Working Towards a Future on Alternative Fuels: The Role of the Automotive Industry

by

Cuicui Chen

Bachelor, Environmental Engineering, Tsinghua University (2010)

Submitted to the Engineering Systems Division
in partial fulfillment of the requirements for the degree of

Master of Science in Technology and Policy

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2012

Author . . . .
Engineering Systems Division
May 11, 2012

Certified by . . . .
Jerry A. Hausman
John and Jennie S. MacDonald Professor, Department of Economics
Thesis Supervisor

Certified by . . . .
Sergey Paltsev
Principal Research Scientist, MIT Joint Program on the Science and Policy of Global Change
Thesis Supervisor

Accepted by . . . .
Joel P. Clark
Professor of Materials Systems and Engineering Systems
Acting Director, Technology and Policy Program

Working Towards a Future on Alternative Fuels: The Role of the Automotive Industry

by

Cuicui Chen

Submitted to the Engineering Systems Division
on May 11, 2012, in partial fulfillment of the
requirements for the degree of
Master of Science in Technology and Policy

Abstract

Complementarity of vehicles and fuels has posed significant barrier for increasing the use of alternative fuels in place of traditional ones. An initial positive number of either alternative fuel vehicle (AFV) users or alternative fueling stations are needed for the diffusion of both. This research examines the incentive of the automotive industry, in particular automobile companies focusing on AFVs, to create a positive number of AFV users by demand-side promotion which increases environmental awareness of consumers, and a positive number of alternative fueling stations by supply-side promotion including funding part of the upfront or operating costs of alternative fueling stations. I first build a static microeconomic model of the vehicle and fuel market and find that the demand-side promotion is helpful in creating a positive number of AFVs and alternative fueling stations under a wider range of situations than is supply-side promotion. AFV companies are found to have incentive to do these promotions given affordable promotion costs. Furthermore, using data on vehicle purchase and characteristics of U.S. consumer units from 2005 to 2010 merged with information on state-level fuel prices, fueling stations, and designation of clean cities, I find that the addition of 1 clean city or 100 refueling stations of E85, an alternative fuel used in flex-fuel vehicles, is equivalent to a reduction of $0.04 or $0.19 in the E85 price on the effect of increasing flex-fuel vehicle choice probability respectively. Both the theoretical and empirical results suggest that AFV companies evaluate business opportunities in supply- and demand-side promotions, and that policy makers consider potential contributions of the market to bringing about a future on alternative fuels.

Thesis Supervisor: Jerry A. Hausman
Title: John and Jennie S. MacDonald Professor, Department of Economics

Thesis Supervisor: Sergey Paltsev
Title: Principal Research Scientist, MIT Joint Program on the Science and Policy of Global Change

Acknowledgments

I am first and foremost grateful to my advisors, Jerry Hausman and Sergey Paltsev, for their tremendous help in making this work possible. Jerry's insightfulness and dedication have greatly impressed me. Not only has Jerry provided extremely useful suggestions on this work, especially on the empirical analysis, but he has also inspired me to strive for excellence in whatever I pursue. It is Sergey who first exposed me to the importance of refueling infrastructure in order for alternative fuel technologies to diffuse. I am deeply indebted to him for many of the policy insights in this research, and numerous helpful advice on better communicating this research, from which my future research will hugely benefit.

I would also like to thank my classmates, colleagues and other professors who would listen to my ideas in the process of this work, no matter how unorganized they were, and provide truly useful suggestions on various occasions. In particular, Arthur Gueneau, Claudia Octaviano and Vivek Sakhrani in the student lunch of the MIT Joint Program on the Science and Policy of Global Change; Ross Collins, Devin Helfrich, and Cody Sumter in the ESD.80 Seminar in Technology and Policy Research; and Bill Clark at the Harvard Kennedy School spring reception for PhD students. I would also like to extend thanks to Rob Stavins, who would provide impetus for me to accelerate the pace of this work through the course Seminar on Environmental Economics and Policy at Harvard. Last but not least, I would like to thank my friend Ruize Xu, who was also writing his thesis, for the peer pressure that he unconsciously gave me throughout my thesis writing.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Increasing the use of alternative fuels in place of conventional fuels such as gasoline and diesel is a potential way to enhance energy independence and reduce air pollution (U.S Department of Energy, 2011a). These alternative fuels include ethanol, biodiesel, compressed natural gas, liquified natural gas, electricity, hydrogen, etc. Due to complementarity of vehicles and fuels, reaching this goal requires both a widespread adoption of alternative fuel vehicles (AFVs) and easy accessibility of refueling infrastructure for alternative fuels.

During the diffusion process of AFVs and alternative fueling stations, indirect network effects are expected to play a key role. Pioneered by Katz and Shapiro (1985), indirect network effects arise when the utility that a consumer derives from consumption of a good increases with the number of other consumers consuming the same good because the latter correlates positively with the availability of the complement of this good. Hence, given the symmetry of complimentarity, indirect network effects can potentially contribute to the joint diffusion of both goods. In the context of AFVs and alternative fueling stations, this implies that all else equal, the market share of AFVs[1] will likely increase as the density of alternative fueling

[1] The market share of AFVs is defined in this research as the percentage of AFVs used with the corresponding alternative fuel in the pool of gasoline vehicles and these AFVs. While the term "used with the corresponding alternative fuel" is immaterial for single-fuel AFVs, which exclusively use one alternative fuel, it is important to apply this term to dual-fuel AFVs, which can use both gasoline and one alternative fuel. This is because it is the market share of dual-fuel AFVs used with the corresponding alternative fuel that is relevant to the goal of increasing alternative fuel use. In

stations increases, and vice versa.

For the diffusion process to begin, a positive number of either AFVs or alternative fueling stations (or both) is needed. Some literature recognizes the difficulty to start the diffusion without significant change in fueling infrastructure, such as Di Pascoli *et al.* (2001), Parry *et al.* (2008), and Kuby and Lim (2007). Other literature focuses on the other direction, where a positive number of AFVs helps spawn alternative fueling stations, such as Corts (2009). The situation where the market shares of both AFVs and alternative fueling stations are negligible is usually referred to as a chicken-and-egg problem (Romm, 2006), where neither side of the market has had incentive to take unilateral action and the diffusion process has been unable to begin.

There are several factors that can potentially affect the initial number of AFVs and alternative fueling stations. For a consumer, she may consider factors such as the vehicle price, the fuel price, her environmental awareness, and the expected availability of refueling infrastructure which depends on her expectation of the fuel provider's decision on how many alternative fueling stations to set up. For a fuel provider, she may consider factors such as the upfront investment cost of an alternative fueling station, its operating cost, and the expected number of AFV owners which depends on her expectation of consumers' choice between AFVs and traditional vehicles.

The government can influence these factors in order to create incentive for consumers to buy AFVs or fuel providers to set up alternative fueling stations in the presence of the chicken-and-egg problem arises. For example, in the case of hydrogen vehicles and fuels, subsidizing the upfront infrastructure cost of alternative fueling stations has been examined by researchers (Melaina, 2005; Melaina and Ross, 2000), advocated by industry (Gross *et al.*, 2007; McCormick, 2003), and supported by government agencies (California Environmental Protection Agency, 2005; Florida Department of Environmental Protection, 2007). On the other hand, the government can also provide tax credit to AFV buyers in order to create a positive market share

reality, dual-fuel AFVs can be used mostly with gasoline instead of the corresponding alternative fuel. For example, the use of E85 fuel, or gasoline which contains 85% volume share of ethanol, is negligible, despite the fact that the market share of flex-fuel vehicles (FFVs), which can run on up to 85% volume share of ethanol, including gasoline, is not (Figure C-1).

of AFVs in the first place. U.S. Department of Energy (2011b) provides a complete list of related federal and state incentives and laws.

What is more interesting, however, is the question whether the automotive industry has a role to play in solving the chicken-and-egg problem. First, this is where indirect network effects embodied in the car and fuel market can be further explored than in the government intervention described above. This is because the potential profits of AFV companies will also be entangled in the indirect network effects, in addition to those of consumers and fuel providers only as is the case in government intervention. Intuitively, car companies, especially those whose business focuses on AFVs,[2] may have incentive to increase the sale of AFVs by means such as increasing consumers' environmental awareness through advertisement, if the cost of doing so is expected to be outweighed by the benefit from the increased AFV sale as a response to the increase in the number of alternative fueling stations thanks to the initial increase in the market share of AFVs. Conversely, AFV companies may also have private interest to increase the number of alternative fueling stations by means such as sponsoring upfront investment of alternative fueling stations, if the cost of doing so is expected to be outweighed by the benefit from the increased AFV sale as a response to the increase in the number of alternative fueling stations.[3] Second, studying the incentive problem of AFV companies in the context of indirect network effects is meaningful also because this can potentially provide an additional policy option for the government to consider in order to increase the use of alternative fuels in place of traditional ones. If AFV companies do have incentive to make possible a positive number of either AFV owners or alternative fueling stations (or both) at the first place, then this option can be compared with government intervention, which is traditionally used in an attempt to solve the chicken-and-egg problem, in terms of aggregate benefit and cost, cost-effectiveness, and welfare effects. As a result, the government will likely be able to make a better decision on how to increase the use

[2] Car companies who produce both AFVs and traditional vehicles face a tradeoff between producing AFVs and traditional vehicles, and thus their incentive problem may be more complicated. This research mainly focused on car companies whose business focuses on AFVs.

[3] In fact, both GM and Ford have helped install hundreds of E85 fueling stations through partnerships with fuel providers (Thomas, 2007).

of alternative fuels in place of traditional ones.

This research aims at assessing, both theoretically and empirically, the potential role of the automotive industry, especially those who focus on AFVs, in helping increase the consumption of alternative fuels in place of gasoline in the context of indirect network effects embodied in the vehicle and fuel market. Specifically, how does demand-side promotion, such as increasing the environmental awareness of consumers, or supply-side promotion, such as funding part of the upfront investment or operating cost of alternative fueling stations, affect the market share of AFVs? Do AFV companies have incentive to do these promotions? Furthermore, do we observe empirically that consumer awareness or refueling availability increases the probability of consumers choosing AFVs?

There have been few studies on microeconomics of the fuel and car market in the context of indirect network effects. To my best knowledge, the only relevant study is Greaker and Heggedal (2010), which models the interaction between consumers and fuel providers as a simultaneous-move game to study the possibility of a lock-in situation for hydrogen vehicles. They find that several market equilibria may exist due to indirect network effects, of which one is likely to Pareto dominate the others, hence the possibility of a lock-in situation. However, if either the upfront cost of a hydrogen fueling station is too high or the hydrogen car technology is in its infancy, the only market equilibrium is the current traditional vehicle technology equilibrium. Although in their model the car producers earn zero profit due to marginal cost pricing and hence the incentive of car producers cannot be studied by this model, future research on the incentive of hydrogen car producers to sponsor hydrogen filling stations is suggested.

Several empirical studies have examined the indirect network effects in the fuel and car market. Corts (2009) studies the effectiveness of the government acquisition mandate which is aimed at increasing the incentive for the infrastructure providers to build infrastructure in response to the increased ownership of FFVs in government fleets in Minnesota. He finds that the policy does lead to an increase in retail E85 stations. However, the paper does not examine how effective the increase at E85 stations is in stimulating private ownership of AFVs, which is the one of the aims of the empirical part in this research. Most of the other related empirical studies look at how AFV choice depends on car characteristics, consumer demographics, and fueling availability. For example, Bunch *et al.* (1993) uses nested multinomial logit (NMNL) models and binomial logit models based on data from the 1991 California survey which asked for stated preference for AFVs given choice variables including hypothetical refueling availability and consumer awareness. Brownstone *et al.* (2000) uses data from the 1993-1994 California surveys which asked for stated preference and revealed preference for AFVs given choice variables including hypothetical refueling availability, and proposes a joint estimation method. Achitnicht *et al.* (2012) uses standard multinomial logit (MNL) models based on the stated-preference data gathered Germany from 2007 to 2008, also including choice variables such as hypothetical refueling availability and consumer awareness.

In this research, I seek to contribute to the existing literature on the indirect network effects of the car and fuel market in two ways. First, I advance the microeconomic model of the car and fuel market in the context of indirect network effects by exploring the dynamics of the equilibria of the simultaneous-move game involving consumers and fuel providers, embedding the incentive problems of the AFV manufacturers, and expanding the above analysis to dual-fuel AFVs instead of focusing merely on single-fuel AFVs. Second, I explore the use of revealed preference data (as opposed to stated preference data) and realized fueling availability data (as opposed to responses to hypothetical choices) in empirical studies of the indirect network effects of the car and fuel market, in particular on the effects of fueling availability or consumer awareness campaigns on the choice probability of AFVs. A dataset comprising of public use micro data in Consumer Expenditure Surveys, designation of clean city coalitions, and numbers and locations of alternative fueling stations is complied and used in a multinomial logit model.

This research provides both private and public policy insights for stakeholders. For AFV companies, this research helps discover their potential role and profitability in increasing the consumption share of alternative fuels in the context of indirect network effects. Not only will the theoretical analysis provide intuitions of the behavior of consumers and fuel providers and the potential profitability of demand- or supply-side promotion, but the empirical analysis also informs the car companies of the magnitude of the effects of fueling availability or consumer awareness campaigns on AFV choice probability so that they can better assess the benefits of supply- or demand-side promotion. For public policy makers, this research suggests a new perspective of looking for solutions to the chicken-and-egg problem. This option can be analyzed in terms of its strengths and weaknesses relative to other policy options, which will improve decision making on how to best increase the use of alternative fuels in place of traditional ones.

The paper proceeds as follows. Chapter Two presents the microeconomic models of the simultaneous-move game between consumers and fuel providers, looking at single-fuel and dual-fuel AFVs respectively. Analysis of the Nash equilibria and their dynamics as a result of demand- or supply-side promotion is presented. Chapter Three examines the incentive of the AFV companies in doing demand- or supply-side promotion by parameterizing the theoretical models described in Chapter Two for selected AFVs. Chapter Four describes the empirical framework, the data, and results and discussion based on the empirical model. Chapter Five concludes and provides future research questions.

Chapter 2

The Model: Behavior of Consumers and Fuel Providers

This chapter describes the theoretical model of the behavior of consumers and fuel providers in the context of indirect network effects embodied in the vehicle and fuel market. A single-fuel AFV simultaneous-move game is introduced first, where consumers choose between the gasoline vehicle and the AFV, and fuel providers decide whether to set up alternative fueling stations. The AFV in this game is assumed to be able to run only on the corresponding alternative fuel. Variables that the AFV companies can change are built in the model, including the targeted percentage increase in environmental awareness of consumers on the demand side, the percentage of upfront investment funded and fueling cost funded of alternative fueling stations on the supply side. Dynamics of the Nash equilibria due to changes in these variables are examined. Similar analysis of a dual-fuel AFV simultaneous-move game follows, in which the AFV is assumed to be able to run on both the alternative fuel and gasoline. For both games, I assume competitiveness for the markets of gasoline vehicles, gasoline, and alternative fuels.

It should be noted that analyses of the Nash equilibria and the dynamics of them in this chapter have not yet involved AFV companies. The analyses are based on the games involving only consumers and fuel providers. As a result, the variables that AFV companies can change, such as the targeted percentage increase in environmental awareness of consumers and the percentage of upfront investment funded of alternative fueling stations, are not restricted to the jurisdiction of AFV companies; they can also be changed by the government. In Chapter Three, however, the focus will be on the question if AFV companies, instead of the government, have incentive to change these variables in their own interests.

2.1 The Single-Fuel AFV Game

In this game, fuel providers decide whether to set up alternative fueling stations, and at the same time consumers decide whether to purchase a gasoline vehicle or some single-fuel AFV. The equilibrium outcome is made up of the density of alternative fueling stations and the AFV market share.

The model setup is based on Greaker and Heggedal (2010), which uses the Salop circle (Salop, 1979) to model the entry decision of fuel providers, and the vertical differentiation model (Shaked and Sutton, 1982) to model consumer choice. Let q^r denote the AFV market share, and q^g the market share of gasoline vehicles, with $q^r + q^g = 1$. Assume that consumers live in a city center and commute by driving along a circle of unit circumference about the city center. Each consumer is assumed to drive the same mileage throughout the lifetime of a vehicle, and let the fuel prices, p^r and p^g for AFVs and gasoline vehicles respectively, be lifetime fuel costs. Fueling stations are distributed evenly along the circle. The income of fuel stations from providing fueling services is assumed to be incurred in a single period.

2.1.1 Fuel Providers

Alternative Fueling Stations

Let n^r denote the number of alternative fueling stations on the circle. Since the circle is of unit circumference, such that n^r can be interpreted as the density of alternative fueling stations. The alternative fueling station α sets its alternative fuel price p^r_α. The distance between alternative stations is $\frac{1}{n^r}$, as the alternative fueling stations are assumed to be distributed evenly along the circle.

A consumer located at a distance $x \in [0, \frac{1}{n^r}]$ from the alternative fueling station α is indifferent between fueling her AFV at this station and at this station's closest neighbor β, which sells the alternative fuel for the price p^r_β, if:

$$p^r_\alpha + t^r x = p^r_\beta + t^r(\frac{1}{n^r} - x) \tag{2.1}$$

where t^r is the per distance cost of driving to the fueling station along the circle, which may include both a fuel cost and a time cost.[1].

Solving (2.1) for x gives the cut-off location of a consumer indifferent between fueling at fueling station α and at its closest neighbor β. Considering the symmetry of a circle and given fuel provider α's expectation for a uniform distribution of consumers along the circle, the demand facing the alternative fueling station α is:

$$D_\alpha = 2xq^r = \frac{-p^r_\alpha + p^r_\beta + t^r/n^r}{t^r} q^r \tag{2.2}$$

Suppose the gross upfront cost for alternative fueling stations, f^r, and the cost of providing lifetime fueling for an AFV, c^r, are uniform across stations. Let ϕ_1 denote the percentage of upfront investment funded of alternative fueling stations by either the government or the AFV company, and ϕ_2 the percentage of fueling cost funded, both of which are assumed to be uniform across stations as well. The alternative fueling station α's problem is thus:

$$\max_{p^r_\alpha} [(p^r_\alpha - (1 - \phi_2)c^r) D_\alpha - (1 - \phi_1) f^r] \tag{2.3}$$

This is a convex function in p^r_α, so the best response can be solved from the following first order condition:

$$\frac{-p^r_\alpha + p^r_\beta + t^r/n^r}{t^r} q^r = [p^r_\alpha - (1 - \phi_2)c^r] \frac{q^r}{t^r} \tag{2.4}$$

[1]Driving from the center onto the circle is assumed to have zero costs. The fuel cost of driving to the fueling station is considered negligible relative to the lifetime fuel cost p^r

By symmetry, $p^r_\alpha = p^r_\beta$. Let $p^r = p^r_\alpha = p^r_\beta$. The price of the alternative fuel, which is the same for all alternative fueling stations, is thus:

$$p^r = p^r_\alpha = (1-\phi_2)c^r + t^r/n^r \tag{2.5}$$

Note that this price is dependent on the density of alternative fueling stations n^r.

Based on the optimal price of the alternative fuel, the profit that an alternative fueling station makes is:

$$\pi^r = \pi^r_\alpha = [p^r - (1-\phi_2)c^r]D_\alpha - (1-\phi_1)f^r = \frac{t^r q^r}{n^{r2}} - (1-\phi_1)f^r \tag{2.6}$$

Free entry drives the profit to zero. By setting π^r in equation (2.6) to zero, the density of alternative fueling stations is obtained:

$$n^r = \sqrt{\frac{t^r q^r}{(1-\phi_1)f^r}} \tag{2.7}$$

Gasoline Stations

Assume that gasoline stations entered the market when AFVs were not available yet, which means that $q^g = 1$. Also assume that the number of gasoline stations has not shrunk since then. By substituting t^g, q^g, f^g, ϕ_1 for their alternative fueling counterparts in (2.7) and setting $\phi_1 = 0$ and $q^g = 1$, the density of gasoline stations along the circle is:

$$n^g = \sqrt{\frac{t^g}{f^g}} \tag{2.8}$$

And the optimal gasoline price is:

$$p^g = c^g + t^g/n^g \tag{2.9}$$

2.1.2 Consumers

Let ω^g and ω^r denote the prices of gasoline vehicles and AFVs respectively. The expected distance to the nearest fueling station is $\frac{1}{4n^j}, j = r, g$. Indeed, the possible distance to the nearest fueling station ranges from zero when the consumer is at the fueling station, to half the inter-station distance $\frac{1}{n^j}, j = r, g$, when she is in the midpoint between two neighboring stations. The distance to the nearest fueling station cannot exceed $\frac{1}{2n^j}$, because a consumer at a distance from the station α of more than this distance must have a neighboring station β within this distance, and thus the nearest station is β with a distance not exceeding $\frac{1}{2n^j}$. With the assumption that consumers are uniformly distributed, the expected distance to the nearest fueling station is thus $\frac{1}{4n^j}, j = r, g$.

The expected utility of the consumer i buying a gasoline vehicle (and hence using only gasoline) is:

$$EU_i^g = \lambda_i \Gamma^g - \frac{1}{4n^g} t^g - \omega^g - p^g \tag{2.10}$$

where $\lambda_i \Gamma^g$ is the gross utility from a gasoline car. λ_i represents consumer heterogeneity in valuing vehicles regardless of fuel choice, which is independent of whether the vehicle is a gasoline vehicle or an AFV and uniformly distributed on $[m, m+1]$ with $m > 0$. Γ^g represents the base value of a gasoline vehicle.

The expected utility of the consumer i buying an AFV is:[2]

$$EU_i^r = \lambda_i \Gamma^r - \gamma \frac{t^r}{4n^r} - \omega^r - p^r + \lambda_i Z \tag{2.11}$$

where $\lambda_i \Gamma^r$ is the gross utility of an AFV, and γ is a markup factor reflecting the difference in fueling frequency between alternative fuels and gasoline. Fueling frequency is determined by both fuel economy and the size of fuel storage. For example, an FFV will be fueled more often than a gasoline vehicle due to lower energy content in ethanol provided that they have the same size of fuel storage, in which case the markup factor is greater than 1. The frequency of 'fueling' an EV is also different from that of fueling a gasoline due to differences in both fuel economy and the size of fuel storage. $\lambda_i Z$ is the additional utility that consumer i derives from using alternative fuels relative to gasoline, which can attributed to the warm glow effect proposed

[2] I assume that $n^r > 0$ for now in order that the expected utility is well-defined. I will allow $n^r = 0$ when discussing the dynamics of the equilibria as a result of the supply- and demand-side promotion in Section 2.1.4.

by Andreoni (1990), or the increase in utility due to the "good" feeling of having done something good to others. The warm-glow utility of using the renewable fuel vary across consumers by λ_i, which is the same coefficient for producing the gross utility of a vehicle. It is plausible that all else equal, the more one values owning and driving AFVs, the more likely that one will care about the 'green' advantage of AFVs over gasoline vehicles, which is mainly embodied in the use of a green fuel instead of gasoline.

The consumer's problem is to choose between the gasoline vehicle and the AFV by comparing expected utilities formulated in (2.10) and (2.11). She will be indifferent between these two options if:

$$EU_i^r = EU_i^g \tag{2.12}$$

which yields the cut-off value of λ_i:

$$\lambda^{g,r} = \frac{\omega^r + p^r + \gamma\frac{t^r}{4n^r} - \omega^g - p^g - \frac{t^g}{4n^g}}{Z + \Gamma^r - \Gamma^g} \tag{2.13}$$

In order for $\lambda^{g,r}$ to be non-negative, I assume that $Z + \Gamma^r > \Gamma^g$. This is plausible because for a given consumer, all else equal, she will probably get higher utility from AFVs than from gasoline vehicles due to the warm glow effect. Furthermore, I assume that $\omega^r + p^r + \gamma\frac{t^r}{4n^r} - \omega^g - p^g - \frac{t^g}{4n^g} > m(Z + \Gamma^r - \Gamma^g)$, so that there will always be a positive demand for gasoline vehicles. Finally, in order to ensure a full market coverage, I assume that $m\Gamma^g > \frac{t^g}{4n^g} + \omega^g - p^g$ so that every consumer buys a vehicle. The demand for AFVs can then be written as:

$$q^r = \begin{cases} 0, & \text{if } \lambda^{g,r} \geq m+1 \\ m + 1 - \lambda^{g,r}, & \text{if } m < \lambda^{g,r} < m+1 \end{cases} \tag{2.14}$$

It should be noted that environmental awareness of consumers is treated in a highly stylized way throughout this research. In this single-fuel AFV model, environmental awareness of consumers is represented by $Z + \Gamma^r - \Gamma^g$, which is the value base of alternative fuels and vehicles relative to their traditional counterparts. Demand-side promotion to be talked about in the following dynamics analysis is assumed to be able to affect this term only. More specifically, if AFV companies target at 5% increase in this term when designing their demand-side promotion, such as special emphasis of the environmental benefits of using an AFV and using it with the corresponding alternative fuel by a salesperson to a potential buyer, this term will increase by 5%. Demand-side promotion is assumed to have no effect on the scale parameter, λ_i, which is assumed to be innate for each consumer. In the dual-fuel AFV model, on the other hand, the key parameter of interest is the environmental awareness of consumers for the fuel (as opposed to that for both the fuel and the vehicle as in the single-fuel AFV model described above), which is represented by Z, the value base of the alternative fuel relative to its traditional counterpart.[3]

2.1.3 Nash Equilibria

The Nash equilibria are of the form (n^r, q^r).

Proposition 1. *In a single-fuel AFV market, there will be three sets of equilibria:*

- *When the ratio of the cost premium of the AFV over its benefit premium relative to the gasoline vehicle is high, there will be a unique Nash equilibrium with a zero density of alternative fueling stations and a zero market share of AFVs.*

- *When the ratio is not high, a unique zero Nash equilibrium will still be likely, particularly when the upfront and operating costs of an alternative fueling station are high.*

- *When the ratio is not high, and the upfront and operating costs of an alternative fueling station are not high, three Nash equilibria will be likely, of which one is the zero equilibrium, one is the low-realization equilibrium, and the other is the high-realization equilibrium. The high-realization equilibrium is the most stable.*

[3] In reality, however, environmental awareness of consumers is hard to define. Furthermore, it is difficult to measure environmental awareness of consumers. Future research, in particular empirical work, needs to better address the definition and measurement of environmental awareness of consumers for either AFVs or the alternative fuel.

Proof. First observe that $(0,0)$ is always a Nash equilibrium under all three cases, because not buying an AFV is the best response to there being no fueling infrastructure, and vice versa.

Define:

$$\bar{\lambda}^{g,r} = \frac{\omega^r + p^r - \omega^g - p^g - \frac{t^g}{4n^g}}{Z + \Gamma^r - \Gamma^g} \tag{2.15}$$

This is the ratio of the cost premium of the AFV over its benefit premium.

Suppose $\bar{\lambda}^{g,r}$ is high such that $\bar{\lambda}^{g,r} \geq m+1$. Assume by way of contradiction that there is another Nash equilibrium which is not $(0,0)$. Having any positive number of alternative fueling stations, that is, adding a positive $\gamma\frac{t^r}{4n^r}$ term to the numerator of (2.15), will only result in a $\lambda^{r,g}$ even greater than $m+1$. By (2.12), no consumer will buy AFV, because the cut-off value exceeds the upper bound of its support $[m, m+1]$. Then existing alternative fuel stations will quit the market, reverting to the zero equilibrium (the *Case I zero* equilibrium). Hence uniqueness.

Suppose $\bar{\lambda}^{r,g}$ is not high, such that:

$$m < \bar{\lambda}^{g,r} < m+1 \tag{2.16}$$

Assume by way of contradiction that there exists a solution other than the zero equilibrium. Then $n^r \neq 0$, and (2.13) is hence well defined. Any positive market share of fueling stations which makes $\lambda^{g,r}$ exceed the upper bound $m+1$ cannot exist in a Nash equilibrium. Otherwise, by inserting (2.5), (2.7), (2.8), (2.9), and (2.13) into (2.14), I have:

$$q^r = m + 1 - \frac{\Delta\omega + \Delta c + \frac{4+\gamma}{4}\sqrt{\frac{t^r(1-\phi_1)f^r}{q^r}} - \frac{5}{4}\sqrt{t^g f^g} - \phi_2 c^r}{\Delta\Gamma + Z} \tag{2.17}$$

where $\Delta\omega = \omega^r - \omega^g$, $\Delta c = c^r - c^g$,and $\Delta\Gamma = \Gamma^r - \Gamma^g$.

In order to solve (2.17) for q^r, define:

$$a = -(m+1) + \frac{\Delta\omega + \Delta c - \phi_2 c^r - \frac{5}{4}\sqrt{t^g f^g}}{\Delta\Gamma + Z} \tag{2.18}$$

$$b = \frac{(4+\gamma)\sqrt{(1-\phi_1)t^r f^r}}{4(\Delta\Gamma + Z)} \tag{2.19}$$

$$\Theta = \frac{b^2}{4} + \frac{a^3}{27} \tag{2.20}$$

If $\Theta > 0$, there is one unique real root, which turns out to duplicate the zero equilibrium (the *Case II zero* equilibrium) (refer to Appendix C of Greaker and Heggedal (2010)). (2.20) suggests that high upfront infrastructure costs and high operating costs are likely to make Θ larger than 0, leading to the unique zero equilibrium.

Now, if $\Theta < 0$,[4] there will be three real roots, of which one turns out to duplicate the zero equilibrium. The other two real roots, however, correspond to two positive equilibria (refer to Appendix C in Greaker and Heggedal (2010)), as long as (2.16) with $\lambda^{g,r}$ replacing $\bar{\lambda}^{g,r}$ still holds. A low realization-equilibrium is:

$$q_1^r = -\frac{4a}{3}\cos^2(\frac{\theta + 4\pi}{3}), n_1^r = \sqrt{\frac{t^r q_1^r}{(1-\phi_1)f^r}} \tag{2.21}$$

and a high-realization equilibrium is:

$$q_2^r = -\frac{4a}{3}\cos^2(\frac{\theta}{3}), n_2^r = \sqrt{\frac{t^r q_2^r}{(1-\phi_1)f^r}} \tag{2.22}$$

where

$$\cos\theta = \frac{-b}{2\sqrt{\frac{-a^3}{27}}} \tag{2.23}$$

and θ is restricted in $[0, \pi]$. The high-realization equilibrium (the *Case III high-realization* equilibrium) is the most stable (refer to Appendix B of Greaker and Heggedal (2010)). □

2.1.4 Dynamics

Supply-side promotion (increase in ϵ, to be discussed shortly) and demand-side promotion (increases in ϕ_1, ϕ_2) can move one equilibrium to another by changing the

[4] For simplicity, I do not consider the case $\Theta = 0$.

conditions under which the equilibrium is possible. For the sake of simplicity for the following dynamics analysis, I assume that the pool of car owners, once created, does not change in the dynamics analysis. For example, in order to study the process of transforming from the *Case I zero* equilibrium to a *Case III high-realization* equilibrium as a result of promotion, I assume for the *status quo* that the pool of car owners is created from those who have chosen gasoline vehicles instead of AFVs due to low consumer awareness for AFVs. Given this pool, any promotion only affects the car owners in this pool, who will re-compare their utility from buying an gasoline vehicle with that from choosing an AFV given the effects of the promotion. Some car owners in this pool may want to change their initial choice as a result of the promotion. By the assumption of a zero transaction cost, these car owners will return their initial purchase, get refund, and make a new purchase.[5]

The directions of transformation in question are: 1) from the *Case I zero* equilibrium to a *Case III high-realization* equilibrium, with possibility of going through the *Case II zero* equilibrium; 2) from the *Case II zero* equilibrium to a *Case III high-realization* equilibrium; and 3) from a *Case III high-realization* equilibrium to a higher one. In all of the above processes, a non-decreasing trend of the density of alternative fueling stations is anticipated, as well as the market share of AFVs. By restricting the dynamics analysis to these directions of transformation, instead of the opposite directions where the density of alternative fueling stations have to decrease when moving from high-realization equilibria to zero, will therefore not introduce significant inconsistency with the reality for fuel providers, who in practice cannot easily undo a refueling station once they set it up because of sunken investment costs.

Promotion may work differently for different AFVs depending on their cost relative to gasoline vehicles, and it is thus useful to divide AFVs into two groups by (2.18). *Category I* AFVs include LNGVs, FFVs, biodiesel vehicles, inexpensive EVs, and expensive hybrids. These are vehicles which have positive values (several thousands dollars) of $\Delta\omega + \Delta c - \frac{5}{4}\sqrt{t^g f^g}$ in (2.18) (see Appendix D and Table B.1), indicating

[5] Arguably these are strong assumptions, but making these assumptions is useful in keeping things simple and allowing the model to be able to capture the main ideas.

that without considering the availability of alternative refueling infrastructure to be endogenously determined in this model, represented by $\frac{4+\gamma}{4}\sqrt{\frac{t^r(1-\phi_1)f^r}{q^r}}$ in (2.17), the cost premium of these AFVs over gasoline vehicles is high. The first term is the model price difference between AFVs and gasoline vehicles, the second term is the fuel price difference, and the third terms measures the availability of gasoline stations. *Category II* AFVs include CNGVs and inexpensive hybrids. These are vehicles which have negative values (negative several thousands dollars) of the above expression, indicating that they have a cost advantage over gasoline vehicles without considering the availability of alternative refueling infrastructure. Single-fuel AFVs that will be discussed here are LNGVs, CNGVs, and inexpensive EVs.

The effects of supply- and demand-side promotion on the equilibria dynamics are summarized in the following proposition:

Proposition 2. *In a single-fuel AFV market:*

- *Given the Case I zero equilibrium, demand-side promotion is necessary in order to transform to a Case III high-realization equilibrium. During the process of transformation, being trapped in the Case II zero equilibrium is possible, particularly when the upfront cost for an alternative fueling station is high.*

- *Given the Case II zero equilibrium, demand-side promotion is in general helpful for Category I single-fuel AFVs to transform to a Case III high-realization equilibrium, and supply-side promotion is in general helpful for all single-fuel AFVs.*

- *Given a Case III high-realization equilibrium, demand-side promotion is in general helpful for Category I single-fuel AFVs to transform to a higher-realization equilibrium, and supply-side promotion is in general helpful for all single-fuel AFVs.*

Proof. Given the *Case I zero* equilibrium, the necessity to increase the consumer awareness is obvious in order to transform to a *Case III high-realization* equilibrium. Indeed, given $\bar{\lambda}^{g,r} \geq m+1$, in order to make possible $\lambda^{g,r} < m+1$, $Z + \Delta\Gamma$ must increase, because the fuel providers do not have the incentive to unilaterally set up alternative fueling stations since having a positive n^r will make $\lambda^{g,r} > m + 1$.

Let ϵ denote the percentage increase in $Z + \Delta\Gamma$. Suppose $Z + \Delta\Gamma$ is raised such that $\bar{\lambda}^{g,r}(\epsilon) < m + 1$. Then, the Θ criterion becomes relevant. A *Case III high-realization* equilibrium is likely if $\Theta(\epsilon)$ is below zero, which is particularly possible when the upfront cost f^r is modest. However, $\Theta(\epsilon)$ could be positive especially the upfront cost is high, and the process of transformation will thus be trapped in the *Case II zero* equilibrium.

Now suppose that we are in the *Case II zero* equilibrium. This means $\bar{\lambda}^{g,r} < m+1$ and a positive Θ. In order to transform to a *Case III high-realization* equilibrium, Θ needs reducing below zero and at the same time we should ensure that $\lambda^{g,r}(\epsilon, \phi_1, \phi_2) < m + 1$. While increasing either ϕ_1 or ϕ_2 from zero will reduce Θ for sure, an increase in $Z + \Delta\Gamma$ will have ambiguous effects on Θ. Indeed, first observe that the latter increase will reduce b by (2.19). For a in (2.18), if the numerator of the second term in the expression is positive, such an increase will result in an decrease in a, which, coupled with the decreasing b, can bring Θ below zero. If, however, the numerator of the second term in the expression of a in (2.18) is negative, then an increase in $Z+\Delta\Gamma$ will result in an increase in a, and it becomes unclear if Θ will fall below zero. Hence, while supply-side promotion such as a positive ϕ_1 or ϕ_2 is in general helpful for all single-fuel AFVs to transform to a *Case III high-realization* equilibrium, demand-side promotion such as an increase in consumer awareness is in general helpful for *Category I* single-fuel AFVs.[6]

Given a *Case III high-realization* equilibrium, the impact of supply-side promotional efforts can be easily deduced from equations (2.18) through (2.23). An increase in ϕ_1 from zero will reduce b by (2.19), which in turn will increase q_2^r by (2.22) through a decrease in θ by (2.23) considering the constraint that $\theta \in [\frac{1}{2}\pi, \pi]$ (see Appendix C.1). By (2.22), such an increase in ϕ_1 from zero will increase the station coverage,

[6]It should be noted that this is not saying that there is no effect of demand-side promotion for *Category II* single-fuel AFVs; the effect is just not clear from analytical analysis. However, the results from Chapter 3 where the theoretical model is parameterized indicate that demand-side promotion may also be helpful for *Category II* single-fuel AFVs in some cases.

n_2^r, either directly through a reduced denominator, or indirectly through a increased q_2^r in the numerator. Similarly, an increase in ϕ_2 from zero will reduce a by (2.18), which in turn will directly and indirectly increase q_2^r and n_2^r by (2.22). In terms of demand-side promotion, an increase in $\Delta\Gamma + Z$ will always reduce b. For *Category I* single-fuel AFVs, an increase in $\Delta\Gamma + Z$ will reduce a as well, which, combined with a reduced b, will reduce θ by (2.20), and indirectly and directly increase q_2^r and n_2^r by (2.22). However, again, for *Category II* single-fuel AFVs, the effect of demand-side promotional efforts is unclear. □

Proposition 3 has important policy implications. For a policy maker who wants to make use of supply-side or demand-side promotion in order to increase consumption of alternative fuels by some single-fuel AFV which has a negligible market share *status quo*,[7] it is important first to distinguish between the *Case I zero* equilibrium and the *Case II zero* equilibrium. That is, whether the negligible consumption of alternative fuels is mainly due to low consumer awareness, or to difficulties faced by fuel providers such as high upfront costs. If the former, then increasing consumer awareness by demand-side promotion is necessary. Put in another way, it is fruitless in this situation to merely subsidize fuel providers.

2.2 The Dual-Fuel AFV Game

Users of dual-fuel AFVs can choose between gasoline and the corresponding alternative fuel to fuel their vehicles. For simplicity, I assume that AFV users do not make such choice based on their locations along the circle. That is, before AFV users appear on the circle with their vehicles, they have already decided which fuel to use based on their utility maximization problem (to be discussed in Section 2.2.2). Once on the circle, they just act according to their decisions off the circle.

[7] Although this thesis focuses on the role of the automotive industry in increasing consumption of alternative fuels, the government can also make use of the promotion described here in order to increase consumption of alternative fuels.

2.2.1 Fuel Providers

Let q^{rr}, the effective AFV market share, and q^{rg} denote the proportion of AFV users who use gasoline or renewable fuels respectively, with $q^{rg} + q^{rr} = q^r = 1 - q^g$. The number of alternative fueling stations can then similarly be derived according to (2.7):

$$n^r(q^{rr}, s^r) = \sqrt{\frac{t^r q^{rr}}{(1-\phi_1)f^r}} \tag{2.24}$$

while the number of gasoline stations is the same as in (2.8).

2.2.2 Consumers

The expected utility of a consumer i buying an AFV and using the corresponding alternative fuels is:[8]

$$EU_i^{rr} = \lambda_i \Gamma^r - \gamma \frac{t^r}{4n^{rr}} - \omega^r - p^r + \lambda_i Z \tag{2.25}$$

And the expected utility of a consumer i buying an AFV and using gasoline is:

$$EU_i^{rg} = \lambda_i \Gamma^r - \frac{t^g}{4n^g} - \omega^r - p^g \tag{2.26}$$

A consumer buying an AFV will be indifferent between using gasoline and the alternative fuel if:

$$EU_i^{rr} = EU_i^{rg} \tag{2.27}$$

which yields the cut-off value of λ_i:

$$\lambda^{rg,rr} = \frac{p^r + \gamma \frac{t^r}{4n^{rr}} - p^g - \frac{t^g}{4n^g}}{Z} \tag{2.28}$$

There are three cases to consider:

(1) If $\lambda^{rg,rr} \geq m+1$, then all the consumers who buy an AFV will choose gasoline.

[8] Again, I assume $n^{rr} > 0$ for now so that the expected utility is well-defined. I will allow $n^{rr} = 0$ when talking about the dynamics of the equilibria as a result of the supply- and demand-side promotion in Section 2.2.3.

In this case, the indifference condition requires equating (2.26) with (2.10), which yields:

$$\lambda^{g,rg} = \frac{\omega^r - \omega^g}{\Gamma^r - \Gamma^g} \tag{2.29}$$

Again, we assume that $\Gamma^r > \Gamma^g$ by the warm glow effect, and $\omega^r - \omega^g > m(\Gamma^r - \Gamma^g)$ by positive demand for gasoline vehicles. Note that (2.28) and (2.29) do not have common variables. Hence, if $\lambda^{rg,rr} \geq m+1$ (*Case A*):

$$q^{rr} = 0 \tag{2.30}$$

$$q^{rg} = \begin{cases} 0, & \text{if } \lambda^{g,rg} \geq m+1 \\ m+1-\lambda^{g,rg}, & \text{if } m < \lambda^{g,rg} < m+1 \end{cases} \tag{2.31}$$

(2) If $\lambda^{rg,rr} \leq m$, then all the consumers who buy an AFV will choose the alternative fuel. In this case, the indifference condition requires equating (2.25) with (2.10). The cutoff value of $\lambda^{g,rr}$ is almost the same as in (2.13) except the substitution of n^{rr} for n^r:

$$\lambda^{g,rr} = \frac{\omega^r + p^r + \gamma\frac{t^r}{4n^{rr}} - \omega^g - p^g - \frac{t^g}{4n^g}}{Z + \Gamma^r - \Gamma^g} \tag{2.32}$$

I also make similar assumptions such that the demand for gasoline vehicles is positive, that is, $\lambda^{g,rr} > m$. Hence, if $\lambda^{rg,rr} \leq m$ (*Case D*):

$$q^{rg} = 0 \tag{2.33}$$

$$q^{rr} = \begin{cases} 0, & \text{if } \lambda^{g,rr} \geq m+1 \\ m+1-\lambda^{g,rr}, & \text{if } m < \lambda^{g,rr} < m+1 \end{cases} \tag{2.34}$$

(3) If $m+1 > \lambda^{rg,rr} > m$, if we do not care about equalities, there are only two possibilities: $\lambda^{g,rg} < \lambda^{g,rr} < \lambda^{rg,rr}$, or $\lambda^{g,rg} > \lambda^{g,rr} > \lambda^{rg,rr}$,[9] as can be concluded from

[9] For simplicity, I do not consider cases where there is at least one equality here.

the formulation of these variables.[10] In the former case (*Case B*),

$$q^{rg} = \lambda^{rg,rr} - \lambda^{g,rg} \tag{2.35}$$

$$q^{rr} = m + 1 - \lambda^{rg,rr} \tag{2.36}$$

In the latter case (*Case C*),

$$q^{rg} = 0 \tag{2.37}$$

$$q^{rr} = \begin{cases} 0, & \text{if } \lambda^{g,rr} \geq m+1 \\ m+1-\lambda^{g,rr}, & \text{if } m < \lambda^{g,rr} < m+1 \end{cases} \tag{2.38}$$

2.2.3 Nash Equilibria and Dynamics

The procedure for solving for Nash equilibria under each of the cases A, B, C, and D discussed above[11] is similar to that in the proof to Proposition 1, and hence will not be described in length here. In terms of dynamics of the Nash equilibria, this section will focus on only the transition from a *Case A* equilibrium to the other equilibria listed above, which may be of particular interest, given a sizable market share of some dual-fuel AFVs (such as FFVs) of which only a negligible number are fueled with gasoline instead of the alternative fuel *status quo*. Again, the assumption of zero transaction costs applies here.

Proposition 3. *In a dual-fuel AFV monopoly market, in order to move from the Case A equilibrium to the other equilibria:*

- *It is necessary to increase the consumer awareness for fuel.*
- *When the consumer awareness for fuel is raised modestly, in general some pre-existing AFV owners will switch from using gasoline to using the alternative*

[10]When the numerators of two variables add up to that of the third variable and so do the denominators of the two variables, the value of third variable will always stay between the values of the other two.

[11]It should be noted that under each of the four cases described above, there will be conditions under which the *Case II zero* equilibrium as solved for in the proof to Proposition 1 is likely and under which a *Case III high-realization* equilibrium is likely. In the following dynamics analysis, the conditions for a *Case III high-realization* equilibrium are assumed to hold under each of the four cases.

fuel and the corresponding refueling infrastructure will begin to diffuse, but no existing gasoline vehicle owner will switch from gasoline vehicles to AFVs.

- *When the consumer awareness for fuel is raised further, in general all the pre-existing AFV owners will switch from using gasoline to using the alternative fuel, and some gasoline vehicle owners will switch from gasoline vehicles to AFVs, which are used with the alternative fuel. The corresponding refueling infrastructure will further diffuse.*

Proof. Define:

$$\bar{\lambda}^{rg,rr} = \frac{p^r - p^g - \frac{t^g}{4n^g}}{Z} \tag{2.39}$$

$$\bar{\lambda}^{g,rr} = \frac{\omega^r + p^r - \omega^g - p^g - \frac{t^g}{4n^g}}{Z + \Gamma^r - \Gamma^g} \tag{2.40}$$

The necessity to increase the consumer awareness for fuel is obvious. Indeed, given $\bar{\lambda}^{rg,rr} \geq m+1$, in order to make possible $\lambda^{rg,rr} < m+1$, Z must increase, because the fuel providers do not have the incentive to unilaterally set up alternative fueling stations since having a positive n^{rr} will make $\lambda^{rg,rr} > m+1$.

Suppose Z is raised by ϵ. When ϵ is small such that:

$$m < \lambda^{g,rg} < \bar{\lambda}^{g,rr}(\epsilon) < \bar{\lambda}^{rg,rr}(\epsilon) < m+1 \tag{2.41}$$

then a *Case B* equilibrium will be likely, if the cubic equation derived from plugging (2.24) in (2.28) and then in (2.36) has three trigonometric solutions, and (2.41) with $\lambda^{g,rr}(\epsilon)$ and $\lambda^{rg,rr}(\epsilon)$ replacing $\bar{\lambda}^{g,rr}(\epsilon)$ and $\bar{\lambda}^{rg,rr}(\epsilon)$ still holds. This means that in general, there will be positive market shares for both AFVs used with the alternative fuel and those with gasoline. The market share of gasoline vehicle will not be affected by the raise of Z, as:

$$q^g = 1 - (q^{rr}(\epsilon) + q^{rg}(\epsilon)) = \lambda^{g,rg} - m \tag{2.42}$$

which does not depend on ϵ. Since those with the highest λ_i's will switch the fuel use first and they are those who originally own AFVs, it can be concluded that when Z is raised modestly, some of the pre-existing AFV owners will switch from using gasoline to using the alternative fuel, while the original gasoline vehicle owners will not be affected. As the market share of AFVs used with the alternative fuel increases, so does the density of alternative fueling stations according to (2.24).

If ϵ is larger such that:

$$m < \bar{\lambda}^{rg,rr}(\epsilon) < \bar{\lambda}^{g,rr}(\epsilon) < \lambda^{g,rg} < m+1 \tag{2.43}$$

then a *Case C* equilibrium will be likely, if the cubic equation derived from plugging (2.24) in (2.32) and then in (2.38) has three trigonometric solutions, and (2.41) with $\lambda^{g,rr}(\epsilon)$ and $\lambda^{rg,rr}(\epsilon)$ replacing $\bar{\lambda}^{g,rr}(\epsilon)$ and $\bar{\lambda}^{rg,rr}(\epsilon)$ still holds. In this equilibrium, the market share of AFVs used with gasoline is zero, and those with λ_i's which are between $\lambda^{g,rr}(\epsilon)$ and $\lambda^{g,rg}$ will switch from gasoline vehicles, which they originally own, to AFVs used with the alternative fuel. As the market share of AFVs used with the alternative fuel increases, so does the density of alternative fueling stations according to (2.24).

If ϵ is further raised such that:

$$\bar{\lambda}^{rg,rr}(\epsilon) < m < \bar{\lambda}^{g,rr}(\epsilon) < \lambda^{g,rg} < m+1 \tag{2.44}$$

then a *Case D* equilibrium will be likely, if the cubic equation derived from plugging (2.24) in (2.32) and then in (2.38) has three trigonometric solutions, and (2.42) with $\lambda^{g,rr}(\epsilon)$ and $\lambda^{rg,rr}(\epsilon)$ replacing $\bar{\lambda}^{g,rr}(\epsilon)$ and $\bar{\lambda}^{rg,rr}(\epsilon)$ still holds. In this equilibrium, the market share of AFVs used with gasoline is zero, and those with λ_i's which are between $\lambda^{g,rr}(\epsilon)$ and $\lambda^{g,rg}$ will switch from gasoline vehicles, which they originally own, to AFVs used with the alternative fuel. As the market share of AFVs used with the alternative fuel increases, so does the density of alternative fueling stations according to (2.24). Note that this conclusion is identical to the previous one. □

Chapter 3

Parameterizing the Model: Incentive of the Automotive Industry

This chapter illustrates how the model can be used to examine the incentive of the automotive industry, in particular automobile companies which focus on AFVs, to do supply- or demand-side promotion in various scenarios in the context of indirect network effects embodied in the vehicle and fuel market.

Several assumptions are necessary to capture the main insights. First, monopoly for the market of AFVs of each alternative fuel type in question is assumed. This will assume away potential spillover effects in supply- and demand-side promotion. For example, in the case of duopoly in the FFV market, sponsoring an alternative fueling station by one of the FFV company will not only benefit users of the FFVs produced by this company, but also users of the FFVs produced by the other company, which does not sponsor the fueling station at all. As a result, the incentive problem of the FFV companies will be more complicated than that in the monopoly case. The monopoly assumption, although strong, may be justifiable considering the limited public perception of AFV brands of the same fuel type. Second, consumers are assumed to make a purchase choice between an AFV and a gasoline vehicle, as opposed to that among multiple AFVs and a gasoline vehicle. This will simplify the utility maximization problem that consumers face. Third, technology learning in the AFV market is assumed away. Fourth, since the focus here is on the AFV monopoly's incentive to do supply- or demand-side promotion rather than strategic pricing, it is assumed that the variables that the AFV monopoly alters to achieve utility maximization are restricted to the targeted percentage increase in consumer awareness ϵ, the percentage of upfront investment cost of alternative fueling stations funded by the AFV monopoly ϕ_1, and the percentage of fueling cost of alternative fueling stations funded by the AFV monopoly ϕ_2, all of which are denoted as *control variables*, while keeping other variables such as the price of the AFV fixed.

To illustrate how the model can be used to examine the AFV monopoly's incentive, scenarios of interests are first identified. Figure C-2 shows the scenarios under which the incentive of the single-fuel AFV monopoly will be examined. Each cube represents a scenario characterized by the *control variable* that the monopoly can use, the transition of equilibria that the monopoly intends to alter the *control variable* to achieve, and the category of AFVs that the monopoly produces. The question for a cube would be whether the category of AFV monopoly has incentive to alter the *control variable* to achieve the transition of equilibria. For example, the question for the front-lower-right cube is if the *Category I single-fuel AFV* monopoly would achieve a higher utility by funding part of the fueling cost in order to move from the *Case II zero* equilibrium to a *Case III high-realization* equilibrium than by doing nothing and hence staying in the *Case II zero* equilibrium. The cubes with a cross sign are those scenarios which may not need examining due to ineffectiveness of the *control variable* in that scenario or low relevance to the reality. For example, regardless of AFV categories, in moving from the *Case I zero* equilibrium to a *Case III high-realization* equilibrium, neither funding part of the upfront cost nor funding part of the fueling cost will be effective, because increasing consumer awareness is a necessary condition by Proposition 2. As a result, the AFV monopoly will not have incentive to do either of them, because doing either of them will incur costs but there will be no benefits. Put in another way, both funding part of the upfront cost and funding part of the fueling cost are strictly dominated by increasing consumer awareness. The rear-left column does not need to be examined either, because extremely low consumer awareness would be required in order that *Category II* single-fuel AFVs be trapped in the *Case I zero* equilibrium by Proposition 1, which may not be a realistic scenario worth examining. Thus, after the elimination of several cubes, seven scenarios are left to be examined.

Figure C-3 shows the scenario of interests in which the incentive of the dual-fuel AFV monopoly will be examined. I will focus on FFVs, one of the *Category I* dual-fuel AFVs. The market of FFVs is a typical manifestation of the chicken-and-egg problem for dual-fuel AFVs, with high upfront cost on the supply side, and a positive market share of FFVs which mostly run on gasoline on the demand side. For the transitions of equilibria, I will focus on the transition from a *Case A* equilibrium to a *Case C* or *Case D* equilibrium. The market of FFVs currently approximately corresponds to a *Case A* equilibrium. The FFV monopoly does not have incentive to move from a *Case A* equilibrium to a *Case B* equilibrium, because this will not bring any new AFV buyers by Proposition 3. Regarding the *control variable*, I focus on increasing consumer awareness for fuel, which is a necessary condition to move from a *Case A* equilibrium by Proposition 3.

Having identified the scenarios of interest, I identify key influencing variables of interest, if any, that can influence the profitability of making use of *control variables.* For example, the key influencing variable of interest in this research for increasing consumer awareness is the unit promotion cost, h, defined as the cost of doubling consumer awareness of a single consumer. The key influencing variable of interest in this research for funding part of the fueling cost is the normalized upfront cost, f, which is the upfront cost of setting up a renewable fueling station in reality divided by the size of the local vehicle market that is served by this alternative fueling station.

Third, estimates of the measurable variables with which to parameterize the theoretical model are obtained from various sources. These include the net margin of the AFV in question, price premium of the AFV, price premium of the alternative fuel, upfront cost, and mark-up factor for alternative fueling. Table B.2 lists the values of the measurable variables for the single-fuel AFV model. Expensive EVs and LNGVs are chosen as examples of *Category I* single-fuel AFVs, and CNGVs as an example of *Category II* single-fuel AFVs. Table B.4 lists the values of the measurable variables for the duel-fuel AFV model. FFVs are chosen as an example of *Category I* dual-fuel AFVs.[1]

Fourth, consumer awareness ($Z + \Delta\Gamma$ for the single-fuel model, and Z for the dual-fuel model) is calibrated such that the starting equilibrium in the transition of equilibria in question can be realized. Ideally one would like to measure consumer awareness and plug it in the equilibrium-determining conditions to determine which equilibrium the reality is in. However, given the lack of quantitative knowledge on consumer awareness, this research will calibrate the consumer awareness scenario by scenario by setting $m = 0.5$[2] without attempting to determine which equilibrium the reality is in. Table B.2 and B.4 lists the calibrated values of consumer awareness used in the single-fuel and dual-fuel AFV models, respectively.

3.1 Incentive of the Single-Fuel AFV Monopoly

In this section, the seven scenarios identified in Figure C-2 will be examined in order to study the incentive of the single-fuel AFV monopoly in doing demand- or supply-side promotion in the context of indirect network effects.

The additional utility that the single-fuel AFV monopoly gets from increasing consumer awareness by ϵ is:

$$U_{AFV}^{demand-side}(\epsilon) = (\omega^r - c_{AFV})\Delta q^r(\epsilon) - h\epsilon \tag{3.1}$$

where c_{AFV} is the production cost of an AFV, and $\Delta q^r(\epsilon)$ is the additional AFV market share that results from the demand-side promotion. For transitions from the *Case I zero* equilibrium or the *Case II zero* equilibrium to a *Case III high-realization* equilibrium, $\Delta q^r(\epsilon) = q^r(\epsilon)$ because the AFV market share in the starting equilibria is zero. Note that the total promotion cost, $h\epsilon$, is assumed to be devoted to the whole

[1]The rationales for choosing these AFVs as examples are described in the following sections.
[2]m and $Z + \Delta\Gamma$ or Z can be re-scaled with respect to each other.

vehicle market rather than dependent on the AFV market share.

The additional utility that the single-fuel AFV monopoly gets from funding ϕ_1 of the upfront investment is:

$$U_{AFV}^{supply-side,upfront}(\phi_1) = (\omega^r - c_{AFV})\Delta q^r(\phi_1) - \phi_1 f^r \Delta n^r(\phi_1) \tag{3.2}$$

where $\Delta n^r(\phi_1)$ is the additional number of alternative fueling stations that results from this supply-side promotion. For transitions from the *Case I zero* equilibrium or the *Case II zero* equilibrium to a *Case III high-realization* equilibrium, $\Delta n^r(\phi_1) = n^r(\phi_1)$ because the number of alternative fueling stations in the starting equilibria is zero.

The additional utility that the single-fuel AFV monopoly gets from funding ϕ_2 of the refueling cost is:

$$U_{AFV}^{supply-side,fueling}(\phi_2) = (\omega^r - c_{AFV})\Delta q^r(\phi_2) - \phi_2 c^r \Delta D_r(\phi_2) \tag{3.3}$$

where $\Delta D^r(\phi_2)$ is the additional demand for the alternative fuel that results from this supply-side promotion. For transitions from the *Case I zero* equilibrium or the *Case II zero* equilibrium to a *Case III high-realization* equilibrium, $\Delta D^r(\phi_2) = D^r(\phi_2) = \frac{q^r(\phi_2)}{n^r(\phi_2)}$ because the demand for the alternative fuel in the starting equilibria is zero.

3.1.1 Moving from the Case I Zero Equilibrium to a Case III High-Realization Equilibrium

In order to examine the incentive of the single-fuel AFV monopoly to do demand-side promotion to move from the *Case I zero* equilibrium to a *Case III high-realization* equilibrium, *i.e.*, the upper-front-left cube in Figure C-2, the consumer awareness should be calibrated such that the condition for the initial realization of the *Case I zero* equilibrium is met. That is, the values of $\Delta\Gamma + Z$ and Γ^g should be chosen such that:

$$\bar{\lambda}^{g,r} = \frac{\Delta\omega + \Delta c - \frac{5}{4}\sqrt{t^g f^g}}{\Delta\Gamma + Z} \geq m + 1 \tag{3.4}$$

$$m\Gamma^g - \frac{5}{4}\sqrt{t^g f^g} + \omega^g - c^g > 0 \tag{3.5}$$

The first condition makes sure that due to low consumer awareness, no consumer buys an AFV. The second condition makes sure that all consumers buy vehicles. Table B-1 lists the calibrated values of $\Delta\Gamma + Z$ used in this research.[3]

In order to reach a *Case III high-realization* equilibrium, the following conditions which restrict the values of the *control variable* ϵ should be satisfied:

$$m < \lambda^{r,g}(\epsilon) = \frac{\Delta\omega + \Delta c + \frac{4+\gamma}{4}\sqrt{\frac{t^r f^r}{q^r(\epsilon)}} - \frac{5}{4}\sqrt{t^g f^g}}{(1+\epsilon)(\Delta\Gamma + Z)} < m + 1 \tag{3.6}$$

$$\Theta \doteq \frac{b^2(\epsilon)}{4} + \frac{a^3(\epsilon)}{27} < 0 \tag{3.7}$$

Based on the acceptable range of ϵ and the corresponding AFV market share q^r and the density of alternative fueling stations n^r, the additional utility of the single-fuel AFV monopoly by making use of demand-side promotion can be calculated according to (3.1).

Figure C-4 plots the results for inexpensive EVs and LNGVs, which illustrate the effects of the unit promotion cost and the upfront infrastructure cost on the equilibrium outcome. The starting value of the x axis is the lower bound of ϵ which makes possible the realization of a *Case III high-realization* equilibrium. Expensive EVs and LNGVs are selected, first because they belong to *Category I* single-fuel AFVs, which are very likely to be initially trapped in the *Case I zeroequilibrium*. Second, they differ significantly in upfront infrastructure cost; a plug-in station for EVs is in general much less expensive than an LNG station.[4]

In terms of the effect of the unit promotion cost h, Figure C-4 shows that the lower the unit promotion cost, the more likely that the utility will be positive. This

[3] The values of Γ^g are not listed because they are not relevant in the calculation of equilibria.

[4] It should be noted that while Figure C-2 presents three main dimensions for this research, further sub-dimensions and hence further variable controls may be needed, depending on the specific questions of interests. Here, the question is whether the upfront infrastructure cost matters. I thus select inexpensive EVs and LNGVs for comparison, which differ along the sub-dimension of infrastructure cost while the other dimensions such as the AFV category, transition of equilibria (and hence consumer awareness), and the *control variable* are controlled for.

suggests that the single-fuel AFV monopoly will have incentive to increase consumer awareness given affordable unit promotion costs. Intuitively, as the demand-side promotion makes the consumers with the highest valuation of driving, *i.e.*, the highest λ, potentially willing to switch from gasoline vehicles to AFVs, some fuel providers will decide to install refueling infrastructure, which, by the indirect network effect, will induce more consumers opt for AFVs together. Hence, in the equilibrium, there will be both a positive number of fueling stations and a positive AFV share. This is evident in the increasing grey area in Figure C-4, which denotes the AFV market share. For the AFV monopoly, as long as the marginal increase in the gross profit from selling AFVs outweighs the marginal promotion cost, the single-fuel AFV monopoly will have incentive to make the demand-side promotion.

In terms of the effect of the upfront infrastructure cost, Figure C-4 first suggests that the AFVs with a high upfront infrastructure cost for its fueling stations may require a higher minimum percentage increase in consumer awareness in order to move beyond the *Case II zero* equilibrium to a *Case III high-realization* equilibrium. Moreover, given the same percentage increase in consumer awareness and unit promotion cost, the additional utility of the LNGV monopoly from doing the demand-side promotion is lower than that of the inexpensive EV monopoly. Intuitively, consumers know that the number of LNG stations may be harder to be increased by the increase in the consumer base than that of EV stations because of higher infrastructure cost. Consequently the AFV market share in the equilibrium will be lower as evident in the smaller grey area given the same targeted increase in consumer awareness. This will further render a lower utility for the LNGV monopoly given the same unit promotion cost.

3.1.2 Moving from the Case II Zero Equilibrium to a Case III High-Realization Equilibrium

In order to examine the incentive of the single-fuel AFV monopoly to do demand- or supply-side promotion to move from the *Case II zero* equilibrium to a *Case III* *high-realization* equilibrium, *i.e.*, the remaining cubes in Figure C-2, the consumer awareness should be calibrated such that the condition for the initial realization of the *Case II zero* equilibrium is met. That is, the values of $\Delta\Gamma + Z$ and Γ^g should be chosen such that:

$$\bar{\lambda}^{g,r} = \frac{\Delta\omega + \Delta c - \frac{5}{4}\sqrt{t^g f^g}}{\Delta\Gamma + Z} < m + 1 \tag{3.8}$$

$$m\Gamma^g - \frac{5}{4}\sqrt{t^g f^g} + \omega^g - c^g > 0 \tag{3.9}$$

$$\Theta \doteq \frac{b^2}{4} + \frac{a^3}{27} > 0 \tag{3.10}$$

Table B-1 lists the values of $\Delta\Gamma + Z$ used in this research.

In order to reach a *Case III high-realization* equilibrium, the following conditions which restrict the values of the *control variables* should be satisfied:

$$m < \lambda^{r,g}(\epsilon, \phi_1, \phi_2) = \frac{\Delta\omega + \Delta c + \frac{4+\gamma}{4}\sqrt{\frac{(1-\phi_1^r)t^r f^r}{q^r(\epsilon,\phi_1,\phi_2)}} - \frac{5}{4}\sqrt{t^g f^g}}{(1+\epsilon)(\Delta\Gamma + Z)} < m + 1 \tag{3.11}$$

$$\Theta \doteq \frac{b^2(\epsilon, \phi_1, \phi_2)}{4} + \frac{a^3(\epsilon, \phi_1, \phi_2)}{27} < 0 \tag{3.12}$$

Based on the acceptable range of the *control variables*, the corresponding AFV market share q^r and the density of alternative fueling stations n^r, the additional utility of the single-fuel AFV monopoly by making use of demand-side promotion can be calculated according to (3.1)-(3.3).

Figure C-5 to C-7 plot the results regarding various *control variables* for LNGVs and CNGVs. Again, the starting values of the x axes are the lower bound of the *control variables* which makes possible the realization of a *Case III high-realization* equilibrium. LNGVs and CNGVs are selected because they differ in their relative cost to gasoline vehicles, the former a *Category I single-fuel AFV* and the latter a *Category II* one, while having comparable upfront infrastructure costs.[5]

Figure C-5 shows that the lower unit promotion cost, the more likely that the utility will be positive, and especially so for higher ϵ. This suggests that the single-fuel

[5]Here the dimension of interest is the AFV category, so I control for infrastructure cost, transition of equilibria (and hence the consumer awareness), and the *control variable*.

AFV monopoly will have incentive to increase consumer awareness given affordable unit promotion costs. While Proposition 2 does not provide that demand-side promotion works for *Category II* single-fuel AFVs to move from the *Case II zero* equilibrium to a *Case III high-realization* equilibrium, Figure C-5 shows so. It also appears that in order for CNGVs, an example of *Category II* single-fuel AFVs, to move from the *Case II zero* equilibrium to a *Case III high-realization* equilibrium, more ambitious consumer awareness increase will be needed. This may be because *Category II* single-fuel AFVs, which already have a cost advantage over gasoline vehicles, being trapped in the *Case II zero* equilibrium implies very low consumer awareness. This may translate into more demand-side promotion effort in order to realize a non-zero market share, and lower profitability for the AFV monopoly given the same unit promotion cost.

Figure C-6 shows that the single-fuel AFV monopoly may have incentive to fund part of the upfront cost, as utility is positive for the given range of the funding percentage. The impact of the normalized infrastructure cost f on the incentive of the AFV monopoly is not shown here, as it is obvious that this will have a negative impact on the incentive of the AFV monopoly. Indeed, the higher the normalized infrastructure cost, the smaller the market share of AFV will be due to lower density of fueling stations in the equilibrium. In the mean time, there will be higher funding cost for the AFV monopoly. These two forces work together to discourage the AFV monopoly to fund part of the upfront cost.

Figure C-7 shows that the lower the normalized upfront infrastructure cost, the more likely that the utility will be positive. This suggests that the single-fuel AFV monopoly will have incentive to fund part of the fueling cost given an affordable upfront infrastructure cost. Unlike in the analysis of upfront cost funding where it is obvious that the lower the normalized infrastructure is, the higher the utility will be, here there are two forces working against each other. The lower the normalized upfront infrastructure cost, the more refueling stations will result in the equilibrium, which in turns attracts more consumers into buying an AFV and thus a higher gross profits, but there will also be higher demand for alternative fuels and thus a higher cost for funding the fueling cost. Figure C-7 suggests that the former force outweighs the latter.

3.2 Incentive of the Dual-Fuel AFV Monopoly

In this section, only one scenario will be examined in this research, as shown in Figure C-3. First, only the incentive of the duel-fuel AFV monopoly to do the demand-side promotion will be examined, since the demand-side promotion is necessary according to Proposition 4. Furthermore, only the transition from a *Case A* equilibrium to a *Case C* or *D equilibrium* will be studied, because the dual-fuel AFV monopoly does not have incentive to do the demand-side promotion moving a *Case A* equilibrium only up to a *Case B* equilibrium, which will not give rise to new sales of AFVs according to Proposition 4.

The AFV monopoly's utility from doing the demand-side promotion which realizes either a *Case C* or *D equilibrium* is:

$$U_{AFV}^{demand-side}(\epsilon) = (\omega^r - c_{AFV})(\lambda^{g,rg} - \lambda^{g,rr}(\epsilon)) - h\epsilon \tag{3.13}$$

where $\lambda^{g,rg} - \lambda^{g,rr}(\epsilon)$ is the share of additional AFV buyers resulting from the demand-side promotion. Again, the cost of the demand-side promotion is $h\epsilon$ as the demand-side promotion is assumed to target at the whole vehicle market.

Table B-3 lists the values for the measurable variables and the calibrated consumer awareness, Z and $\Delta\Gamma$. Specifically, Z should be calibrated such that:

$$\bar{\lambda}^{rg,rr} = \frac{\Delta c - \frac{5}{4}\sqrt{t^g f^g}}{Z} \geq m + 1 \tag{3.14}$$

$$m\Gamma^g - \frac{5}{4}\sqrt{t^g f^g} + \omega^g - c^g > 0 \tag{3.15}$$

Moreover, $\Delta\Gamma$ should be calibrated such that the benchmark FFV market share, $m + 1 - \lambda^{g,rg} = m + 1 - \frac{\Delta\omega}{\Delta\Gamma}$ is consistent with the real-world FFV market share shown in Figure C-1, which is expected to approximate 5% in 2012.

In order to reach a *Case C* or *D equilibrium*, the following conditions which restrict the values of the ϵ should be satisfied:

$$m < \lambda^{g,rr}(\epsilon) = \frac{\Delta\omega + \Delta c + \frac{4+\gamma}{4}\sqrt{\frac{t^r f^r}{q^r(\epsilon)}} - \frac{5}{4}\sqrt{t^g f^g}}{\Delta\Gamma + (1+\epsilon)Z} < \lambda^{g,rg} = \frac{\Delta\omega}{\Delta\Gamma} \tag{3.16}$$

$$\Theta \doteq \frac{b^2(\epsilon)}{4} + \frac{a^3(\epsilon)}{27} < 0 \tag{3.17}$$

Based on the acceptable range of ϵ and the corresponding AFV market share $q^r r$ and the density of alternative fueling stations $n^r r$, the additional utility of the dual-fuel AFV monopoly by making use of demand-side promotion can be calculated according to (3.13).

Figure C-8 plots the utility of the dual-fuel AFV monopoly and the resulting total effective market share of AFVs. The starting value of the x axis is the lower bound of ϵ which makes possible the realization of a *Case C* equilibrium.

The results in Figure C-8 are similar to what is found for single-fuel AFVs. It shows that the lower the unit promotion cost, the more likely that the utility will be positive. This suggests that the dual-fuel AFV monopoly will have incentive to increase consumer awareness given affordable unit promotion costs.

Chapter 4

Empirical Analysis

The main purpose of the empirical investigation is to examine if refueling availability or the consumer awareness campaign increases AFV choice probability. The theoretical analysis in Chapter Two illustrates that in equilibria where neither the effective AFV market share nor the density of alternative fueling stations is zero,[1] they are positive correlated for both single- and dual-fuel AFVs by (2.7) and (2.24) respectively. The empirical investigation here examines one of the directions of effects, that is, if the increase in the number of alternative fueling stations increased the probability of consumers choosing AFV in the next year during 2005-2010. In terms of consumer awareness campaigns, the theoretical analysis in Chapter Two provides that given a non-zero equilibria, increasing consumer awareness is in general helpful for *Category I* AFVs to transform to equilibria with even higher market shares by Proposition 2.[2] The empirical investigation here examines if the Clean City Coalition program[3] conducted by the U.S. Department of Energy, with increasing consumer awareness as one of its goals, increased the AFV choice probability as well during 2005-2010. It

[1]The empirical analysis here chooses FFVs, which has a positive yet very small effective market share and number of E85 fueling stations. It should be noted, though, that in the analysis of the incentive problem of the FFV monopoly in Section 3.2, the very small market share of FFVs and E85 fueling stations was interpreted as negligible and thus ignored to facilitate the capture of key ideas by the theoretical model.

[2]This holds for both single- and dual-fuel *Category I* AFVs although Proposition 2 is only stated for single-fuel AFVs. The two models share the procedure for calculating high-realization solutions and hence the expressions and comparative statics of the high-realization solutions.

[3]See `http://www1.eere.energy.gov/cleancities/` for program details.

thus tests the aggregate effect of the program increasing consumer awareness and of the increased consumer awareness increasing AFV choice probability.

The results of the empirical investigation are relevant to the automotive industry, although the increase in refueling availability or the consumer awareness campaign that the empirical investigation makes use of may not be related to the automotive industry at all. If the increase in the number of alternative fueling station is not found to increase the AFV choice probability, the automotive industry may well not consider doing supply-side promotion. In terms of demand-side promotion, if the consumer awareness campaign by the U.S. Department of Energy is not found to be effective in increasing the AFV choice probability, the automotive industry may not have much incentive to launch a demand-side promotion itself. Conversely, if either factor is found to have positively affected the AFV choice probability, the automotive industry may then consider taking on the government's role in working towards a future on alternative fuels in its own interests..

4.1 Data

The data set for the purpose of this study has three components, which are the vehicle choice data, the fuel data, and the campaign data. The fuel data and the campaign data are matched to the vehicle choice data by the state and year that the vehicle purchase took place in. For the period from 2005 to 2010, there are 8,586 observations in the data set which contain complete information of all the variables in the econometric model to be described in the following section.

The vehicle choice data are drawn from the public use micro data of the Consumer Expenditure Survey (CES), collected for the U.S. Bureau of Labor Statistics by the U.S. Census Bureau. CES consists of the Quarterly Interview Survey and the Diary Interview Survey, which provide information on the buying habits of consumers in the U.S., including data on expenditures and characteristics of consumer units[4] (U.S.

[4] According to U.S. Department of Labor (2012), a consumer unit consists of any of the following: (1) All members of a particular household who are related by blood, marriage, adoption, or other legal arrangements; (2) a person living alone or sharing a household with others or living as a roomer

Department of Labor, 2012). This research uses data from the Quarterly Interview Surveys from 2005 to 2010. The Quarterly Interview Survey marked with a given year is conducted every three months from the first quarter of that year to the first quarter of the next year, totaling 5 sets of quarterly data. 20% of the consumer units surveyed in a quarter are replaced with new consumer units for the next quarterly survey. I draw from the *Owned Vehicle* ('*ovb*') table all the observations which are not found in previous surveys, or newly reported vehicle ownership information.[5] These observations contain information on consumer unit identification numbers and vehicle-specific variables, such as purchase year, net purchase price, fuel type, etc. Only entries where the vehicle was purchased for own use during 2005 and 2010 are retained, excluding those where the vehicle was a gift to or from the consumer unit or those where the acquisition took place before 2005. The fuel types are gasoline, diesel, hybrid, and other. By tracing the vehicle makes in the entries with the 'other' fuel type in the AFDC vehicle database (U.S. Department of Energy, 2012c), I find that almost all of these entries correspond to FFVs as opposed to vehicles using the remaining alternative fuels, such as CNG, LNG, etc, which are typically government fleet instead of private vehicles. It is reasonable to believe that these FFVs are almost all used with E85 instead of gasoline due to the way in which the question was asked of the consumer unit ('What was the vehicle fueled by?'). The vehicle purchase information is then merged with the consumer unit characteristics data drawn from the *Family*('*fmli*') table, also contained in the Quarterly Interview Survey, by the consumer unit identification number.

The second component of the data set compiled for the purpose of this research is the fuel data, including the fuel price and number of fueling stations by state, year

in a private home or lodging house or in permanent living quarters in a hotel or motel, but who is financially independent; or (3) two or more persons living together who use their incomes to make joint expenditure decisions. Financial independence is determined by spending behavior with regard to the three major expense categories: Housing, food, and other living expenses. To be considered financially independent, the respondent must provide at least two of the three major expenditure categories, either entirely or in part.

[5]It should be noted that newly reported vehicle ownership in a given quarterly survey does mean that the acquisition of the vehicle was made in that quarter solely; the ownership was just not reported in previous surveys. This could be because this is a new consumer unit surveyed, in addition to the case that the acquisition was made in that quarter.

and fuel type from 2003-2010.[6] Of the fuel price data, the gasoline and diesel price data are obtained from U.S. Energy Information Administration (U.S. Department of Energy, 2012d), of which the annual average retail prices (including tax) of gasoline (of all grades) and diesel (of all types) are used. These prices by state are available for California, Colorado, Florida, Massachusetts, Minnesota, New York, Ohio, Texas, and Washington. For other states, the average prices in the corresponding region are used, which are New England, Central Atlantic, Midwest, Gulf Coast, Rocky Mountain, and West Coast less California. The E85 prices are drawn from AFDC (U.S. Department of Energy, 2012b), with the similar resolution on the state dimension. Information on the number of E85 fueling stations are obtained from AFDC (U.S. Department of Energy, 2011c). These fuel data are merged with the vehicle choice data by the state and the year that the purchase took place in.

The third component of the data set is the campaign data. This research focuses on the Clean City Coalition program. Since 1993, A national network of nearly 100 Clean Citiescoalitionshave brought together stakeholders in the public and private sectors to reduce petroleum use, with one of the approaches being "developinginformation resourcesthat educate transportation decision makers about the benefits of using alternative fuels, advanced vehicles, and other measures that reduce petroleum consumption"(U.S. Department of Energy, 2012e). The information of interest is the number of clean cities by state and year, which is arranged from the *Coalition in Order of Designation* table by the U.S. Department of Energy (2011d). These campaign data are merged with the vehicle choice data by the state and the year that the purchase took place in.

4.2 Model Specification

Two discrete-choice model specifications are looked at in this research, the standard multinomial logit (MNL) model and the nested multinomial logit (NMNL) model.

[6] The fuel data for 2003 and 2004 are included for the purpose of possible variable lagging in the econometric model.

The former is relatively easy to calculate, but relies on the assumption of independence of irrelevant alternative (IIA) (Luce, 1959). That is, the relative choice probabilities of any two alternatives do not depend on other alternatives. The NMNL model, on the other hand, does not require the IIA assumption, but induces additional computational burden (McFadden, 1981).

The MNL model is adopted in place of the NMNL, since the IIA assumption fails to be rejected. To test if the IIA assumption is valid, I conduct a Hausman-McFadden test (Hausman and McFadden, 1984) on the MNL model, which suggests that the IIA assumption cannot be rejected.

For the MNL model, the utility that a consumer unit i gets from buying the vehicle with fuel type j is:

$$\begin{aligned} V_{ij} =& V_{ij}(fuel\_price, model\_age, transaction, type, norm\_model\_price, \\ & fam\_size, education, num\_of\_clean\_cities, num\_of\_E85\_stations\_previous) + \epsilon_{ij} \end{aligned}$$

where V_{ij} is a linear combination of i- or j-specific covariates with j-specific coefficients, and ϵ_{ij} is the identically and independently distributed error term. $fuel\_price$ is the dollar price of gasoline, diesel, and E85 per gasoline gallon equivalent (gge) in the year of purchase in the same state. $Model\_age$ is the age of the vehicle at the year of purchase. $Transaction$ is a dummy variable, a new vehicle when purchased being 1 and an old one being 0. $Type$ is a dummy variable, automobile being 0 and trucks, minivans, vans, or SUVs being 1. $Norm\_model\_price$ is the net purchase price of the vehicle normalized by the after-tax annual income of the consumer unit at the time of survey.[7] Fam_size is the size of the consumer unit at the time of survey. $Education$ is a dummy variable, the reference person in the consumer unit not having a bachelor's degree being 0 and having a bachelor's degree or higher being 1 at the time of survey.

[7]The combined use of the income and the purchase price with different timing is justified by the permanent income hypothesis (Friedman, 1957), which states that consumer spending behavior is largely affected by permanent changes in income rather than temporary ones. In particular, it is reasonable to believe that consumers base the vehicle purchase decision largely on the expected income in the years to come, which is more relevant to the permanent income than is the current income.

$Num\_of\_clean\_cities$ is the number of clean cities in the year of purchase in the same state. $Num\_of\_E85\_stations\_previous$ is the number of E85 stations in the previous year of purchase in the same state. Using the number of E85 stations in the previous year of purchase instead of that in the current year enables the model to examine the effect of the refueling availability on the vehicle choice probability. Otherwise, it would be difficult to distinguish between the effect of the refueling availability on the vehicle choice probability and the effect of the latter on the former in the same year.

The probability that a consumer unit i chooses alternative j out of K alternatives takes the following closed form, if the error term is assumed to follow type I standard extreme-value distribution:

$$P_{ij} = \frac{\exp(V_{ij})}{\sum_{k=1}^{K} \exp(V_{ik})} \tag{4.1}$$

Maximum likelihood estimation is performed to maximize the log sum of choice probabilities across consumer units. Since the difference of these coefficients across alternatives, rather than the coefficients themselves, are relevant and may be identified, one of the alternative must be used as a benchmark, meaning that the coefficients for that alternative are all zero. Here, the set of alternatives are gasoline, diesel, hybrid, and E85, and the gasoline is used as the benchmark.

One might be concerned about the potential correlation between the number of clean cities and the number of E85 stations in the same state. First, different states may have different innate "greenness", or environmental friendliness, which will affect both the number of clean cities and the number of E85 stations. Furthermore, even if the state "greenness" is controlled for, there may also be a direct effect of clean city coalition campaigns on the number of E85 stations. In the specification in this research, the second concern is resolved by using the number of E85 stations in the year preceding the vehicle purchase year, instead of that within the same year, based on the belief that the number of E85 stations will not be affected by the clean city coalition campaign in the next year if the state "greenness" is controlled for. The first concern will be resolved in future research.

4.3 Results and Discussion

Table B.4 presents estimates of the MNL model, in which gasoline vehicles are used as a benchmark. The key findings are that both the number of clean cities in the same state in the year of purchase and the number of E85 refueling stations in the same state in the previous year are significantly positively correlated with the purchase probability of FFVs. On magnitude, by normalizing the coefficients with that of the E85 price in the same state, I find that the addition of one clean city in the same state is equivalent to a reduction in the E85 price of $0.04 per gasoline gallon equivalent in terms of their effects on the FFV choice probability, and that the addition of one hundred E85 fueling stations is equivalent to a reduction of $0.19 per gasoline gallon equivalent.

To interpret this, suppose that a consumer faces a choice among the four types of vehicles. For some reason, the E85 fuel price drops by $0.04 per gasoline gallon equivalent. According to the results of the model, this will increase the consumer's relative preference of buying an FFV over a gasoline vehicle. Depending on the consumer's characteristics such as income, education, etc., this increase in relative preference may result in a higher utility of getting an FFV instead of a gasoline vehicle (if not yet so), and consequently the consumer may opt for an FFV if the utility of getting the hybrid vehicle or the diesel vehicle is lower. This effect of this amount of reduction in the E85 fuel price on the purchase behavior of this consumer is the same as that of establishing an additional clean city in the same state. Similarly, the effect of the reduction of $0.19 per gasoline gallon equivalent in the E85 fuel price on the purchase behavior of this consumer is the same as that of having 100 more E85 fueling stations.

In addition, there is also significant evidence that people tend to prefer younger but used FFVs compared to gasoline vehicles. This could mean that if a consumer faces a choice between a gasoline vehicle, a recently-produced but used FFV, and a brand-new FFV produced several years ago, she may well choose the recently-produced but used FFV if the gasoline vehicle is not chosen anyway. This may suggest that consumers' trust in the private use of FFVs is built on existing FFV owners' experience, and on recent production technologies.

Other factors, including characteristics of consumer units, are not found to significantly affect the FFV choice probability. I only find suggestive evidence that the higher the gasoline price or the lower the income-normalized net purchase price of FFV, the more likely that consumers will choose AFVs, although such effects are intuitive as the gasoline and E85 fuels are substitutes, and FFVs are normal good and are consistent with the law of demand. Likewise, it is suggested that the education level may be negatively correlated with the AFV choice probability.

Chapter 5

Conclusions

In this research, a theoretical static model which models the behavior of consumers and fuel providers is used to examine the incentive of the automotive industry in doing supply- or demand-side promotion to increase the use of alternative fuels in place of gasoline in the context of indirect network effects. Following the theoretical analysis, an empirical econometric model which tests the effects of refueling infrastructure availability and the Clean City Coalition program on private vehicle choice informs the automotive industry of the potential effectiveness of supply- and demand-side promotion.

For the market of single-fuel alternative fuel vehicles (AFVs), which exclusively use one alternative fuel, both low consumer environmental awareness and high infrastructure and operating costs can cause a zero single-fuel AFV market share and keep alternative fueling infrastructure out of the market. Demand-side promotion, such as campaigns aimed at increasing the consumer environmental awareness, and supply-side promotion, such as funding part of the upfront investment of setting up an alternative fueling station and funding part of the fueling costs, are helpful in creating both consumer demand for single-fuel AFVs and the diffusion of alternative fueling infrastructure, with different effectiveness. In particular, demand-side promotion is necessary if the negligible market penetration of single-fuel AFVs and alternative fueling stations is due to low consumer environmental awareness. However, while supply-side promotion is helpful when fuel providers face difficulty in terms of high upfront and operating costs, increasing consumer awareness will also be helpful in creating AFV demand and incentivizing fuel providers to set up alternative fueling stations.

Thanks to potential effects of demand- or supply-side promotion, the single-fuel AFV monopoly will have incentive to initiate such promotion in their own interests when the promotion costs are affordable. By parameterizing the theoretical single-fuel AFV model using estimates of expensive electric vehicles, compressed natural gas vehicles and liquified natural gas vehicles, all of which have negligible private-use market share, I illustrate that the single-fuel AFV monopoly is more likely to have incentive: 1) to work to increase consumer awareness if the unit promotion cost is lower; and 2) to fund part of the fueling cost if the upfront investment for a refueling station, normalized by size of served customers, is lower. They are also likely to have incentive to fund part of the upfront investment of alternative fueling stations.

The market of dual-fuel AFVs, which utilize both gasoline and one alternative fuel, is found also subject to the obstacle set by low consumer awareness or high infrastructure and operating costs, but additional complication on the structure of the non-zero AFV market share arises due to the fuel choice flexibility of dual-fuel AFVs. The consumer awareness specifically for the environment-friendliness of alternative fuels, as opposed to for that of the combination of alternative fuels and vehicles, is the key factor in deciding what form the non-zero AFV market shares take. Indeed, given an initial market of all pre-existing duel-fuel AFV owners using gasoline in place of alternative fuels, as consumer awareness for fuel increases, more of them will switch to the use of alternative fuels, followed by more consumers who do not previously own duel-fuel AFVs choosing them and fueling them with alternative fuels. Increasing consumer awareness of fuels is necessary to increase the use of alternative fuels in place of gasoline in the market of dual-fuel AFVs.

Similarly, thanks to the potential effect of increasing consumer awareness for fuel on bringing more dual-fuel AFV users, the dual-fuel AFV monopoly will have incentive to initiate such supply-side promotion in their own interests when the promotion costs are affordable. By parametrizing the theoretical duel-fuel AFV model using estimates of flex-fuel vehicles (FFVs), which now enjoy a positive market share but are rarely dedicated to using E85 fuels, I illustrate that the dual-fuel AFV monopoly is more likely to have incentive to work to increase consumer awareness if the unit promotion cost is lower.

The empirical analysis, based on a multinomial logit model, finds strong evidence that both the diffusion of alternative refueling infrastructure and consumer awareness campaigns increase the probability of consumers choosing AFVs. Using a unique data set comprising of vehicle purchase behavior and characteristics of consumer units in the United States, and information on the historical fuel price and number of fueling stations for gasoline, diesel, and E85 from 2005-2010, I find that the addition of 1 clean city or the addition of 100 E85 refueling stations in the state where the consumer unit is are equivalent to a reduction of \$0.04 or \$0.19 in the E85 fuel price in terms of their effects of increasing the FFV choice probability respectively.

This research provides both private and public policy implications. On private policy, the automotive industry may wish re-evaluate the business opportunities in doing demand- or supply-side promotion, based on an improved understanding of the indirect network effects between the alternative fuels and vehicles, as illustrated theoretically and empirically in this research. It should be noted that the incentive of the automotive industry studied in this research is the lower bound in that this research only considers monetary profit. If car companies care about other dimensions of "profits" such as the reputation of being an environment-responsible entity in addition to the monetary dimension, they will be more dedicated to the demand- or supply-side promotion.

On public policy, policy makers may need to think twice about the current policy practice and before implementing future policies related to increasing the consumption of alternative fuels in place of traditional fuels. Although this research does not provide a comprehensive benefit-and-cost analysis for the automotive-industry-initiated promotion or the government-initiated policies, it demonstrates the possibility of the well-informed market being able to solve this chicken-and-egg problem of alternative fuels and vehicles. Keeping this idea in mind, policy makers may be able to better evaluate and critique policies with similar ends and come up with a more efficient system of policies by engaging more market force.

Many avenues remain to be explored along the line of theoretical analysis. First, a model assuming various market structures other than monopoly is needed. Among the potential differences that the assumption of other market structures may induce for the findings, the most interesting one will be related to spillover effects across market players. For example, the incentive problem of AFV duopolies is expected to be different from what has been discussed in this research, as one AFV manufacturer's sale of AFVs is able to benefit from there being more alternative fueling infrastructure thanks to the other manufacturer's sponsorship of upfront infrastructure investment.

Second, the AFV choice set can be enlarged to accommodate competition among several AFVs and traditionally-fueled vehicles. The theoretical models in this research assume that consumers choose either the gasoline vehicle or the AFV by comparing the expected utilities of only these two choices. However, in reality, consumers may face a much larger choice set and base their purchase decision on the comparison among multiple AFVs and traditionally-fueled vehicles.

Third, the game specification can incorporate more justifiable considerations. The causes of the lock-in problem may be much more complicated than low consumer awareness and high infrastructure and operating costs which have been discussed in this research. Justifiable considerations can be given to the imperfect and incomplete information of consumer awareness perceived by fuel providers and car companies, and that of infrastructure and operating costs perceived by consumers and car companies. Moreover, the private information held by the car companies may also affect the strategy of consumers and fuel providers.

Future empirical research topics can include how the vehicle price and fuel price interact with consumer demographics in determining consumer vehicle choice pattern. The seminal paper by Hausman (1979) on how consumers of different characteristics trade off between upfront capital costs and expected operating costs, which are incurred later, when purchasing energy-using durables finds that consumers of higher income have lower discount rates. Facing a higher vehicle cost and a lower fuel cost, which are typical of many currently available AFVs, do consumers display similar purchase behavior? In addition, it also remains to be examined if the payment structure of vehicle purchase, which is typically composed of a down payment upfront and monthly payment later on, may mitigate the sensitivity to the vehicle cost of consumers, in particular those of lower income.

Appendix A

Acronyms and Abbreviations

Table A.1: Acronyms and abbreviations

AFDC	Alternative Fuel Data Center
AFV	Alternative fuel vehicle
CNG	Compressed natural gas
CNGV	Compressed natural gas vehicle
EV	Electric vehicle
FFV	Flex-fuel vehicle
GGE	Gasoline gallon equivalent
IIA	Independence of irrelevant alternative
LNG	Liquified natural gas
LNGV	Liquified natural gas vehicle
MNL	Multinomial logit
MPG	Miles per gallon
NMNL	Nested multinomial logit

Appendix B

Tables

Table B.1: Determining the sign of $\Delta w + \Delta c - \frac{5}{4}\sqrt{t^g f^g}$: model and fuel costs of selected AFVs relative to those of gasoline vehicles

Parameter	Inexpensive EV	**LNGV**	**CNGV**	**FFV**
$\Delta\omega(\$)$[a]	6,000	6,000	6,000	100
$\Delta c(\$)$[b]	-3,000	3,812	-5,311	4,583

[a] LNGVs and CNGVs are several thousand dollars more expensive than the gasoline vehicle (Gable and Gable, 2012), while the price of FFVs are comparable to that of gasoline vehicles (Romm, 2006; Gable and Gable, 2012). The numbers are assumed based on these claims. A relatively low price premium for EV is used in this model. According to Karplus *et al.* (2010), EV is usually estimated to be more than $10,000 more expensive than vehicles powered solely by an internal combustion engine, including gasoline vehicles. An estimate of $30,000 for gasoline vehicles is used, which may be a relatively high price. According to Simpson (2006), vehicles powered solely by an internal combustion engine, including gasoline and diesel vehicles, is estimated to be around $23,392. It should be noted that all the values of parameters are used for illustrative purposes only. Users of the models described in this research can substitute for estimates of the parameters from other sources for their respective purposes.

[b] These estimates are mainly based on the national average fuel prices in January 2012 collected by U.S. Department of Energy (2012b). See Appendix D for derivation details.

Table B.2: Parameterizing the model: the values of measurable parameters for the single-fuel AFV model

Parameter	Meaning	Inexpensive EV	LNGV	CNGV
$\omega^r - c_{AFV}(\$)$	Net margin of the AFV[a]	5,400	5,400	5,400
$\Delta\omega(\$)$	Price premium of the AFV[b]	6,000	6,000	6,000
$\sqrt{t^g f^g}(\$)$	Square root of the per-distance driving cost multiplied by the upfront infrastructure cost: gasoline[c]	866	866	866
$\sqrt{t^r f^r}(\$)$	Square root of the per-distance driving cost multiplied by the upfront infrastructure cost: alternative fuels[d]	100	1,082	843
$\Delta p(\$)$	Price premium of the alternative fuel[e]	-3,000	3,812	-5,311
γ	Markup factor of alternative fueling	2	1.2	1.2

[a] Net margin of the AFV is assumed to be 15% of the assumed AFV price \$36,000.

[b,e] See Table B.1.

[c] This term is numerically equivalent to the lifetime gross margin of gasoline by (2.8) and (2.9). By Johnson and Melendez (2007), the gross margin (net transport cost) for gasoline is about 6 percent of the price. I use the per gasoline equivalent fuel prices in January, 2012 from the Alternative Fuel Data Center (U.S. Department of Energy, 2012b), of which the gasoline price is \$3.37 per gallon. Hence the gross margin of gasoline per gallon is $3.37 \times 0.06 = \$0.2022$ per gallon. The lifetime gross margin can be estimated by multiplying this number by the lifetime mileage divided by fuel economy of gasoline vehicles, which yields $0.2022 \times 128,500/30 = \$866$. Both the average fuel economy of gasoline vehicles and the lifetime average mileage of a vehicle in U.S. are obtained from U.S. Department of Transportation (2011). Note that this term is not calculated directly from f^g and t^g because of the difficulty in assigning available meaningful real-world estimates to them.

[d] This is estimated by comparing the meaningful real-world estimates of t^g and f^g with their gasoline counterpart. The upfront cost (including land) for setting up a gasoline station is estimated to be \$2,000,000, and for setting up a Level 2 commercial facility EV charging infrastructure is around \$30,000 (equipment plus land cost) (Morrow *et al.*, 2008). The ratio of per-distance driving cost is assumed to be approximated by the ratio of the per mile fuel price. The per mile gasoline price is $3.37/30 = 0.11$ dollar, and the per mile fuel cost savings for EV is $\$0.02 \sim \$0.04$ (U.S. Department of Energy, 2012b). Hence the per mile fuel price ratio of gasoline over electricity is around 1.2. Based on these ratios, the term in question is estimated to be \$100. The LNG and CNG numbers are similarly derived from an upfront cost for a LNG station around \$2,500,000 (Rood Werpy *et al.*, 2010) and a CNG station around \$3,000,000 (PR Newswire, 2011), and the per gasoline equivalent price for LNG \$4.26 and for CNG \$2.13 (U.S. Department of Energy, 2012b).

Table B.3: Parameterizing the model: the calibrated values of consumer awareness for the single-fuel AFV model

Equilibrium	**Inexpensive EV**	**LNGV**	**CNGV**
Case I zero: ϵ[a]	1,484	5,117	/
Case II zero: ϵ[b]	/	7,676	378
Case II zero: ϕ_1[c]	/	12,794	630
Case II zero: ϕ_2[d]	/	19,191	945

[a] The numbers in this row are 80% of the values which make (3.4) an equality.
[b] The numbers in this row are 120% of the values which make (3.8) an equality.
[c] The numbers in this row are 200% of the values which make (3.8) an equality.
[d] The numbers in this row are 300% of the values which make (3.8) an equality.

Table B.4: Parameterizing the model: the values of measurable parameters and the calibrated values of consumer awareness for the dual-fuel AFV model

Parameter	**Meaning**	**FFV**
$\omega^r - c_{AFV}(\$)$	Net margin of the AFV[a]	4,515
$\Delta\omega(\$)$	Price premium of the AFV[b]	100
$\sqrt{t^g f^g}(\$)$	Square root of the per-distance driving cost multiplied by the upfront infrastructure cost: gasoline	866
$\sqrt{t^r f^r}(\$)$	Square root of the per-distance driving cost multiplied by the upfront infrastructure cost: alternative fuels[c]	971
$\Delta p(\$)$	Price premium of the alternative fuel[d]	4,583
γ	Markup factor of alternative fueling	1.2
Z	Consumer awareness for fuel[e]	2,329
$\Delta\Gamma$	Difference in consumer awareness for AFVs and gasoline vehicles[f]	69

[a] Net margin of the AFV is assumed to be 15% of the assumed AFV price \$30,100.

[b] See Table B.1.

[c] This number is similarly derived from an upfront cost for an individual E85 station around \$2,100,000 (equipment plus land cost) (U.S. Department of Energy, 2008), and the per gasoline equivalent price for E85 \$4.44 (U.S. Department of Energy, 2012b).

[d] See Table B.1.

[e] The consumer awareness for fuel is 80% of the value which makes (3.14) an equality.

[f] The difference in consumer awareness for AFVs and gasoline vehicles are calibrated to match the real-world FFV market share shown in Figure C-1.

Table B.5: Estimates of the standard multinomial logit model for consumer vehicle choice, 2005-2010.

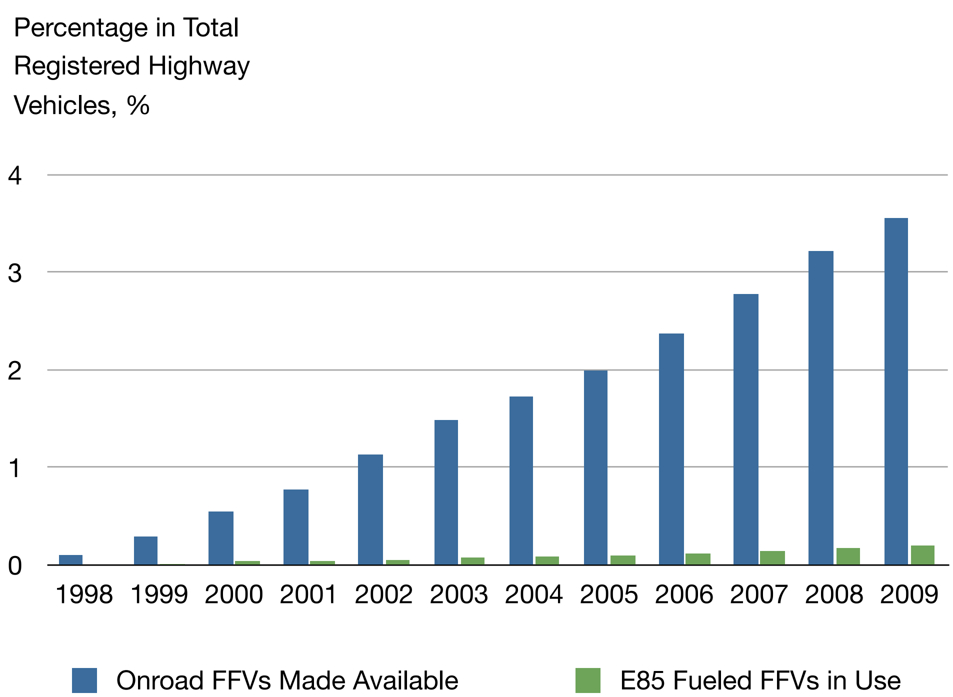
Variable	**Diesel**	**Hybrid**	**Flex-fuel**
Gasoline price in the same state ($ per gge)	0.339	4.17***	5.92
	(1.06)	(1.33)	(5.19)
Diesel price in the same state ($ per gge)	-0.551	-2.89***	-2.50
	(0.865)	(1.05)	(3.95)
E85 price in the same state ($ per gge)	-0.0474	-0.0828	-4.80*
	(0.348)	(0.438)	(2.60)
Model age (year)	-0.0200	-0.387***	-0.701**
	(0.0219)	(0.105)	(0.305)
Transaction (0=used, 1=new)	0.538**	0.135	-1.53*
	(0.246)	(0.372)	(0.882)
Type (0=automobile, 1=trucks, minivans, vans, or SUVs)	1.54***	-1.29***	0.988
	(0.233)	(0.311)	(0.730)
Net purchase price normalized by after-tax income	-0.0936	-0.0000489	-0.108
	(0.110)	(0.00100)	(0.382)
Family size	-0.0791	-0.116	0.162
	(0.0656)	(0.0935)	(0.212)
Education (0=no bachelor degree, 1=bachelor and higher degree)	-0.274	1.33***	-0.274
	(0.221)	(0.258)	(0.735)
Number of Clean Cities in the same state	-0.0243	-0.0463	0.194*
	(0.0322)	(0.0350)	(0.115)
Number of E85 fueling stations in the same state in the previous year (thousand)	-0.471	1.75	9.29**
	(2.28)	(2.42)	(4.04)
Constant	-4.27***	-7.31***	-0.539
	(1.11)	(1.50)	(3.96)

Gasoline vehicles are used as a benchmark. Log likelihood = -969.53527. Asterisks denote statistical significance on the $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$ level.

Appendix C

Figures

Figure C-1: The market share of FFVs, 1998-2009.



Source: U.S. Department of Energy (2012a), U.S. Department of Transportation (2011).

Figure C-2: Scenarios for examining the incentive of the single-fuel AFV monopoly

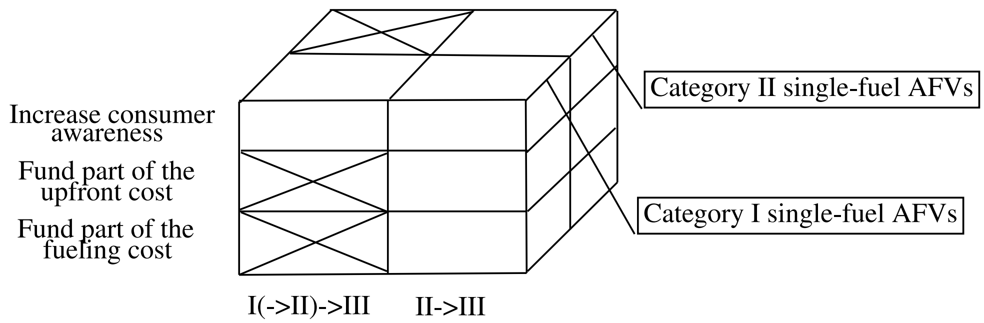


Figure C-3: The scenario for examining the incentive of the dual-fuel AFV monopoly

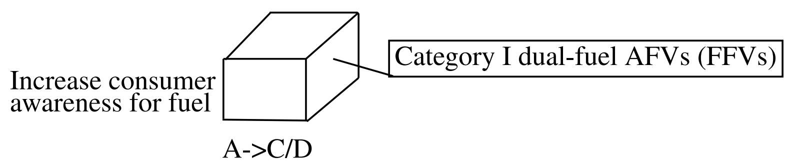


Figure C-4: The utility of the single-fuel AFV monopoly by only demand-side promotion in order to move from the Case I zero equilibrium to a Case III high realization equilibrium and the resulting AFV market share, given various unit promotion costs h: inexpensive EV versus LNGV

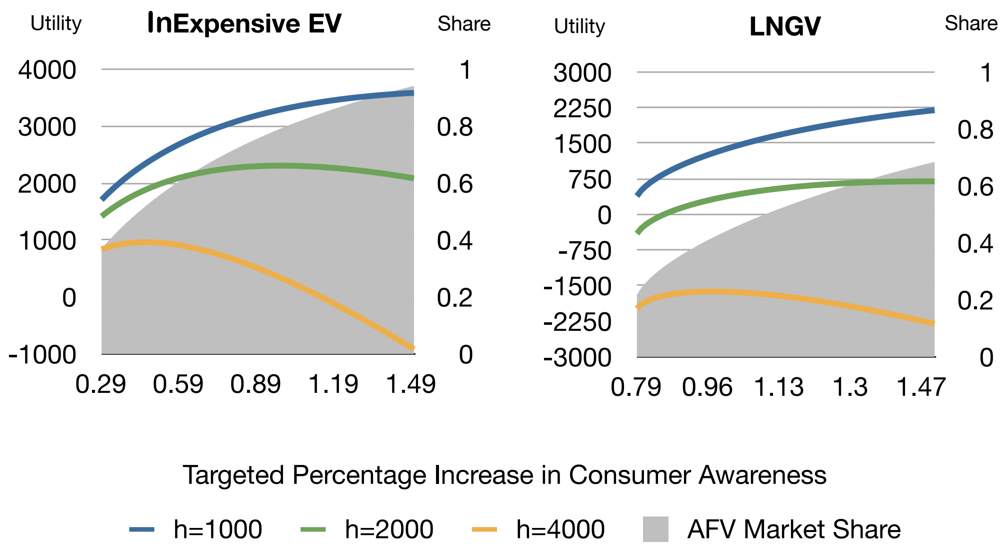


Figure C-5: The utility of the single-fuel AFV monopoly by only demand-side promotion in order to move from the Case II zero equilibrium to a Case III high realization equilibrium and the resulting AFV market share, given various unit promotion costs h: LNGV versus CNGV

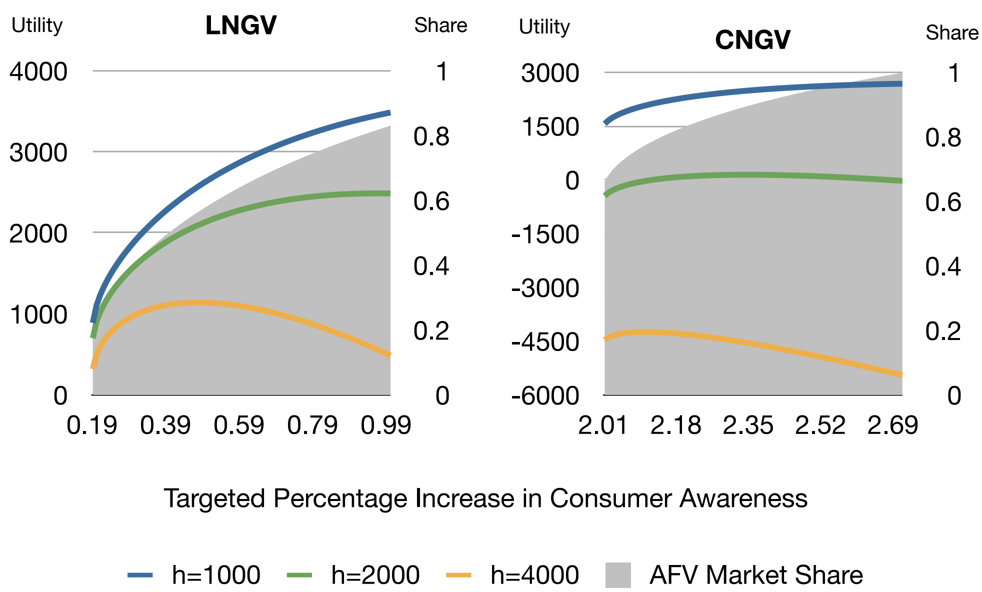


Figure C-6: The utility of the single-fuel AFV monopoly by only funding upfront investment in order to move from the Case II zero equilibrium to a Case III high realization equilibrium and the resulting AFV market share: LNGV versus CNGV

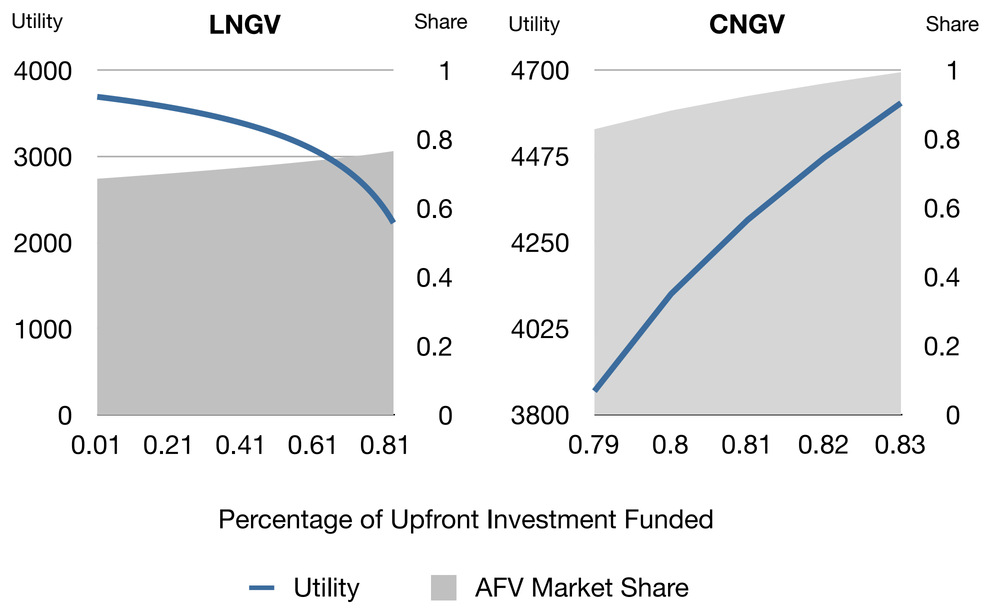


Figure C-7: The utility of the single-fuel AFV monopoly by only funding the fueling cost in order to move from the Case II zero equilibrium to a Case III high realization equilibrium and the resulting AFV market share, given various normalized upfront costs f: LNGV versus CNGV

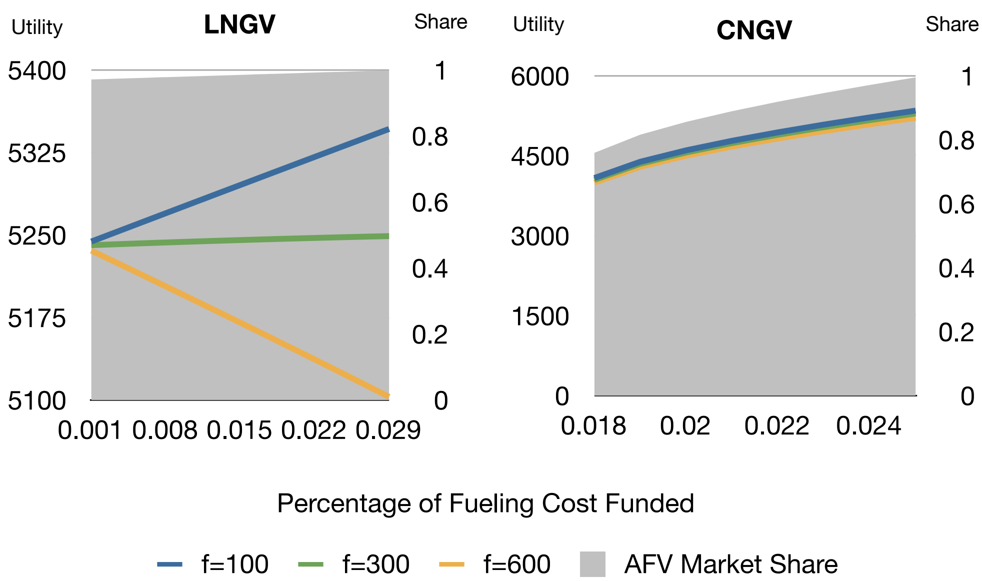
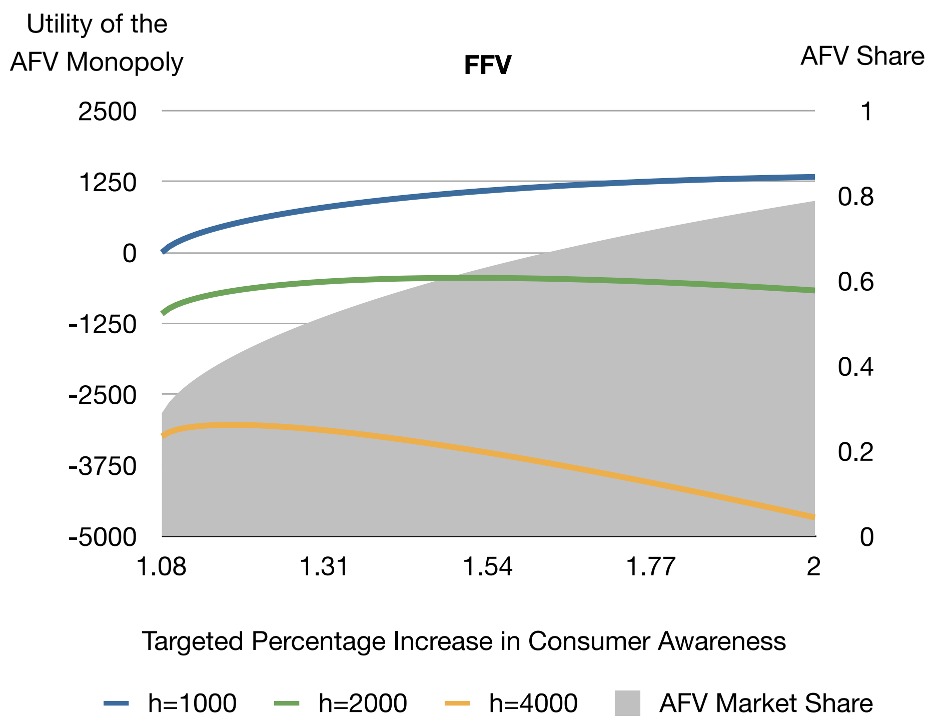


Figure C-8: The utility of the dual-fuel AFV monopoly by only demand-side promotion in order to move from the Case A equilibrium and the resulting AFV market share: FFV



Appendix D

Determining the Sign of $\Delta w + \Delta c - \phi_2 c^r - \frac{5}{4}\sqrt{t^g f^g}$

To evaluate the comparative statics of a with respect to $\Delta\Gamma + Z$ in equation (2.18), it is essential to determine the sign of $\Delta w + \Delta c - \phi_2 c^r - \frac{4}{5}\sqrt{t^g f^g}$. I use data from various sources to parameterize this expression in order to estimate the sign.

Δw is the price premium of AFVs over gasoline vehicles. This varies across AFV types. For hybrids, CNGVs and LNGVs, this is usually several thousand dollars, while FFVs and diesel vehicles (which can run on biodiesel) are available at prices comparable to those of gasoline vehicles (Gable and Gable, 2012). EVs are usually estimated to be more than \$10,000 more expensive than vehicles powered solely by an internal combustion engine, which include gasoline and diesel vehicles (Valerie *et al.*, 2009).

Δc is the lifetime fueling cost premium of alternative fuels over gasoline faced by the fueling stations. For simplicity, I approximate this cost premium with the price premium. First, I obtain national fuel prices in January 2012 from the AFDC (U.S. Department of Energy, 2012b) as follows (per gasoline gallon equivalent): \$ 3.37 for gasoline, \$3.46 for diesel, \$2.13 for CNG, \$4.44 for E85, \$ 4.26 for LNG, \$3.61 for B20, and \$4.14 for B99-100. The AFDC also provides that the per mile fuel price saving for hybrids is \$0.05∼\$0.07, and that for EVs is \$0.02∼\$0.04 (U.S. Department of Energy, 2011e). Second, I multiply the above per gallon price premiums with the average life span of a vehicle in U.S., which is about 128,500 miles, and (for non-electricity fuels only) further divide this value by the average fuel economy of gasoline vehicles, which is about 30 miles per gallon (MPG) (U.S. Department of Transportation, 2011). Thus, Δc is approximately -\$5,311 for CNG, \$4,583 for E85, \$3,812 for LNG, \$1,028 for B20, \$3,298 for B99-100, -\$6,425∼-\$8,995 for hybrids, and -\$2,570∼\$-5,140 for pure electricity.

For $\sqrt{t^g f^g}$, note that $\sqrt{t^g f^g} = \frac{t^g}{n^g} = p^g - c^g$ by (2.8) and (2.9). That is, this term is equivalent to the lifetime gross margin of gasoline. According to Johnson and Melendez (2007), the gross margin (net transport cost) is about 6 percent of the gasoline price. Hence, the lifetime gross margin, $p^g - c^g$, is approximately $0.06 \times 3.37 \times 128,500 \times \frac{1}{30} = \$866$. Also see Table B.2.

Therefore, with the term $-\phi_2 c^r$ excluded, the expression in question take on values of approximately positive several thousands for inexpensive EVs, LNGVs, FFVs, and biodiesel vehicles (*Category I* AFVs), negative several thousands for CNGVs (*Category II* AFVs), and can range from negative several thousands to positive several thousands for hybrids, depending on how expensive hybrids are.

Bibliography

Andreoni, J. (1990), "Impure Altruism and Donations to Public Goods: A Theory of Warm-Glow Giving," *The Economic Journal*, 100, 401, pp. 464-477.

Rood Werpy, M., Bumham, A., and Bertram, K. (2010), "Propane Vehicles: Status, Challenges, and Opportunities," Argonne National Laboratory Report ANL/ESD/10-2, Argonne, IL (USA). http://www.transportation.anl.gov/pdfs/AF/633.PDF. Last checked April 25, 2012.

Achtnicht, M., Bühler, G., and Hermeling, C. (2012), "The Impact of Fuel Availability on Demand for Alternative-Fuel Vehicles," *Transportation Research Part D: Transport and Environment*, 17, 3, pp. 262-269.

Brownstone, D., Bunch, D.S., and Train, K. (2000), "Joint Mixed Logit Models of Stated and Revealed Preferences for Alternative-Fuel Vehicles," *Transportation Research Part B: Methodological*, 34, 5, pp. 315-338.

Bunch, D.S., Bradley M., Golob, T.F., and Kiramura, R. (1993), "Demand for Clean-Fuel Vehicles in California: A Discrete-Choice States Preference Pilot Project," *Transportation Research Part A: Policy and Practice*, 27, 3, pp. 237-253.

California Environmental Protection Agency (2005), "California Hydrogen Blueprint Plan", Volume 1, CA (USA). http://www.hydrogenhighway.ca.gov/plan/reports/bpplan_vol1.pdf. Last checked April 19, 2012.

Corts, K.S. (2009), "Building out Alternative Fuel Retail Infrastructure: Government Fleet Spillovers in E85," Center for the Study of Energy Markets, University of California Energy Institute, Berkeley, CA (USA), http://escholarship.org/uc/item/0h90r7k2. Last checked April 19, 2012.

Di Pascoli, S., Femia, A., and Luzzati, T. (2001), "Natural Gas, Cars, and the Environment: A (Relatively) 'Clean' and Cheap Fuel Looking for Users," *Ecological Economics*, 38, 2, pp. 179-189.

Florida Department of Environmental Protection (2007), "Florida's Hydrogen Program: H2 Florida", FL (USA). http://www.pnl.gov/fuelcells/docs/summits/

summit8/presentations/day1/bedwell_1230pm.pdf. Last checked April 19, 2012.

Friedman, M. (1957), "The Permanent Income Hypothesis," in *A Theory of the Consumption Function*, Princeton University Press, Princeton, NJ (USA).

Gable, C. and Gable, S. (2012), "How Much Does an Alternative Fuel Vehicle Cost?," http://alternativefuels.about.com/od/alternativefuels101/a/afvfaq5.htm. Last checked April 25, 2012.

Greaker, M. and Heggedal T.-R. (2010), "Lock-in and the Transition to Hydrogen Cars: Should Governments Intervene?," *The B.E. Journal of Economic Analysis & Policy*, 10, 1, Article 40.

Gross B.K., Sutherland, I.J., and Mooiweer, H. (2007), "Hydrogen Fueling Infrastructure Assessment," GM Research and Development Center, Warren, MI (USA). http://www.renewableenergyworld.com/assets/documents/2008/10Things.pdf. Last checked April 19, 2012.

Hausman, J.A. (1979), "Individual Discount Rates and the Purchase and Utilization of Energy-Using Durables," *The Bell Journal of Economics*, 10, 1, pp. 33-54.

Hausman, J.A., and McFadden, D. (1984), "Specification Tests for the Multinomial Logit Model," *Econometrica*, 52, 5, pp. 1219-1240.

Johnson, C. and Melendez, M. (2007), "E85 Retail Business Case: When and Why to Sell E85," National Renewable Energy Laboratory Technical Report NREL/TP-540-41590, Golden, CO (USA). http://www.afdc.energy.gov/afdc/pdfs/41590.pdf. Last checked April 25, 2012.

Karplus, V.J., Paltsev, S., and Reilly, J.M. (2010), "Prospects for Plug-in Hybrid Electric Vehicles in the United States and Japan: A General Equilibrium Analysis," *Transportation Research Part A*, 44, pp. 620-641.

Katz, M.L. and Shapiro, C. (1985), "Network Externalities, Competition, and Compatibility," *The American Economic Review*, 75, 3, pp. 424-440.

Kuby, M. and Lim, S. (2007), "Location of Alternative-Fuel Stations Using the Flow-Refueling Location Model and Dispersion of Candidate Sites on Arcs," *Networks and Spacial Economics*, 7, 2, pp. 129-152.

Luce, R. D. (1959), *Individual Choice Behavior*, Wiley, New York, NY (USA).

McCormick, J.B. (2003), "Hydrogen and Fuel Cell Overview: Transition to the Transportation of Tomorrow", Senate Science and Technology Caucus, Washington, DC

(USA).

McFadden, D. (1981), "Econometric Models of Probabilistic Choice", in *Structure Analysis of Discrete Data*, ed. by Manski, C. and McFadden, D. MIT Press, Cambridge, MA (USA).

Melaina, M.W. and Ross, M.H. (2000), "The Ultimate Challenge: Developing an Infrastructure for Fuel Cell Vehicles," *Environment*, 42, pp. 10-22.

Melaina, M.W. (2005), "Initiating Hydrogen Infrastructures: Analysis of Technology Dynamics during the Introduction of Hydrogen Fuel for Passenger Vehicles," PhD Dissertation, School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI (USA).

Morrow, K., Karner, D., and Francfort, J (2008), "Plug-in Hybrid Electric Vehicle Charging Infrastructure Review," The Idaho National laboratory Report INL/EXT-08-15058, Idaho Falls, ID (USA). `http://avt.inel.gov/pdf/phev/phevInfrastructureReport08.pdf`. Last checked April 25, 2012.

Parry, I.W.H., Walls, M., and Harrington, W. (2008), "Automobile Externalities and Policies," Resources for the Future Discussion Paper No. 06-26.

PR Newswire (2011), "Compressed Natural Gas Fueling Stations Get Green Light in Georgia," `http://www.prnewswire.com/news-releases/compressed-natural-` urlgas-fueling-stations-get-green-light-in-georgia-133023448.html. Last checked April 25, 2012.

Romm, J. (2006), "The Car and Fuel of the Future," *Energy Policy*, 34, pp. 2609-2614.

Salop, S. (1979), "Monopolistic Competition with Outside Goods," *Bell Journal of Economics*, 10, pp. 141-156.

Shaked, A., and Sutton, J. (1979), "Relaxing Price Competition Through Product Differentiation," *Review of Economics Studies*, XLIX, pp. 3-13.

Simpson, A. (2006), "Cost-Benefit Analysis of Plug-in Hybrid Electric Vehicle Technology," National Renewable Energy Laboratory report NREL/CP-540-40485, Golden, CO (USA).

Thomas, K. (2007), "'Flex-Fuel' Vehicles Touted," `http://www.usatoday.com/money/autos/environment/2007-05-05-ethanolvehicles_N.htm`. Last checked April 19, 2012.

U.S. Department of Energy (2008), "Cost of Adding E85 Fueling Capability to Existing Gasoline Stations," National Renewable Energy Laboratory report NREL/FS-

540-42390, Golden, CO (USA). http://www.afdc.energy.gov/afdc/pdfs/42390.pdf. Last checked April 25, 2012.

U.S. Department of Energy (2011a), "Alternative & Advanced Fuels," http://www.afdc.energy.gov/afdc/fuels/index.html. Last checked April 19, 2012.

U.S. Department of Energy (2011b), "Federal & State Incentives & Laws," http://www.afdc.energy.gov/afdc/laws/matrix/tech. Last checked April 19, 2012.

U.S. Department of Energy (2011c), "Data, Analysis & Trends: Infrastructure," http://www.afdc.energy.gov/afdc/data/infrastructure.html. Last checked April 23, 2012.

U.S. Department of Energy (2011d), "Coalitions in Order of Designation," http://www.afdc.energy.gov/cleancities/coalitions/coalition_designation.php. Last checked April 23, 2012.

U.S. Department of Energy (2011e), "Alternative & Advanced Vehicles: Benefits of Hybrid and Plug-In Electric Vehicles," http://www.afdc.energy.gov/afdc/vehicles/electric_benefits.html. Last checked April 25, 2012.

U.S. Department of Energy (2012a), "Data, Analysis & Trends: Vehicles," http://www.afdc.energy.gov/afdc/price_report.html. Last checked April 23, 2012.

U.S. Department of Energy (2012b), "Information Resources: Alternative Fuel Price Report," http://www.afdc.energy.gov/afdc/price_report.html. Last checked April 23, 2012.

U.S. Department of Energy (2012c), "Alternative & Advanced Vehicles," http://www.afdc.energy.gov/afdc/vehicles/index.html. Last checked April 23, 2012.

U.S. Department of Energy (2012d), "Weekly Retail Gasoline and Diesel Prices," http://www.eia.gov/dnav/pet/pet_pri_gnd_a_epm0_pte_dpgal_w.htm. Last checked April 23, 2012.

U.S. Department of Energy (2012e), "About Clean Cities," http://www1.eere.energy.gov/cleancities/about.html. Last checked April 23, 2012.

U.S. Department of Labor (2012), "Consumer Expenditure Survey," http://www.bls.gov/cex/. Last checked April 23, 2012.

U.S. Department of Transportation (2011), "National Transportation Statistics," http://www.bts.gov/publications/national_transportation_statistics/pdf/entire.pdf. Last checked April 25, 2012.