lever is possible, but unlikely.

5.6.2. Increasing the Gasoline Tax

The effect of increasing the gasoline tax on emissions was simulated by increasing the price of gasoline in ten cent intervals. The model estimates at baseline parameter values the tons of CO_2 emitted for each increase. Fuel consumption is estimated by dividing the VMT by the MPG for each value in the empirical joint probability distribution for these two variables. The weighted average of fuel consumption is calculated using the probability of a VMT / MPG pair as the weights. This average is then multiplied by the total fleet size to get the fleet's annual fuel consumption. The total fuel consumption is multiplied by the increase in the gasoline tax to estimate the cost of the increase to consumers. This cost is divided by the decrease in the gasoline tax to arrive at an estimated marginal abatement cost. The marginal abatement cost for an increase in the gasoline tax is depicted in Figure 3. Each marked point on the marginal abatement cost curve represents an increase (from left to right) in the gasoline tax of an additional 10 cents.

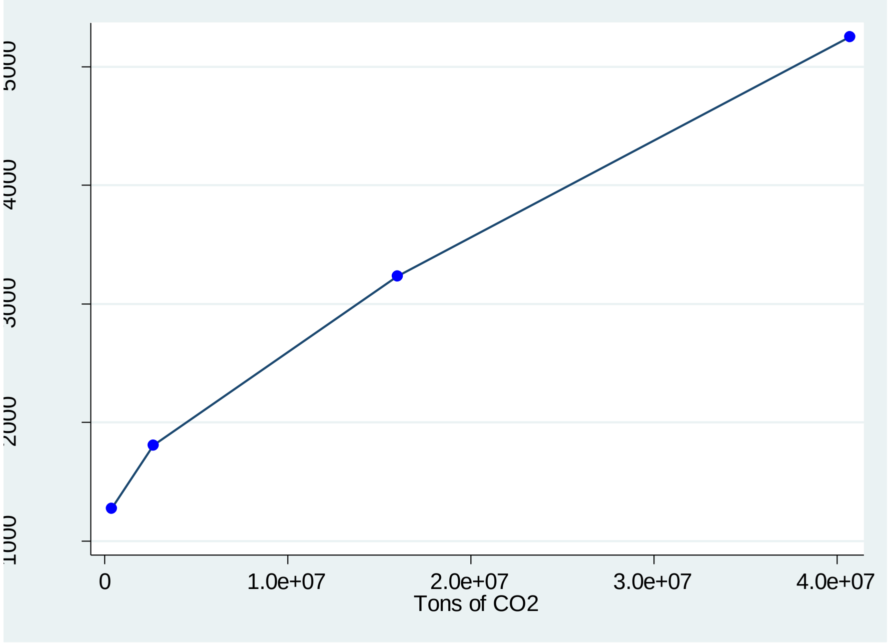

Figure 5-2. Marginal abatement cost of subsidizing NGVs

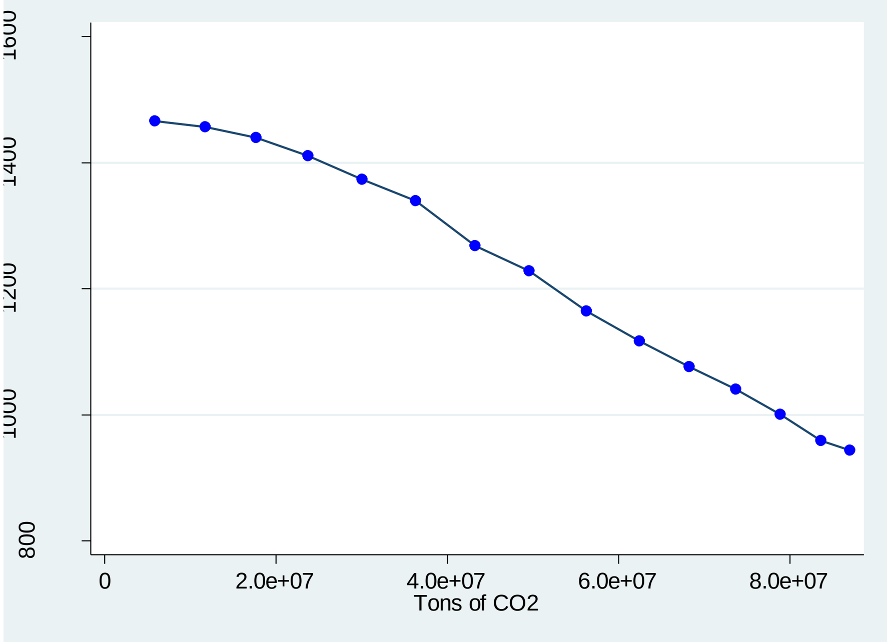

Figure 5-3. Marginal abatement cost of gasoline tax

The most prominent feature of this marginal abatement cost curve is that it is decreasing in emissions. The decreasing marginal abatement cost is somewhat counterintuitive because conventional economic theory suggests that marginal abatement costs should be increasing. This decrease, however, reflects the ability of consumers to substitute to alternative fuels. The model predicts that as the gasoline tax increases consumers will attempt to avoid the tax by switching from conventional gasoline to natural gas. Adoption of NGVs begins with the most polluting vehicles first, but they represent a small portion of the fleet. As more consumers adopt natural gas to avoid the tax, tax revenues begin to fall. At the same time the remaining gasoline vehicles are driven less intensively. Therefore the combined effect of adopting NGVs and the income effect response decrease tax revenues more rapidly than the increase from the rising tax rate. These effects account for the joint decrease in emissions and marginal abatement costs.

Decreasing marginal abatement costs have serious implications for the existence and uniqueness of a socially optimal solution. Particularly, the downward sloping marginal abatement cost curve implies non-convexities in the abatement technology in question.

Finally, the marginal abatement costs, despite decreasing over the relevant range, are very large. The model predicts that the marginal abatement costs of increasing the gasoline tax are between \$943 /ton CO_2 and \$1,465 /ton CO_2. These large costs probably preclude the existence of a socially optimal level of emissions.

5.6.3. Subsidizing Natural Gas as a Transportation Fuel

To simulate the effect of subsidizing natural gas as a fuel, the price of natural gas was decreased incrementally by 10 cents. The model was otherwise evaluated at baseline parameter values. The total cost of the program was calculated in a similar fashion as the increase to the gasoline tax. The fuel consumption for each VMT / MPG pair was calculated for each pair in the joint probability distribution for which natural gas was financially advantageous. The weighted average of these values was calculated using the probabilities as weights. This calculation gave total natural gas fuel consumption, which was multiplied by the subsidy. The model produced estimates of CO_2 emissions. The total cost of the program was divided by the total emissions abated to give an estimate of the marginal abatement costs.

Figure 5.4 depicts the marginal abatement costs of subsidizing natural gas as a transportation fuel. Each point (from left to right) indicates an increase of an additional 10 cents to the fuel subsidy that ranges from \$0.10 to \$1.50. The marginal abatement cost curve for this program is backward-bending. The backward bending marginal abatement cost curve is caused by tension between the substitution and income effects. NGV adoption decreases total emissions, but it comes with cheaper fuel. The less expensive fuel encourages the vehicle to be driven more intensively. As the operating costs of the vehicle decrease beyond a critical threshold, the decrease in emissions is overwhelmed by the increase in the behavioral response to low fuel costs. In the rebound effect literature this net increase is known as backfire (Druckman, Chitnis, Sorrell, & Jackson, 2011; Madlener & Alcott, 2009; Sorrell, 2009; Sorrell et al., 2009). The model suggests that at baseline parameter values backfire occurs at \$1.30 subsidy to natural gas fuel. This level for the subsidy implies a marginal abatement cost of \$4,602/ t CO_2. A rational social planner would not place a subsidy greater than this amount on natural gas fuels. We, therefore, consider this to be the upper bound on the relevant range for this type of subsidy.

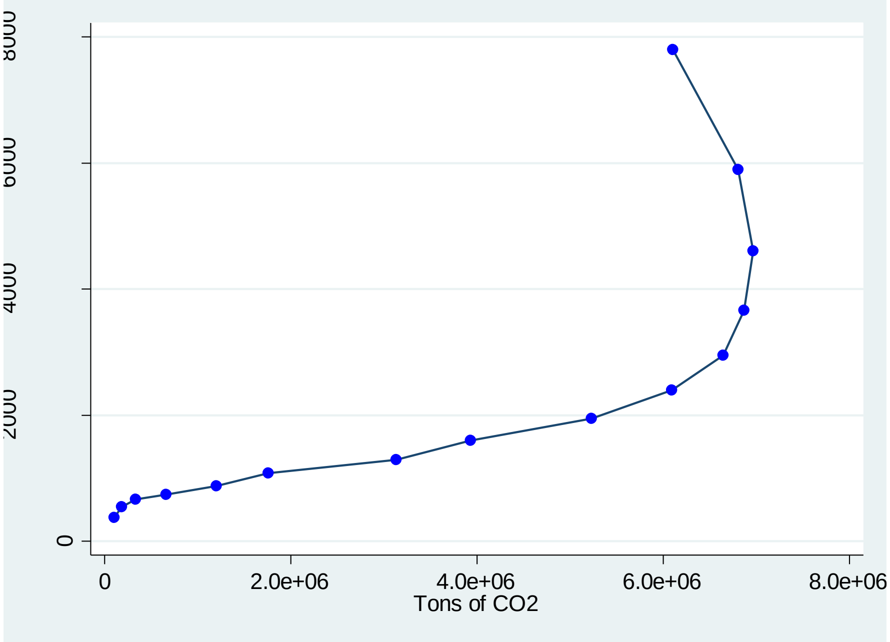

Figure 5-4. Marginal abatement cost of subsidizing natural gas as transportation fuel

Excluding the backward bending portion of the marginal abatement cost curve, it is positively sloped, as theory would predict. This program can also be considered the most efficient program of the three, because the lower bound on the range of marginal abatement costs is lower than the other two. The relevant range of marginal abatement costs is \$372/ ton CO_2 to \$4,602/ ton CO_2.

Even though the necessary condition for a socially optimal subsidy is satisfied over the relevant range (upward sloping marginal abatement cost curve), the sufficient condition may not be satisfied (marginal social damages with no abatement are greater than \$372/ ton CO_2). The socially optimal subsidy, if it exists, may still be an inefficient use of resources.

5.7. Cost Effectiveness of NGVs

The cost effectiveness of policies designed to decrease emissions by increasing NGV adoption can be compared to alternative abatement programs. Table 5.4 lists a few alternative abatement programs. These programs differ significantly from each other in terms of abatement technology.

Electric vehicles are the most comparable in terms of program attributes. The purchase of an electric vehicle is a similar decision to the purchase of an NGV. Electric vehicles, in contrast to NGVs, eliminate all tailpipe CO_2 emissions. This elimination of tailpipe emissions substantially decreases the marginal abatement cost estimates for this class of vehicles. Electric vehicles do not directly emit CO_2, but the generation of electricity to charge their batteries does. On the basis of these indirect emissions, Kesicki (2012) estimates the abatement costs of electric vehicles. Kok, Annema, and van Wee (2011) investigate the influence of methodological differences on the marginal abatement costs, and present a range of estimates from the literature. These estimates range between \$67/t CO_2 - \$507/t CO_2. Electric vehicles are therefore, a more cost effective abatement technology than natural gas. Estimates of the marginal abatement cost for electric vehicles range between \$67/t CO_2 to \$507/t CO_2. Additionally, the federal tax incentive for hybrid electric vehicles has a CO_2 abatement cost of \$177/ t CO_2.

In comparison to subsidizing natural gas, the federal government already has a program to subsidize the blending of ethanol with gasoline. This program expired in 2011. Metcalf (2008) estimated the implied CO_2 abatement costs of this program at \$1700 /t CO_2. This figure is most comparable to our estimates of the implied cost of abatement by encouraging the conversion of vehicles to natural gas.

Table 5-4. Comparison of Marginal Abatement Costs

Policy	Marginal Abatement Cost	Sources
CNG Vehicle subsidy	\$1,274/t CO_2 - \$5,750/t CO_2	This study
Gasoline tax	\$943/t CO_2 - \$1,465/t CO_2	This study
CNG fuel subsidy	\$372/t CO_2 - \$7,796/t CO_2	This study
Electric Vehicles	\$67/t CO_2 - \$507/t CO_2	Kok et al. (2011) Kesicki (2012)
Cash for Clunkers	\$92 /t CO_2 - \$365 /t CO_2	Li et al. (2013) Knittel (2009)
Waxman Markey bill –(Cap and Trade)	\$17/t CO_2 - \$22/t CO_2	Environmental Protection Agency (2009)
Ethanol Excise Tax Credit	\$1700 /t CO_2	Metcalf (2008)
Hybrid Vehicle Income Tax Credit	\$177 /t CO_2	Beresteanu & Li(2011)

The cash for clunkers program was a popular economic stimulus program during the financial crisis of 2008. This policy was designed to provide financial stimulus to the economy, while improving the fleet's fuel economy. The Cash for Clunkers (CfC) program is often described as being inefficient in terms of reducing emissions because the program probably just shifted demand from adjacent time periods to the program time frame (Li et al., 2013). This program, however, was more cost efficient at reducing emissions than any policy designed to increase NGV adoption considered in this paper. Knittel (2009) gives a rough estimate of the abatement costs of CO_2 under the CfC program. His entire range (\$237 /t CO_2 - \$365 /t CO_2) of marginal abatement costs for the cash for clunkers program is below the smallest marginal abatement cost for a NGV program (\$372 /t CO_2). Li et al.

(2013) improve on Knittel's (2009) methodology by counterfactually estimating sales of new vehicles without the CfC program using a difference in difference estimator. They find lower abatement costs for the CfC program (\$92/ t CO_2 - \$288/ t CO_2). These results highlight the cost ineffectiveness of programs designed to reduce CO_2 emissions by increasing NGV conversions.

In comparison to programs targeted at reducing emissions from the light-duty vehicle fleet are programs that focus on other aspects of CO_2 emissions. For example, cap and trade systems, such as that proposed in the American Clean Energy and Security Act. The EPA's analysis (2009) of the bill projected the allowance price of CO_2 to be \$17/tCO_2 -\$22 /t CO_2 in 2020.

5.8. Conclusion

At first appearances, the price decline in natural gas seems to indicate NGVs are a natural stopgap technology for abating CO_2 in the light-duty fleet. Natural gas appears to be a cheaper cleaner fuel than traditional gasoline. However, further investigations reveal that because of the chemical properties of natural gas, the emissions in the light-duty fleet are necessarily inelastic with respect to the NGV adoption rate. This inelastic behavior is expected for a stopgap abatement technology. The initial purchase price of a natural gas vehicle makes them infeasible, when compared to traditional fuel vehicles, for many consumers. The infeasibility of NGVS mutes the adoption rate, and compounds the inelastic emissions.

Programs designed to increase the adoption of natural gas vehicles can only address the infeasibility problem. The inelastic emissions represent a physical constraint for policy maker which is imposed by the laws of chemistry. Policymakers must also combat the perverse effects that their policies have on consumers. The positive effects associated with these policies often balance out with the unintended effects. The income effects associated with these policies are known as rebound effects. In the case of a tax (subsidy), these rebound effects will decrease (increase) emissions. Taxes on gasoline and subsidies on natural gas also encourage adoption of natural gas vehicles. This adoption represents a substitution effect which will increase (decrease) the emissions associated with the policy.

Combining the inelastic nature of the emissions with respect to adoption, and the tendency for the opposing effects of the income and substitution effects causes the apparent advantages of using NGVs as a stopgap abatement technology evaporate. Comparing these meager reductions in emissions to other abatement technologies serves to confirm that NGVs are an inefficient abatement technology. Other programs of CO_2 abatement are far more cost effective than encouraging consumers to purchase NGVs.

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CHAPTER 6

SUMMARY OF RESEARCH AND CONCLUSIONS

6.1. Summary of Research

The main question asked in this dissertation was “Does it make sense to use natural gas as a transportation fuel?” In the preceding chapters, I have investigated the relationship between the prices of oil and natural gas, the effect that liquefied natural gas (LNG) has had on the international trade of natural gas, calculated the percentage of the population that would find natural gas a financially advantageous fuel for their transportation needs, and the effect that subsidizing natural gas as a transportation fuel would have on the environment via CO_2 abatement. The main conclusion that we may draw from these studies is that natural gas is very rarely an economically advantageous transportation fuel.

In the first chapter of this dissertation the relationship between the price of oil and the price of natural gas was examined. This relationship is key to the use of natural gas as a transportation fuel because the main advantage that natural gas has over conventional fuels is that it is cheaper than those fuels. However, historically the price of natural gas and oil on an energy density basis has been more or less at parity. It has only been recently that these prices have “decoupled” for a protracted period of time. The main results of this chapter indicate that the price relationship of natural gas and oil entered a period of instability early in 2014. This instability indicates that natural gas may not retain its price advantage over conventional fuels. A loss of this price advantage would devastate the attractiveness of natural gas as a transportation fuel.

The next chapter of the dissertation looked at the use of LNG as a technology that reduces the transportation costs of natural gas. The natural gas industry has historically been segregated into various regional markets due to the fact that natural gas is difficult to transport because it is in a gaseous state. The ability to liquefy natural gas allows it to be transported in a similar manner to other fuels, primarily oil. This chapter showed that LNG has contributed to the de-regionalization of the natural gas market, and that the natural gas market is transforming into a truly global market. This transformation leads to a global price of natural gas that may contribute to the erosion of the price differences between natural gas and oil. This chapter only put forth one of many possible explanations for why the price of natural gas and oil may have become decoupled in recent years, since the price of natural gas is less dependent on the price stability of natural gas across different regions. However, one should be careful to note that the price of natural gas will not necessarily diverge from the price of oil because of separate global markets. The prices may yet converge again in the future due to the price of fuels being governed by their relative energy densities.

The third main chapter of this dissertation focused primarily on a micro-level behavior of consumers whereas the previous two chapters focused on the macro-forces that shape the natural gas market. In this chapter, the financial advantages of natural gas were compared to the main financial disadvantage of natural gas as a transportation fuel which is the cost of a vehicle that can run on natural gas. The model presented in this chapter could generalize to other alternative fuel vehicles. The analysis showed that natural gas vehicles at baseline parameter values are only financially advantageous for about 0.1% of the population, which is close to the currently observed rate of adoption. The low predicted adoption rate is driven primarily by the fact that the initial cost of the vehicle is not justified by the cost savings over the typical length of ownership of a vehicle. Therefore, this chapter answers the main question posed in this dissertation, namely that it rarely makes sense to use natural gas as a transportation fuel for most consumers.

A possible redeeming quality of natural gas (CH_4) comes from its benefit to the environment. It is a less carbon intensive fuel. Therefore, when combusted it creates less CO_2 pollution than more traditional transportation fuels like octane (C_8H_{18}). Therefore even though most individuals would not choose to drive a Compressed Natural Gas (CNG) vehicle due to its up-front expense, governments might want to incent individuals to purchase these vehicles to abate emissions of Greenhouse gases. The final chapter of this dissertation examined the costs of such a program utilizing the model from the previous chapter. Counterfactual policy regimes were simulated to estimate the marginal abatement of CO_2 via CNG adoption. Perverse incentives lead, in one policy regime, to a backwards-bending marginal abatement cost curve. In all cases, the marginal abatement costs due to CNG vehicle adoption is orders of magnitude greater than the marginal abatement costs associated with other programs designed to abate CO_2. These results suggest that governments that wish to subsidize CNG vehicles (either directly via subsidies or indirectly through tax incentives) on the grounds that it will reduce GHG emissions could find better investments than CNG vehicles to reduce pollution.

6.2. Limitations and Extensions

Some limitations of this dissertation include that the inconvenience premium that we use is a derived measure from a study done almost 20 years ago (Walls, 1996). This value is pivotal to obtain the results in both of the last two chapters. Although with an inflation adjusted value of this parameter the model does produce estimates that are consistent with observational data, this value is highly suspect in that is derived from an old estimate. For example, consumer preferences may have changed; infrastructure availability may be different from what it was in 1996; and technology may have advanced in ways that make CNG powered cars less inconvenient than in the past. The results of chapter 4 are the most sensitive to this parameter value. Deviations in this value may radically alter the main conclusion of this dissertation.

Additionally, the results of this dissertation critically depend on a fairly stable relationship between natural gas and oil. Although in chapter two the concept of the stability of different regimes was tested, a permanent break in the price of oil and natural gas where the two commodities are no longer co-integrated may cause large differences in the price differential between gasoline and natural gas. Historically the price differential has been fairly stable with relatively few regime changes, these co-integrating relationships may fade over time. However, I find this limitation to be fairly minor. The fact that natural gas and oil are close substitutes that differ mainly in physical state (gaseous and liquid respectively) and in energy density suggests that the co-integrating relationship will most likely persist into the future, even if the co-integrating relationship itself remains unstable switching between regimes as in chapter 2.

The conclusions that NGVs are not financially advantageous for most individuals and therefore not going to be adopted very much relies on an estimate of the joint distribution of vehicle miles travelled and fuel efficiency which comes essentially from a census of U.S. vehicles. This means that these results are limited to that population. In other countries this distribution may be different and there is no reason to believe that these results will generalize well to other locations. Furthermore, there is no reason to believe that the nature of this distribution will remain constant for the United States. The fleet may become more or less fuel efficient as preferences for vehicles change. Preferences may change for travel distances as commuters find their commute more or less onerous. The results of this dissertation therefore may not generalize to future time periods as well.

On a subtler note, this joint distribution was measured simply as a histogram. No distributional assumptions were made, and the distribution was not parameterized. Furthermore, the distribution was used as measured, on the assumption that the distribution was representative of the population of vehicles. The conclusions drawn therefore rely on the ability for this sample distribution to proxy for the population distribution.

Possible extensions of the research presented in this dissertation include deepening the understanding of the relationship between the price of oil and natural gas. Although much work has been done in this area the true nature of the co-integrating relationship remains contentious (Brown & Yücel, 2009; Neumann, 2009). Namely, does oil mediate the price of natural gas? The first main chapter of this dissertation sought to clarify whether the prices of these two commodities decoupled which are not well understood (Ramberg & Parsons, 2012). Specifically, in this chapter I check for the decoupling of these prices in the sense of whether a temporary or permanent regime change had occurred. The results of this study suggest that the so called decoupling of oil and natural gas may be temporary.

The research in chapter two may be extended to include variables of extreme weather events. Specifically, an understanding of how the trade of natural gas is affected by the extreme weather events in the importing and exporting countries differ. Such a study 0f the trade of natural gas would need to consider heterogeneity of countries weather stations, proximity of weather stations to population centers, and modelling potential asymmetric responses to extremes in heat and extremes in cold as natural gas could be used in the generation of heat and cold. I am not aware of any studies that examine the global pattern of trade of natural gas with respect to weather in such a detailed way.

One of the main drawbacks of the final two chapters is the reliance on the estimate of the inconvenience premium. A simple direct extension of this research could be performed by estimating the modern inconvenience premium via choice experiment methods (Train, 2009). Choice experiments can be used to estimate the marginal willingness to pay for different attributes of the choices. The marketing literature refers to these types of choice experiments as conjoint analysis. This type of analysis could be used to discover the negative willingness to pay for the disutility of various aspects of NGVs discussed in chapter 4. From these estimates one would be able to construct a measure the inconvenience premium that must be paid to operate an NGV.

Furthermore, in the last chapter the notion of pollution was abstracted to an ideal reaction of fuel. A straight forward application of the costs of the pollution abatement model in this chapter is to look at the emissions of other pollutants other than CO_2. CO_2 abatement may not be the ultimate goal of policy makers; rather reductions of airborne particulate matter may be the goal in promoting NGVs. In this case, the model in the final chapter could be modified to assess the cost effectiveness of other pollutants.

6.3. Concluding Remarks

This dissertation answers the question aimed mainly at policy makers. The question is whether or not policy makers should encourage the adoption of NGVs. The stakes for incorrectly assessing the future role of NGVs in the vehicle fleet could be substantial for policy makers. Incorrect decisions could result in substantial investment in infrastructure which would be underutilized in a low adoption scenario or not enough infrastructures to satisfy demand in a high adoption scenario. Likewise, incentives for consumers to purchase NGVs may be more or less generous than is necessary for goals to offset pollution at the rates that policy makers wish. Indeed, a thorough understanding of the adoption rates of NGVs is necessary to develop relevant and cost efficient policies towards NGVs.

The work embodied in this dissertation finds that the answer of whether or not policy makers should encourage the adoption of NGVs is no. The price advantage that natural gas has over conventional fuels is unstable and may not persist. NGV adoption is likely to be low without price supports. GHG abatement through NGVs is also very costly. For these reasons NGVs seem to be a poor investment for policy makers.

The dissertation fills a small gap in the academic literature as well. Specifically, each chapter fills in a different portion of the gap. The first two chapters look at the macro-market for natural gas to provide a backdrop for the next two chapters. The last two chapters specifically answer the main research question of this dissertation.

The first chapter looks into the relationship between the price of oil and natural gas. This relationship has been explored by various researchers attempting to determine if the price of oil and natural gas have become decoupled from each other. Various researchers have found that the price of natural gas is governed by the price of oil (Brown & Yücel, 2008; Mohammadi, 2011; Regnard & Zakoïan, 2011). However, Ramberg and Parsons (2012) show that much of the volatility between the long-run relationship between oil and natural gas can be accounted for by allowing for structural breaks in the cointegration relationship.

In a similar vein this chapter looks for structural breaks in the relationship between oil and natural gas by using a recursive Gregory-Hansen test (Gregory & Hansen, 1996).

The next chapter looks at the question of whether or not a single global market is emerging for natural gas, or if it will continue to be governed by the oil market. This study fits into the literature concerned with price integration between regional natural gas markets and the role that LNG has played in this integration (Brown & Yücel, 2009; Neumann, 2009; Neumann, Siliverstovs, & von Hirschhausen, 2006; Siliverstovs, L'Hégaret, Neumann, & von Hirschhausen, 2005). However, the key difference between the model presented in this chapter and this vein of literature is the novel use of the gravity model to determine the role that LNG plays in the global natrual gas market. This chapter concluded that natural gas markets are becoming less regional and that a separate global natural gas market is emerging (Jensen, 2004) due primarily to trade in LNG.

The next chapter answers the question of what types of adoption rates can be expected for NGV vehicles amongst consumers. This chapter contributes to the set of the literature that deals with the adoption of NGVs. Staub (2013) gives an overview of the use of natural gas in transportation. Deal (2012) studies the conditions under which firms would be willing to adopt NGVs. Walls (1996) values various attributes unique to natural gas. Matic (2005) looks at the opportunities to use natural gas as a transportation fuel. This chapter contributes to this literature by predicting the adoption rate of NGVs by consumers under different price conditions. The main findings of this chapter are that adoption rates are low and will likely continue to be low.

The final chapter examines the question of whether policy makers should encourage the adoption of NGVs to reduce GHG emissions. Specifically, this chapter narrowly focuses on CO_2 emissions. It is similar to other studies that estimate the marginal abatement cost of CO_2 under various abatement mechanisms. For example, Li, Linn, and Spiller (2013) and Knittel (2009) investigate the marginal abatement cost of cash for clunkers. Kok, Annema, and van Wee (2011) and Kesicki (2012) find the marginal abatement cost for electric vehicles. And Bernesteanu and Li (2011) look at hybrid electric vehicles. This chapter finds that in comparison to these studies NGVs have a marginal abatement cost that are orders of magnitude greater than these studies. This indicates that NGVs are an inefficeint CO_2 abatement technology.

In summary, NGVs may seem like a good idea on the surface. The market for natural gas appears to be becoming less dependent on oil to regulate its prices. Furthermore, the natural gas market is becoming The lower fuel costs make them attractive; plus, they are a lower emissions alternative fuel vehicle. However, these redeeming qualities do not make up for the larger upfront cost to purchase or convert the vehicle for most consumers. In order for policy makers to realize the benefits from lower emissions, large incentives are needed to encorage adoption. The large incentives required make natural gas an inefficient abatement technology. Therefore, natural gas vehicles will most likely continue to make up a small portion of the vehicle fleet.

6.4. References

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APPENDIX

APPENDIX

EXPENDITURE MINIMIZATION

This appendix lays out a consumer utility model from which the first order condition is equation 5 of the model in chapter 4.

The consumer must choose to minimize his expenditure subject to a utility target. This is equivalent to the consumer's utility maximization problem. However, due to the complicated nature of the budget constraint, I find that it is easier to illustrate that equation 5 of chapter 4 is a first order condition for this model by minimizing expenditure rather than maximizing utility.

The expenditure function that the consumer must minimize is:

$$(1-\varphi)\left(V_g^* + \sum_{t=0}^{T} p_g(1+r)^{-t}\frac{VMT}{MPG}\right) + \varphi\left(V_c^* + \sum_{t=0}^{T} p_c(1+r)^{-t}\frac{VMT}{MPG}\right), \tag{A-1}$$

where all of the variables are defined as they were in Chapter 4. The only new variable is φ. φ is defined as the share of gasoline vehicle use and is therefore bound on the unit interval. This expression gives the expenditure for the consumer. Therefore the consumer's expenditure minimization problem can be expressed as:

$$\begin{gathered}\min_{\varphi}(1-\varphi)\left(V_g^* + \sum_{t=0}^{T} p_g(1+r)^{-t}\frac{VMT}{MPG}\right) + \left(V_c^* + \sum_{t=0}^{T} p_c(1+r)^{-t}\frac{VMT}{MPG}\right) \\ s.t.\ \bar{u} = u(\varphi) \\ 0 \le \varphi \le 1\end{gathered} \tag{A-2}$$

The Kuhn –Tucker conditions for this expression are:

$$\left(V_g^* - V_c^*\right) + \sum_{t=0}^{T}\left(p_g - p_c\right)(1+r)^{-t}\frac{VMT}{MPG} - \lambda_0 u'(\varphi) - \lambda_1 + \lambda_2 = 0 \tag{A-3}$$

$$\bar{u} - u(\varphi) = 0$$

$$\varphi \ge 0, \lambda_1 \le 0, \varphi\lambda_1 = 0$$

$$1 - \varphi \ge 0, \lambda_2 \le 0, (1-\varphi)\lambda_2 = 0$$

The first of these conditions is equivalent to equation 5 from chapter 4. From these conditions it follows that

(A-4) $$\varphi = 0 \Rightarrow \left(V_g^* - V_c^*\right) + \sum_{t=0}^{T}\left(p_g - p_c\right)(1+r)^{-t}\frac{VMT}{MPG} - \lambda_0 u'(\varphi) < 0$$

And

(A-5) $$\varphi = 1 \Rightarrow \left(V_g^* - V_c^*\right) + \sum_{t=0}^{T}\left(p_g - p_c\right)(1+r)^{-t}\frac{VMT}{MPG} - \lambda_0 u'(\varphi) > 0$$

Since no restrictions were placed on $u(\varphi)$, the value $-\lambda_0 u'(\varphi)$ can represent the inconvenience premium discussed in Chapter 4, which as can be seen here is the marginal disutility associated with a natural gas vehicle, i.e. $u'(\varphi) < 0$. Furthermore, the case where φ^* is an interior solution would correspond to a bi-fuel option. We ignore this case, because bi-fuel vehicles were not present in our data set. We recognize, however, that this case may be of interest to other researchers. Therefore ignoring interior solutions, the optimal value for φ^* is given by the following expression.

(A-6) $$\varphi^* = \begin{cases} 1, & \text{if } \left(V_g^* - V_c^*\right) + \sum_{t=0}^{T}\left(p_g - p_c\right)(1+r)^{-t}\frac{VMT}{MPG} - \lambda_0 u'(\varphi) > 0 \\ 0, & \text{otherwise} \end{cases}$$

This final optimal value expression is equivalent to equation 6 of chapter 5.

CURRICULUM VITAE

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Education

Ph.D. Economics, Utah State University Expected Fall 2016
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Research Fields

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Awards

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Teaching Experience

Lecturer- Analytical Methods in Economics Fall 2013 - Fall 2014

Course Description: Applications of mathematics to agricultural, resource, environmental, and regional economics. Reviews algebraic, single-variable calculus (differentiation and integration); multivariate calculus and optimization; and linear algebra and applications to economics.

Teaching Assistant- To Professor Man-Keun Kim 2011

Course Description: Introduction to economic principles as they apply to the use of natural resources and as they affect environmental quality. Analysis of changes in natural resource use and environmental quality, in order to determine the economic impact upon rural communities and regions.

Research Experience

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Publications

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Barnes, R., Bosworth, R. Energy Economics (Forthcoming)

"Connecting Sensory Quality Characteristics and Local Designations to Willingness to Pay for Cheese at the Retail Level*"*
Barnes, R., Bosworth, R., Bailey, D., Curtis, K.
(*International Food and Agribusiness Management Review VOL.. 17 No. 3*)

Manuscripts and Working Papers

“Under What Price Conditions Do CNG-Powered Passenger Vehicles Make Economic Sense?”
Barnes, R., Bosworth, R. Heaslip, K., Soltani-Sobh, A., & Prestrud, C.

“Heterogeneous Rebound Effects Due to Locational Choices and Distortionary Incentives from Employers”
Barnes, R., Caplan, A., Bosworth, R.

“The Effects and Viability of Incentives to Encourage NGV Adoption on GHG Emissions”
Barnes, R., Bosworth, R., Heaslip, K.

“The Effects of NGV Adoption on Fleet VMT”
Sobh, A.S., Heaslip, K., Bosworth, R., and Barnes, R.

Other Publications

Barnes, R., Bosworth, R., Heaslip, K., and Sobh, A.S., “Effects of Alternative Fuel Infrastructure on Key Transportation Economic Metrics”. Interim Research Report to The State of Washington, Washington State Department of Transportation, 2013

Conferences and Invited Presentations

“Under What Price Conditions Do CNG-Powered Passenger Vehicles Make Economic Sense?”
Barnes, R., Bosworth, R. Heaslip, K., Soltani-Sobh, A., &Prestrud, C.
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“Under What Price Conditions Do CNG-Powered Passenger Vehicles Make Economic Sense?”
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Western Social Science Association 2014 Annual Conference,
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