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Essays on Energy Efficiency and Pricing Behavior in the U.S. Automobile Market: Evidence from Hybrid Electric Vehicles

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Essays on Energy Efficiency and Pricing Behavior in the U.S. Automobile Market: Evidence from Hybrid Electric Vehicles

A Dissertation Presented for the

Doctor of Philosophy

Degree

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Sangsoo Park

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DEDICATION

This dissertation is dedicated to

my father, Jongan Park

and

in loving memory of my mother, Jeomrye Yoon.

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Abstract

This dissertation consists of three essays on the energy efficiency and pricing behavior of firms in the U.S. automobile market with a focus on Hybrid Electric Vehicles (HEVs).

The first essay analyzes the market share of HEVs and evaluates consumers' willingness to pay (WTP) for future fuel cost savings by purchasing fuel efficient HEVs. Estimates of consumers' WTP for future fuel cost savings and the finding of an implicit discount rate of 8.35%$\sim$14.35% suggest that consumers undervalue future fuel cost savings from purchasing HEVs, and that consumers want a return on their investment on fuel cost saving HEV technology in 7$\sim$11 years.

The second essay empirically investigates the existence of quality-based price discrimination in the U.S. automobile market. By estimating a structural model of demand and supply in the automobile market, I can recover marginal costs, markups and percentage markups for all vehicle models sold between 2000 and 2013. The extent of price discrimination is then examined by comparing markup and percentage markup differences between HEVs and gasoline vehicles. The results demonstrate that automobile manufactures charge both higher markups and higher percentage markups on their HEV models. On average, HEVs have higher markups by 11.1% compared to gasoline vehicles, and Toyota, a leader in the HEV market, charges higher markups on their HEV models compared to other manufacturers. The Toyota Prius, the top-selling hybrid car in the U.S. market, particularly enjoys a higher markup and percentage markup than other competitive vehicles.

The third essay provides a model of the automobile market where consumers have heterogeneous preferences, caring about both the environment and the physical quality of the product–specifically its fuel economy. Many of the results found by the model are to be expected: consumers buy fewer vehicles when the environmental damages (emissions) and prices of vehicles increase; more vehicles are sold when vehicles are equipped with better fuel technology; and consumers buy fewer vehicles as they become more pro-environmental. One unexpected finding stands out: a tax on gasoline vehicles always decreases total emissions, while a subsidy for environmentally friendly HEV adoption may not.

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Chapter 1

Market Share and Willingness to Pay for Hybrid Electric Vehicles in the U.S. Auto Market

1.1 Introduction

Since the first generation of two Hybrid Electric Vehicles (HEVs), Toyota Prius and Honda Insight, were introduced in the U.S. automobile market in 1999, there has been growing interest in HEVs. Due to their efficiency and high performance in terms of fuel economy, people expected that HEVs would be successful in the U.S. market. A HEV technology uses both a gasoline fueled engine and an electric motor powered by a rechargeable battery, and provides higher fuel efficiency and fewer emissions than traditional gasoline-powered vehicles.

These distinctive features of HEVs were attractive to both consumers and policy makers. Consumers were seeking more fuel efficient vehicles as gasoline prices started to rise after 2002 (Figure 1.1).

Policy makers have shown concern about the air pollution and energy security related to automobiles, and paid attention to fuel efficient HEVs. Motor vehicle

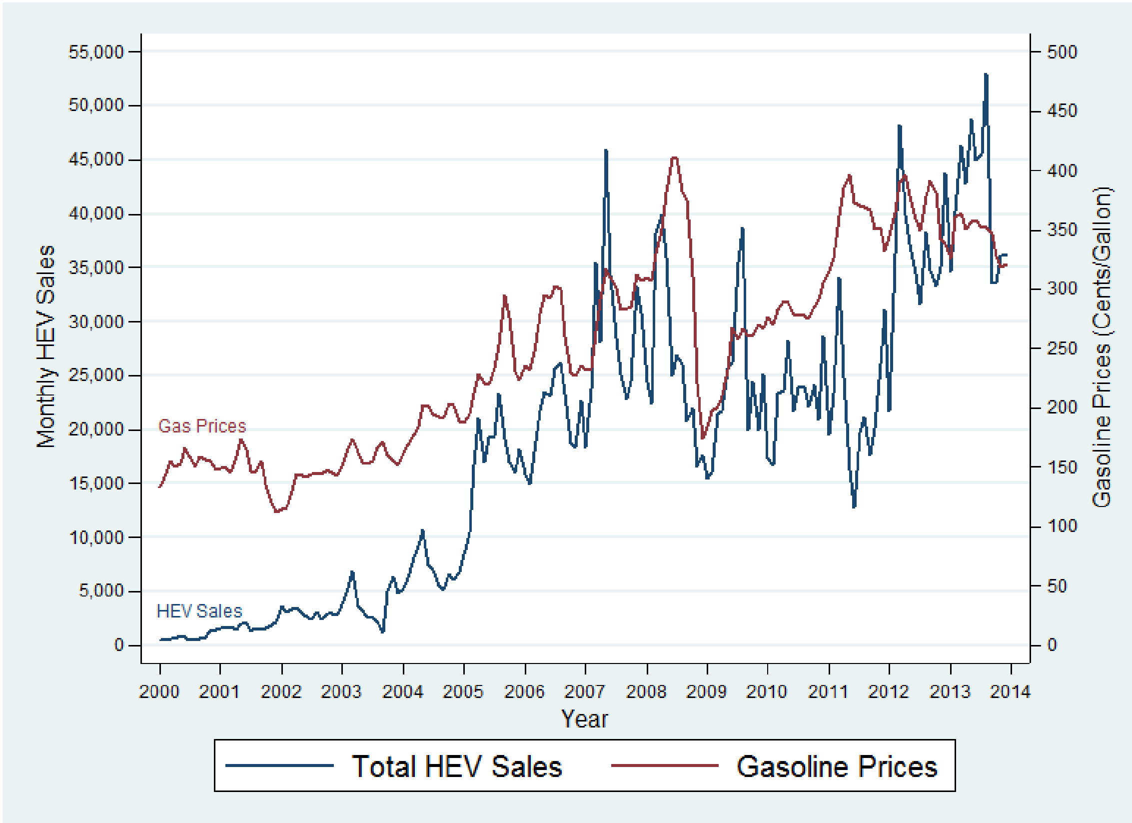

Figure 1.1: Monthly HEV Market Share and Gasoline Prices

emissions such as carbon monoxide (CO), nitrogen oxide (NO) and sulfur oxide (SO) are major sources of air pollution. In 2010, it was reported that the transportation sector alone accounted for 22% of U.S. greenhouse gas emissions and gasoline consumption accounted for almost 25% of total petroleum production (Bento et al. 2010).

With government's efforts[1] to increase HEV sales and the continuous increase of gasoline prices, the market share of total light-duty HEVs kept increasing until 2009 (2.80%) but slightly fell off by 2010 because of the after-effects of recession in 2008. Since then, the HEV market share has started to increase again, and the market share of new light-duty HEV was 3.23% in 2013 (Figure 1.2).

[1] Energy Policy Act of 2005 introduced a personal income tax credit up to $3,400 for HEVs. Some states also have offered various benefits to hybrid owners such as tax incentives, sales tax and fee exemption, and high-occupancy vehicle (HOV) lanes privileges.

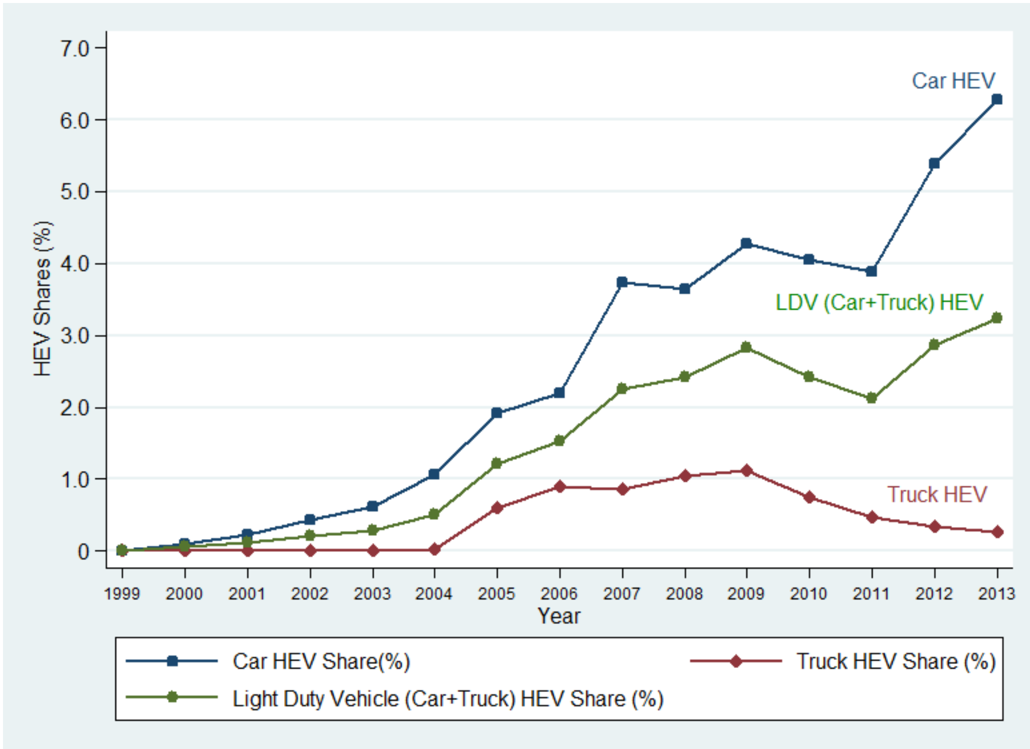

Figure 1.2: HEV Market Share in the U.S. Automobile Market

Though it has been more than a decade since HEVs were first introduced in the U.S. automobile market, few studies have been conducted on HEVs. This is partly due to the relatively recent introduction of HEVs as well as the lack of sufficient data on HEVs. Most of the studies have focused on the first generation of HEV models (e.g. Toyota Prius and Honda Insight) and analyzed the determinants of HEV adoption.

This paper aims to analyze market response to fuel efficient HEVs, and to evaluate whether HEV consumers rationally evaluate increased fuel economy of HEVs. In particular, this study focuses on the effects of 1) fuel efficiency, 2) price premium, and 3) federal tax incentives for HEVs on the market share of HEVs, and how consumers value future fuel cost savings from purchasing fuel efficient HEVs: The energy paradox.

Early studies of hybrid vehicles investigate the effects of federal and state tax incentives on hybrid adoptions. However, due to the limited diversity of HEV makes and models in the market, these studies use aggregate hybrid vehicle sales or the first generation of HEVs, the Prius and the Insight. Gallagher and Muehlegger (2011) study the effects of government tax incentives, gasoline prices and social preference for environmental and energy security on the adoption of hybrid vehicles. They estimated that tax incentives explained a 6% increase, gasoline prices explained a 27% and social preferences explained a 36% increase in hybrid vehicle adoption from 2000 to 2006. From these findings, they finally conclude that recent increase in HEVs sales is more likely to be the result of increases in the price of gasoline and social preferences than government tax incentives for HEVs. Kahn (2007) empirically tests whether environmentalists and non-environmentalists differ with respect to their day-to-day transportation and consumption patterns. The study finds that households living in Green Party areas, consume less gasoline, are less likely to purchase SUVs, and use more public transit. Beresteanu and Li (2011) examine determinants in the demand for HEVs and evaluate the government policies that aim to promote HEV sales using cross-sectional new vehicle registration data. Both rising gasoline prices and government income tax incentive are important factors for explaining HEV sales. The increase in gasoline prices from $1.53 in 1999 to $2.60 in 2006 explained the 14% increase in HEV sales in 2006. The income tax credit in 2006 accounts for 27% of hybrid vehicle sales. They also compare the income tax credit program with a rebate program, and find that a rebate program costs less government revenue in achieving the same fuel-efficiency of new vehicles. Heutel and Muehlegger (2009) investigate the diffusion of hybrid vehicles among consumers. They identify the effect of the penetration rate – total cumulative hybrid sales per capita – on new hybrid purchases. The focus is the effect of Toyota Prius and Honda Insight penetration rates on purchases of hybrid cars. They find that there is positive diffusion effect from the Toyota Prius and negative effect from the Honda Insight. That is, higher Prius penetration yields higher per capita sales of Toyota HEVs, but penetration of Insight has a negative effect on the sales of Honda HEVs. Chandra et al. (2010) study the effect of the tax rebate on HEV sales in Canadian provinces. They found that a $1,000 increase in the provincial sales tax rebate increases the market share of hybrid cars by 31%∼38%, and 26% of all HEVs sold during the rebate programs could be attributed to the rebates. Therefore, increased market share of HEVs crowded out some intermediate cars as well as intermediate SUVs and other high-performance compact cars. Using cross sectional vehicle choice data from NHTS 2009 survey, Liu (2014) estimates consumers' willingness to pay (WTP) for a hybrid choice, and find that consumers undervalue HEV features in that WTP is lower than hybrid premium.

This study contributes to recent empirical studies on exploring hybrid vehicle adoption in that our data set allows us to pair hybrid vehicle models with their gasoline counterparts (e.g. Toyota Camry and Camry Hybrid) and apply a binary choice model. This should help to mitigate potential endogenenity problem caused by correlation between unobserved vehicle attributes and price. One way to overcome price endogeneity problems is the use of valid instrumental variables. As shall be seen, hybrid and non-hybrid gasoline counterparts pairs provide a simple method to address endogeneity. Hybrids and their gasoline counterparts share most of observed (e.g. length, width, height) and unobserved attributes (e.g. prestige), and these attributes will be eliminated in the vehicle choice model (Lloro 2012).

In addition, the use of hybrid and non-hybrid pairs allows us to evaluate consumers' preference on HEVs by identifying the hedonic value of hybrid vehicle models versus gasoline vehicles. The hedonic value of HEVs tells us consumers' subjective evaluation of HEV models. It is important for automobile manufactures to know consumers' true valuation of HEVs from a marketing point of a view. While previous studies have found that the fuel cost saving feature of HEVs is positively correlated with HEV adoption, none of these studies examines consumers' true perception of HEV models.

This study also complements an empirical literature on explaining consumers' valuations of fuel economy. A sizable literature have studied how consumers value fuel efficiency in automobiles and have investigated the energy paradox. The energy paradox explains a phenomena where consumers and firms unexpectedly reluctant to adopt cost saving energy efficient technologies that trade-offs between purchasing capital costs and operating costs from the new technology: consumers and firms undervalue future energy cost savings over the current purchasing cost (Jaffe and Stavins 1994). Such paradox exists in automobile market that consumers substantially undervalue future fuel costs in their choices of vehicles.

Greene (2010) reviews twenty eight recent empirical studies on consumers' valuation of future fuel costs and reaches to the conflicting results that there is no general consensus among studies.[2] A number recent of studies have found that consumers rationally or slightly undervalue fuel economy. Sallee et al. (2009) combine micro-level data on used car transaction with fuel economy and gasoline prices to examine the effect of a gasoline prices on used car prices. The study estimate that consumers match one dollar future gasoline savings with 79 cents of used car prices which is consistent with the undervaluation of fuel economy. Klier and Linn (2010) investigate the impacts of gasoline prices on new vehicle sales between 1978 and 2007 to estimate consumers' valuation of fuel economy. After controlling for potential unobserved consumer and vehicle characteristics, they estimate that a one dollar increase in the price of gasoline is associated with the 0.8∼1 mpg increase in fuel economy. Using used passenger vehicle prices and gasoline prices between 1999 to 2008, Allcott and Wozny (2012) find consumers slightly undervalue future fuel costs when purchasing vehicles. Regression results of vehicle prices on gasoline costs show that one dollar reduction of future gasoline costs are equivalent to 76 cents in vehicle purchase price. Busse et al. (2013) examine consumers' sensitivity of future fuel costs by estimating effects of gasoline prices on vehicle prices and vehicle sales of different fuel economies. Using parameter estimates of hedonic regression, they test whether consumers show myopia about future fuel costs by estimating consumers' willingness to pay for expected future fuel costs, and find no evidence of myopia and conclude that consumers do not undervalue fuel economy. Recent studies by Bento et al. (2012) and Leard (2014) emphasize the importance of unobserved consumer heterogeneity

[2]Among twenty eight studies, twelve studies support consumers' undervaluation of future fuel savings, eight studies imply consumers equally value fuel economy, and other five studies find consumers strongly overvalued.

on the valuation of fuel economy. Bento et al. (2012) point out that failure to account for heterogeneity results in a downward biased estimates (undervaluation of future fuel cost savings), and the bias would be larger with greater heterogeneity. Leard (2014), employing a mixed logit model of new vehicle choices, estimates distribution of consumers' willingness to pay (WTP) for a one dollar fuel cost reduction. The estimated WTP for fuel cost saving is 97 cents, indicating that average consumers fully value fuel cost reduction.

When consumers decide between buying a HEV or a traditional gasoline-powered vehicle, consumers carefully evaluate the trade-off between the expected future fuel cost savings and higher purchase price of HEVs (Hybrid Premium). If consumers undervalue future fuel cost savings, corporate average fuel economy (CAFE) standards could be a more efficient way than gasoline taxes to achieve environmental protection and energy security in transportation sector, as they require manufacturers to sell more fuel efficient vehicles. By identifying consumers' response to fuel cost savings and price premium of HEVs, this study estimates consumers' willingness to pay for future fuel cost savings and their corresponding implicit discount rate, and provides an empirical evidence of consumers' valuation of energy saving technology.

Our empirical findings show that both increased fuel economy and federal tax incentives accelerate hybrid adoption over the sample period. I estimate that consumers would pay \$6.91 and \$7.12 to save \$1 in annual fuel cost reduction with implicit discount rate of 14.47% and 14.03%, suggesting that consumers moderately undervalue future fuel cost savings. Consumers' hedonic valuation of hybrid models versus gasoline counterparts show that consumers prefer gasoline vehicles to hybrid vehicles when expected fuel cost savings and the hybrid premium are exactly balanced. It turns out that Toyota buyers would have to be paid \$2,568.05 to be indifferent between HEVs and gasoline counterparts. This finding suggests that consumers still perceive HEVs as novel products and are skeptical about HEV technology when purchasing new vehicles.

The rest of the paper is organized as follows. Section 1.2 explains the empirical model and specification. In Section 1.3, I present the data source. Section 1.4 reports the estimation results and Section 1.5 draws conclusions from empirical analysis.

1.2 The Model

The binary logit model is applied to investigate the choice of a HEV against a traditional gasoline-powered counterpart. When a consumer makes a decision whether to buy a fuel efficient HEV or an alternative gasoline vehicle, the consumer compares expected fuel cost savings from the fuel efficient HEV technology with higher purchase price (hybrid premium). In other words, the consumer needs to examine the reduced operating cost against the additional capital cost of purchasing a fuel efficient HEV. The binary logit model is used for representing two choices (Train 2009).

A consumer i faces a choice among J alternatives. The consumer would acquire a certain level of utility from a particular alternative. The level of utility that the consumer i obtains from option j, U_{ij}, consists of two parts: 1) representative utility that known by researcher, V_{ij}, and 2) error term which is unknown to researchers, ε_{ij}:

$$U_{ij} = V_{ij} + \varepsilon_{ij} \tag{1.1}$$

The logit model assumes that the error terms are independently and identically distributed across choices and individuals, and have a Type I extremely value distribution. Then the probability density of the error term is

$$f(\varepsilon_{ij}) = e^{-\varepsilon_{ij}} e^{-e^{-\varepsilon_{ij}}} \tag{1.2}$$

and the CDF of error term is

$$F(\varepsilon_j) = e^{-e^{-\varepsilon_j}} \tag{1.3}$$

The probability of consumer i's choosing the alternative j over alternative k is

$$\begin{aligned} P_{ij} &= Prob(V_{ij} + \varepsilon_{ij} > V_{ik} + \varepsilon_{ik}, \forall j \neq k) && (1.4)\\ &= Prob(\varepsilon_{ij} < V_{ij} - V_{ik} + \varepsilon_{ik}, \forall j \neq k) && (1.5)\\ &= \frac{e^{V_{ij}}}{\sum_{k=1}^{J} e^{V_{ik}}} && (1.6) \end{aligned}$$

Representative utility is specified to be linear combination of a vector of observed attributes of the choice alternative j, x_j. That is

$$V_{ij} = \delta_i' x_{ij} \tag{1.7}$$

where δ' are parameters to be estimated. Then, probability of consumer i's choosing alternative j becomes

$$P_{ij} = \frac{e^{\delta_i' x_{ij}}}{\sum_{k=1}^{J} e^{\delta_i' x_{ik}}} \tag{1.8}$$

In this study, a consumer faces two choices; a HEV and straight non-hybrid gasoline counterpart (e.g. Toyota Camry and Camry Hybrid). An advantage of the use of hybrid and non-hybrid counterpart pairs is that both observed and unobserved common attributes between the hybrids and non-hybrid counterparts will be canceled out in the vehicle choice. Suppose the utility from each type of a vehicle can be written as

$$U_{ih} = \delta_i' x_{ih} + \lambda Z + \varepsilon_{ih} \tag{1.9}$$

$$U_{ig} = \delta_i' x_{ig} + \lambda Z + \varepsilon_{ig} \tag{1.10}$$

where h and g denote the hybrid and the gasoline counterpart respectively. x is a vector of distinctive attributes and Z is a vector of common attributes.

Consumer i chooses a hybrid if

$$U_{ih} > U_{ig} \tag{1.11}$$

which is equivalent to

$$\begin{aligned} U_{ih} - U_{ig} &> 0 \\ \delta_i'(x_{ih} - x_{ig}) + \lambda(Z - Z) + (\varepsilon_{ih} - \varepsilon_{ig}) &> 0 \\ \delta_i'(x_{ih} - x_{ig}) + (\varepsilon_{ih} - \varepsilon_{ig}) &> 0 \end{aligned} \tag{1.12}$$

and the common attributes, Z, cancel out in the model of vehicle choice.

If ε_h and ε_g are independently and identically distributed, and have Type I extreme value distributions, the probability of a consumer i's choosing a hybrid vehicle is

$$P_{ih} = \frac{e^{\delta_i' x_{ih}}}{e^{\delta_i' x_{ih}} + e^{\delta_i' x_{ig}}} = \frac{1}{1 + e^{(\delta_i' x_{ig} - \delta_i' x_{ih})}} = \frac{1}{1 + e^{(V_{ig} - V_{ih})}} \tag{1.13}$$

I assume that n consumers in the market are identical which means consumers do not differ in their mean utility getting from choice of a hybrid vehicle. We can now drop subscript i in equations. Also, we can define total HEV sales as

$$S_h = n \times P_h \tag{1.14}$$

The logit (log of the odds ratio) of the relative market share of hybrid vehicle is then

$$\log\left(\frac{S_h}{1 - S_h}\right) = \log\left(\frac{S_h}{S_g}\right) = V_h - V_g = \delta' x_h - \delta' x_g \tag{1.15}$$

where S_h denotes the total HEV sales and S_g denotes the total gasoline vehicle sales.

I assume that hybrid and non-hybrid counterpart vehicles differ in fuel economy and purchase prices. Then, our base empirical model (Model I) is given by

$$\log\left(\frac{S_{hkt}}{S_{gkt}}\right) = \delta_1 Effi_{kt} + \delta_2 Premium_{kt} + \delta_3 Taxcredit_{kt} + \delta_{4j} d_j + \phi_t + \epsilon_{kt} \quad (1.16)$$

where S_{hkt} and S_{gkt} respectively represent the HEV and non-hybrid gasoline counterpart sales for vehicle model k in time t. $Effi_{kt}$ is annual fuel cost savings of HEVs ($). This measures the difference of annual fuel costs between HEVs and gasoline vehicles which is defined as

$$Effi_{kt} = \left[\frac{P_{gt}}{MPG_{hk}} - \frac{P_{gt}}{MPG_{gk}}\right] \times VMT_t \quad (1.17)$$

where P_{gt} is monthly gasoline prices, MPG_{hk} and MPG_{gk} are fuel economy (miles per gallon) of HEVs and gasoline vehicles, and VMT_t is average of annual vehicle miles traveled. $Premium_{kt}$ is the price premium of the HEV model k in time t. This variable is defined as the retail price difference between the HEV model k and its gasoline counterpart. (e.g. Retail price difference between Civic hybrid and Civic gasoline vehicle). $Taxcredit_{kt}$ is federal income tax credit for selective HEV models. Finally, d_j and ϕ_t are manufacturer specific and time fixed effects.

Since higher fuel cost savings of HEVs are attractive to consumes, we can expect a positive sign on δ_1. However the price premium on HEVs lowers market share of HEVs and we can expect negative sign on δ_2. Federal tax credit would help consumers to buy hybrid vehicles and is expected to have a positive sign of coefficient (δ_3). The coefficient δ_{4j} represents consumers' preference for HEV models produced by manufacturer j, holding other things constant. Positive signs on δ_{4j} indicate that consumers prefer HEVs to gasoline vehicles, and consumers are indifferent if δ_{4j} are close to zero.

Note that Model I (Equation (1.16)) does not take into account the fact that future fuel cost savings will be discounted over time. If we assume that the discount rate of fuel cost savings is r, the vehicle utilization rate is $m(t)$, and vehicle lifetime is, L, then the present value of future fuel cost savings can be expressed as

$$Effi = \int_{t=0}^{L} \left[\frac{P_g(t)}{MPG_{hk}} - \frac{P_g(t)}{MPG_{gk}} \right] m(t) e^{-rt} dt \tag{1.18}$$

I further assume that the the price of gasoline follows a random walk so that best prediction of future gasoline prices are current gasoline prices (Klier and Linn 2010). Integrating Equation (1.18) over time yields

$$Effi = \frac{m}{r} \left[\frac{P_g(t)}{MPG_{hk}} - \frac{P_g(t)}{MPG_{gk}} \right] (1 - e^{-rL}) \tag{1.19}$$

Plugging Equation (1.19) into Equation (1.16) yields following estimation equation (Model II):

$$\log\left(\frac{S_{hkt}}{S_{gkt}}\right) = \gamma_1 \left[\frac{m}{r} Effi_{kt}(1 - e^{-rL}) - Premium_{kt} - Taxcredit_{kt} \right] + \gamma_{2j} d_j + \phi_t + \eta_{kt} \tag{1.20}$$

where d_j are manufacturer specific dummy variables.

The bracket in Equation (1.20) is the difference between discounted fuel cost savings and additional cost of purchasing a HEV. This can be explained as the *'Net Cost'* of purchasing a HEV. The magnitude of γ_1 measures the consumers' importance on trade-off between fuel cost savings and additional purchasing cost of HEVs, namely consumers' trade-off between the reducing operating cost and additional capital cost of purchasing fuel efficient HEV technology. Larger γ_1 implies consumers put significant weight on the trade-off between operating and capital cost. Since higher discounted fuel cost savings would decrease the net cost of HEV purchase, we can expect positive sign on γ_1. Again, The coefficient γ_{2j} represent the consumers' hedonic valuation of HEV choice produced by manufacturer j. In addition to parameters above, implicit discount rate, $'r'$ is also estimated using nonlinear leastsquares estimation.

1.3 DATA

1.3.1 Vehicle Sales Data

The primary data for this study is monthly total new car and light-truck sales in the U.S. automobile market. This data was obtained from the Automotive News Data center and covers from January 2000 to December 2013. However, Automotive News Data Center does not include HEV sales data. Therefore, HEV sales data was separately collected from Hybridcars.com. Finally, the data set contains 43 HEV and gasoline counterparts pairs produced by 15 manufactures from 2000 to 2013. Using vehicle sales data, I calculate the odds ratio of each HEV model i by dividing the number of HEV sales by the number of gasoline counterpart sales for each model i.

1.3.2 Gasoline Prices, Fuel Economy, Vehicle Price and HEV Tax Credit

Monthly regular retail gasoline prices are obtained from the Energy Information Administration (EIA). To calculate the annual fuel costs of each vehicle model, I collected fuel economy (EPA combined miles per gallon of gasoline) data from AOL Autos. Fuel cost per mile is calculated by retail gasoline prices divided by fuel economy. Finally, average annual vehicle miles traveled (EIA, Annual Energy Outlook 2013) is multiplied to calculate annual fuel costs ($). Manufacture's suggested retail price (MSRP) of vehicle models are also obtained from AOL Autos. Price premium (additional purchase cost) of HEV is the retail price difference between the HEV and gasoline models of the same vehicle. (e.g. MSRP difference between Civic hybrid and Civic gasoline vehicle). Table 1.1 compares fuel economy, annual fuel cost saving and price premium of top 10 best selling HEVs and non-hybrid gasoline counterparts in 2013. Information about the federal tax credit for HEVs is obtained from the

U.S.Department of Energy, Fuel Economy Guide. All prices are adjusted to year 2012 dollars.

Table 1.1: Top 10 Best-Selling HEVs and Non-hybrid Gasoline Counterparts (2013)

Year	Make & Model	MPG	MPG Difference	Annual Fuel Cost Savings	Price ($2012)	Price Premium
2013	Toyota Prius	49.7	16.6	$416.8	$23,784.8	$4,865.9
2013	Toyota Matrix	33.1			$18,918.9	
2013	Toyota Camry Hybrid	41.2	11.7	$396.6	$26,680.5	$3,425.4
2013	Toyota Camry	29.5			$23,255.1	
2013	Ford Fusion Hybrid	47.0	19.6	$627.0	$27,824.0	$3,311.6
2013	Ford Fusion	27.4			$24,512.4	
2013	Hyundai Sonata Hybrid	37.3	8.3	$317.1	$26,541.9	$1,683.0
2013	Hyundai Sonata	29.0			$24,858.9	
2013	Lexus ES-Series Hybrid	39.6	14.1	$573.9	$39,857.4	$2,851.2
2013	Lexus ES-Series	25.5			$37,006.2	
2013	Toyota Avalon Hybrid	39.6	14.1	$573.9	$36,001.4	$2,336.4
2013	Toyota Avalon	25.5			$33,665.0	
2013	Kia Optima Hybrid	37.8	9.3	$355.6	$26,433.0	$4,356.0
2013	Kia Optima	28.5			$22,077.0	
2013	Chevrolet Malibu Hybrid	30.5	0.5	$20.4	$25,834.1	$2,900.7
2013	Chevrolet Malibu	30.0			$22,933.4	
2013	Lexus RX-Series Hybrid	30.2	9.0	$583.7	$46,351.8	$6,088.5
2013	Lexus RX-Series	21.2			$40,263.3	
2013	Honda Civic Hybrid	44.0	9.9	$273.6	$25,170.8	$1,876.1
2013	Honda Civic	34.1			$23,294.7	

Note: There is no exact gasoline counterpart for Toyota Prius. Instead, Toyota matrix is paired with Prius for comparison following the guidance from Fueleconomy.org.

1.4 Estimation Results

1.4.1 Model I Estimation Results

Estimation results of Model I (Equation (1.16)) are reported in Table 1.2.

$$\log\left(\frac{S_{hkt}}{S_{gkt}}\right) = \delta_1 Effi_{kt} + \delta_2 Premium_{kt} + \delta_3 Taxcredit_{kt} + \delta_{4j} d_j + \phi_t + \epsilon_{kt} \quad (1.16)$$

I use two different dependent variables in estimating model I. In specification (1), I regress the log of monthly HEV sales of vehicle model k in time t, $\log(Sales_{kt})$, on annual fuel cost savings, price premium of HEV and the federal tax credit. Specifications (2)–(5) use the logit (log of the odds ratio), $\log\left(\frac{S_{hkt}}{S_{gkt}}\right)$, as a dependent variable. In order to track down the effects of federal tax credit on HEV adoption during the sample period, I interact federal tax credit with time variable in specifications (3) and (5). In specifications (4) and (5), I include manufacturer dummy variables to capture manufacturer specific fixed effects.

The estimated coefficient on the *Annual Fuel Cost Savings* is positive and significant in all specifications which implies HEV consumers strictly prefer higher fuel economy of HEVs compared to gasoline counterparts. Better fuel efficient technology of HEVs would evidently be attractive to consumers and increases the market share. As expected, the higher purchase price of HEVs has a negative impact (-0.00024) on the market share of HEVs, but federal tax credit for HEVs are positively correlated (0.00011) with HEV adoption (Specification (4)). According to the coefficients on Federal Tax Credit*Time interaction variables in specifications (3) and (5), federal tax credit actually started to increase the market share of HEVs from 2009 as more qualified HEVs for federal tax credits are introduced in the market. Coefficients of each manufacturer dummy variable (δ_{4j}) in specifications (4) and (5) indicate the consumers' preferences for HEV models against gasoline counterparts produced by manufacturer j, holding other factors constant. That is consumers' hedonic valuation

Table 1.2: Model I Estimation Results

Dependent Variable	$\log(Sales_{kt})$		$\log\left(\frac{S_{hkt}}{S_{gkt}}\right)$							
Variables	(1)		(2)		(3)		(4)		(5)	
Annual Fuel Cost Savings ($)	0.00268***	(0.00024)	0.00275***	(0.00023)	0.00275***	(0.0002)	0.00168***	(0.00022)	0.00174***	(0.00023)
Price Premium ($)	-0.00015***	(0.00001)	-0.00016***	(0.00001)	-0.00016***	(0.00001)	-0.00024***	(0.00001)	-0.00024***	(0.00001)
Federal Tax Credit ($)	0.00048**	(0.00005)	0.00028***	(0.00005)			0.00011**	(0.00005)		
Federal Tax Credit ($) 2006					-0.00068**	(0.00028)			-0.00028	(0.00024)
Federal Tax Credit ($) 2007					0.00033**	(0.00013)			0.00008	(0.00012)
Federal Tax Credit ($) 2008					0.00071	(0.00013)			-0.00015	(0.00010)
Federal Tax Credit ($) 2009					0.00037***	(0.00099)			0.00014*	(0.00009)
Federal Tax Credit ($) 2010					0.00041***	(0.00089)			0.00031***	(0.00008)
AUDI							-0.04373	(0.44549)	-0.02911	(0.44446)
BMW							-1.5645***	(0.31010)	-1.5534***	(0.30954)
CHRYSLER							-2.5886***	(0.5798)	-2.7565***	(0.5798)
MERCEDES-BENZ							-2.8043***	(0.34585)	-2.7002***	(0.34758)
FORD							-1.0348***	(0.25147)	-1.1314***	(0.25171)
GM							-2.2622***	(0.25013)	-2.2583***	(0.24986)
HONDA							-2.2426***	(0.22800)	-2.2240***	(0.22732)
HYUNDAI							-0.39110	(0.31614)	-0.38561	(0.31524)
KIA							-0.2034	(0.35881)	-0.19931	(0.35783)
LEXUS							0.06082	(0.2857)	0.07099	(0.28570)
MAZDA							0.56268	(0.34641)	0.74234	(0.35258)
NISSAN							-1.9185***	(0.27052)	-1.9205***	(0.26976)
PORSCHE							-0.60427**	(0.29488)	-0.59626**	(0.29430)
TOYOTA							-0.63674**	(0.26232)	-0.63828**	(0.26291)
VOLKSWAGEN							-0.51301	(0.37789)	-0.50738	(0.37695)
Year Fixed Effects	YES		YES		YES		YES		YES	
R-Squared	0.2642		0.1812		0.1907		0.8822		0.8834	
Observations	2,008		1,615		1,615		1,615		1,615	

Notes:
1. Standard errors in parentheses
2. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

for HEV models when annual fuel cost savings, price premium and federal tax credits are balanced. Therefore, hedonic value measures consumers' subjective perception on HEVs other than fuels cost savings, price premium and federal tax credit. The estimated coefficients show that all consumers except Audi, Hyundai, Kia, Lexus, Mazda and Volkswagen clearly prefer gasoline vehicles to HEVs (coefficients are negative and significant). Audi, Hyundai, KIA, Lexus, Mazda and Volkswagen consumers are indifferent between HEVs and gasoline counterparts (coefficients are insignificant). This finding is consistent with the result from Liu (2014) that consumers' valuation of the hybrid feature is still low.

1.4.1.1 Willingness to Pay and Implicit Discount Rate for Future Fuel Cost Savings of HEVs

The estimated coefficients on *Annual Fuel Cost Savings* and *Price Premium* in Table 1.2 provide estimates of consumers' willingness to pay for $1 reduction in annual future fuel cost savings from increased fuel economy of HEVs and corresponding implicit discount rate. This is equivalent to approximately $8.00 in present value savings, assuming 10 years of vehicle lifetime and annual discount rates of 14.90%. The point estimates of specifications (4)–(5) in Table 1.2 imply that consumers would be willing to pay for $6.91 and $7.12 for $1 future fuel cost savings from HEVs, and corresponding implicit discount rates are 14.47% and 14.03% respectively. See Table 1.3. The range of estimated implicit discount rates in Table 1.3 is higher than 10-year Treasury rate (3.04%∼5.19%) and national 48-month new auto loan rate (4.13%∼7.92%), which implies HEV consumers undervalue future fuel cost savings from purchasing HEVs.[3]

Our estimates of implicit discount rates are lower than estimated implicit discount rates of durable goods from previous researches. Hausman (1979) estimates an implied discount rate of 17%∼27% for air conditioner and Dubin and McFadden (1984) find

[3] 10-year Treasury rate between sample periods of 2006 and 2013 was 3.04%∼5.19% and corresponding 48-month new auto loan rate was 4.13%∼7.92%.

Table 1.3: Willingness to Pay and Implicit Discount Rate

	Specification (4)	Specification (5)
Willingness to Pay	\$6.91 [\$4.90 \$9.26]	\$7.12 [\$5.11 \$9.50]
Implicit Discount Rate	14.47% [10.83% 20.25%]	14.03% [10.56% 19.42%]

Notes:
1. 95% confidence interval in brackets.
2. Confidence interval is estimated using parametric bootstrap method.

the discount rate of 20% for water heating system. Greene (1986) uses market share of diesel and gasoline engine vehicles, and estimates discount rate of 30%∼40% for future fuel savings. Though discount rates vary by durable goods, these studies including ours conclude that consumes undervalue future energy costs.

1.4.2 Model II Estimation Results

The estimate of the implicit discount rate, $'r'$, in model II (Equation (1.20)) crucially depends on the assumptions of annual vehicle usage, m, and the lifetime of the vehicle, L. I use the Energy Information Administration (EIA)'s annual miles traveled over the sample period (EIA, Annual Energy Outlook 2013). Vehicle lifetimes of 5-year, 10-year, 15-year, 20-year and 25-year are used for the estimation, and I report the estimated discount rate implied by each vehicle lifetime in Table 1.4. The parameters are estimated by nonlinear least squares.

$$\log\left(\frac{S_{hkt}}{S_{gkt}}\right) = \gamma_1\left[\frac{m}{r} \mathit{Effi}_{kt}(1-e^{-rL}) - \mathit{Premium}_{kt} - \mathit{Taxcredit}_{kt}\right] + \gamma_{2j}d_j + \phi_t + \eta_{kt} \tag{1.20}$$

The coefficient of *Net Cost* (0.00023) is positive and significant. The coefficient explains the consumers' importance of trade-off between fuel cost savings and additional purchase price of HEVs.

Table 1.4: Model II Estimation Results

Variables	Coefficients	Standard Errors	95% Confidence Interval	
Net Cost ($)	0.00023***	(0.00002)		
Discount rate (r) (L=5 Years)	-0.11606*	(0.05933)	[-0.2324	0.00031]
Discount rate (r) (L=10 Years)	0.0835**	(0.03771)	[0.00961	0.15756]
Discount rate (r) (L=15 Years)	0.12488***	(0.03076)	[0.06453	0.18523]
Discount rate (r) (L=20 Years)	0.13825***	(0.027611)	[0.08410	0.19241]
Discount rate (r) (L=25 Years)	0.14346***	(0.025981)	[0.09250	0.19442]
AUDI	-0.13573	(0.44401)		
BMW	-1.6421***	(0.30841)		
CHRYSLER	-2.7247***	(0.5770)		
MERCEDES-BENZ	-2.920***	(0.34213)		
FORD	-1.0892	(0.25051)		
GM	-2.3186***	(0.24908)		
HONDA	-2.2353***	(0.22824)		
HYUNDAI	-0.43384	(0.3159)		
KIA	-0.25588	(0.35842)		
LEXUS	0.08627	(0.28582)		
MAZDA	0.41388	(0.34000)		
NISSAN	-2.0129***	(0.267)		
PORSCHE	-0.65793**	(0.29419)		
TOYOTA	-0.61153**	(0.26237)		
VOLKSWAGEN	-0.5785	(0.37714)		
Year Fixed Effects	YES			
R-Squared	0.8819			
Observations	1,615			

Notes:
1. Standard errors in parentheses
2. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The large coefficient implies that buyers put significant weight on the trade-off between low operating cost and high purchase cost of HEVs. Estimated implicit discount rates are -11.06%, 8.35%, 12.49%, 13.83%, and 14.35% assuming 5-year, 10-year, 15-year, 20-year and 25-year of vehicle lifetimes respectively. If we take

15-year vehicle lifetime as the benchmark, implicit discount of 12.49% (8 years of payback periods) is still above the 10-year Treasury rate (3.04%∼5.19%) and national 48-month new auto loan rate (4.13%∼7.92%), and consumers still undervalue future fuel cost savings of fuel efficient HEVs. Coefficients signs of manufacturer dummy variables (γ_{2j}) are same as in specification (5) in Table 1.2. In particular, Chrysler (-2.7247) and Mercedes-Benz (-2.920) consumers have a strong preference for the gasoline vehicle models, and Toyota consumers are nearly indifferent (-0.61153) between HEVs and gasoline counterparts.

Table 1.5: Estimates of Consumers' Valuation of HEVs at Zero Net Present Cost

Vehicle Make	Valuation ($)	95% Confidence Interval
AUDI	$-569.99	[$-4,073.32 $2,933.32]
BMW	$-6,896.16	[$-9,816.83 $-3,975.5]
CHRYSLER	$-11,442.35	[$-16,394.30 $-6,490.40]
MERCEDES-BENZ	$-12,263.40	[$-15,773.76 $-8,753.04]
FORD	$-4,574.30	[$-6,529.90 $-2,618.70]
GM	$-9,736.70	[$-12,207.32 $-7,266.08]
HONDA	$-9,386.90	[$-11,658.10 $-7,115.70]
HYUNDAI	$-1,821.85	[$-4,392.27 $748.55]
KIA	$-1,074.53	[$-3,916.32 $1,767.24]
LEXUS	$362.29	[$-1,617.06 $2,341.65]
MAZDA	$1,738.06	[$-859.96 $4,336.08]
NISSAN	$-8,453.23	[$-10,946.56 $-5,959.89]
PORSCHE	$-2,762.93	[$-5,130.11 $-395.75]
TOYOTA	$-2,568.05	[$-4,517.29 $-618.82]
VOLKSWAGEN	$-2,429.72	[$-5,462.90 $603.46]

Note: Confidence interval is estimated using parametric bootstrap method.

1.4.3 Monetary Valuation of HEVs

Parameter estimates from Model II are used to compute consumers' monetary valuation of HEV choice. Since the coefficient γ_{2j} in Model II represents consumers' hedonic valuation of HEVs, and the coefficient γ_1 represents marginal utility of fuel cost savings in dollars, the ratio of γ_{2j}/γ_1 represents the consumers' valuation of HEV choice in dollars, when discounted fuel cost savings are equal to hybrid premium. The estimated monetary valuation and corresponding 95% confidence interval are reported in Table 1.5. I find, on average, Toyota buyers would have to be paid $2,568.05 to be indifferent between HEVs and gasoline counterparts.

1.5 Conclusion

In this paper, I employ two binary logit models to analyze the market share of Hybrid Electric Vehicles (HEVs) utilizing monthly vehicle sales data covering from January 2000 to December 2013. In particular, this paper focuses on consumers' decisions on the trade-off between fuel cost savings and higher purchase price of HEVs, and how this behavior affects the market share of HEVs. 43 HEVs and gasoline counterparts produced by 15 manufacturers in the U.S. automobile market were investigated.

Our findings from two logit models suggest that fuel efficient HEV technology together with government support for HEVs promoted the consumer adoption of HEVs over the sample period. Estimated willingness to pay for future fuel cost savings and implicit discount rates of 8.35%∼14.35% implies that consumers moderately undervalue future fuel cost savings from purchasing HEVs, and consumers would want to get back their investment on fuel cost saving HEV technology in 7∼11 years.[4] Consumers' hedonic valuation of HEV models against gasoline counterparts at net cost of purchasing HEVs reveal that consumers find HEVs are less desirable than gasoline counterparts when expected fuel cost savings and hybrid premium are exactly balanced.

[4] A rational consumer would discount future fuel cost savings over the vehicle lifetime both simple discount rate and annual vehicle usage decline rate. Then, the payback period is calculated by

$$\text{Payback period} = \frac{\left[1 - e^{-(i+\sigma)L}\right]}{i+\sigma} = \frac{1}{r}$$

where i is the simple discount rate, σ is the rate of decline in vehicle use with vehicle age, L is the vehicle lifetime and r is the estimated implicit discount rate.

Our results contain useful information about explaining the trend in the market share of HEVs, and provide evidences of how consumers consider trade-off between operating cost and capital cost when adopting new fuel efficient HEV technology. We can apply these findings when evaluating advanced vehicle technologies such as electric vehicles and fuel cell vehicles.

There still exist limitations, and future studies are needed to advance this line of research. First, when deriving the Model II, I assume that consumers' expectations about gasoline prices remain constant over time. However, this is a very strong assumption. Future study requires that continuous changes of consumers' expectation of gasoline prices need to be integrated into the model. Second, our study does not consider potential consumer heterogeneity. As Bento et al. (2012) pointed out, failing to control for heterogeneous preferences for future fuel costs results in downward biased estimate of willingness to pay for fuel economy. Another source of heterogeneity is consumers' risk aversion to novel technologies. Since HEV is a new technology, the adoption of HEVs may vary among consumers' behavior toward risk aversion, which in turn affect hedonic valuation of HEVs choices. Incorporating such heterogeneity will be another area of future work.

Chapter 2

Identifying Price Discrimination with Quality Difference: Evidence from Hybrid Electric Vehicles

2.1 Introduction

The most common practice of price discrimination occurs when firms are selling the same product at different prices to different consumers. Not only for the same products, but price discrimination exists when price differences of similar products do not reflect cost difference. In many markets, firms offer products that have the similar features with multiple qualities and charge different prices for customers.

A Hybrid Electric Vehicle (HEV) is a good example. A HEV is the higher quality variant of conventional gasoline vehicle that combines the gasoline engine with an electric propulsion motor, and provides better fuel economy and emits fewer carbon emissions. These distinctive benefits of HEVs together with the growing concern of energy prices and environmental issues have made environmentally friendly consumers pay closer attention to HEVs. Early adapters and innovators who desired HEV technology also showed great interest shortly after the HEVs' introduction to the U.S. Market (Heffner et al. 2007). As a result, HEVs market share has continued increasing since the first HEV model, the Honda Insight, was introduced to the U.S. automobile market in 1999. There are 39 HEV models in the market and total market share of HEVs reached 3.23% of total Light-duty Vehicle (Car and Light truck) sales and 6.28% of total car sales in 2013. A well-established literature has shown that the popularity of HEVs came from the rising gasoline prices, government support (Bento et al. 2010; Beresteanu and Li 2011; Sallee 2011; Diamond 2009; Gallagher and Muehlegger 2011) and environmental concern (Kahn 2007).

However, in order to enjoy the fuel savings benefit of HEVs, consumers have to pay extra expenses for these vehicles, known as the Hybrid premium.[1] Price premium of HEVs ranges from $2,900 to $11,000 depending on the vehicle model A question then arises whether the hybrid premium justifies the fuel savings benefit of HEVs. In other words, can the price premium be explained by the extra cost of producing fuel efficient HEV technologies (electric propulsion system, battery pack, etc.)? This implies if the markup of HEVs exceeds that of gasoline vehicles, quality-based price discrimination against HEV consumers exists. Since HEV consumers have higher willingness to pay for a HEV choice, manufacturers have an incentive to charge higher markups and expropriate consumer surplus from those consumers.

The purpose of this paper is to empirically investigate the existence of quality-based price discrimination against HEV consumers. Using the new vehicle sales data from 2000 to 2013, I identify the new vehicle demand following random coefficients discrete choice method taken from the Berry, Levinsohn and Pakes (1995) (henceforth BLP). Marginal cost, markup and percentage markup are recovered by solving firms' profit maximization problem assuming that automobile manufacturers are engaged in Bertrand-Nash competition. Finally, I compare average markups for

[1] For example, MSRP of Toyota Camry hybrid 2014 model is $26,950 and MSRP of a counterpart gasoline model is $23,045 which yields hybrid premium of $3,905.

HEVs and gasoline vehicles to find if manufacturers do engage in quality-based price discrimination.

I find that, on average, hybrid Light-duty vehicles (LDVs) have both higher markups and percentage markups than gasoline LDVs. Average markups of hybrid LDVs and gasoline LDVs between the years 2000 and 2013 are $5,071 and $4,595 and corresponding percentage markups are 19.19% and 18.33% respectively. In addition, HEVs are estimated to have 11.09% higher markups than gasoline vehicles. The results are obtained from all hybrid and gasoline vehicle models in the market. However, firm's ability to attach markups depends on its market power: market share and the number of products produced by the firm. As will be shown, Toyota has the dominant position in the HEV market. By 2013, Toyota produced 9 HEV models and accounted for 63.9% of the total HEV market shares. Thus, Toyota's pricing strategy on HEVs might be somewhat different from other manufacturers. From this point, I then compare average markups for Toyota's HEVs with HEVs produced by other manufacturers. The evidence reveals that Toyota charges higher markups and percentage markups on their hybrid models than other manufacturers' hybrid vehicle models. The Toyota Prius, the top-selling hybrid car particularly enjoys larger markup than other competing vehicles.

Starting from empirical works by Borenstein (1991) and Shepard (1991), a considerable amount of literature has investigated evidence of price discrimination in various industries. Borenstein (1991) tests for price discrimination in gasoline prices at gas stations by varying availability of leaded and unleaded gasoline and found that margins for leaded gasoline were higher and competition was less strong in that market. Similarly, Shepard (1991) compares gas prices at stations with both full-service and self-service pu mps (multi-product stations) against those that offered only one of the two options (single-product stations). Although gasoline station markets were fairly competitive, multi-product stations had strong market power to price discriminate.

In the airline industry, Borenstein and Rose (1994) compare the airfares of different passengers on the same flight. Their findings suggested that substantial fare variations existed between passengers and the price dispersion increased in more competitive markets. However, using panel data, Gerardi and Shapiro (2009) reach opposite results from the findings of Borenstein and Rose (1994). They found that competition and dispersion had a negative relationship and more competition resulted in less price dispersion in the airline industry. Clerides (2002) analyzes pricing behavior in the book publishing industry by comparing markups and percentage markups of two different versions of books, hard cover and paperbacks. The results suggested that hardcover books had both higher margins and markups, and the price discrimination could be explained by quality difference, not by cost difference. Cohen (2008) focuses on the paper towel industry. Using a structural model of demand, the research provided the evidence of second-degree price discrimination with respect to package sizes in the paper towel industry. Average price discrimination, measured by markup differences between 1-roll and multi-roll ranged from 34% to 46%.

There is also a body of empirical studies that examines the evidence of price discrimination in the automobile industry. My work belongs to this literature. Studies by Verboven (1996) and Verboven (2002) attempt to identify price discrimination in the automobile industry. Verboven (1996) compares vehicle prices in Europe and found that markups for the same vehicle were different substantially among different countries. Verboven (2002) estimates markups for diesel and gasoline vehicles in Europe to evaluate price discrimination. The paper suggested that diesel engines had higher quality due to the lower cost of diesel fuel and were sold at higher markups. Using a structural model of automobile demand in Norway, Thomassen (2010) reveals there was second-degree price discrimination with engine variants. Markups were increasing with horsepower, and consumers were paying higher price premium over marginal cost. More recently, Langer (2012) analyzes that car dealers appeared to price discriminate for new cars across demographic groups: Third-degree price discrimination. The study also found that price differences paid for new cars stemmed from consumer knowledge or negotiation strength.

To my knowledge, this paper is the first study that investigates the presence of the quality-based price discrimination against HEV consumers. The remainder of this paper is structured as follows. Next section briefly describes the HEV market and industry. Section 2.3 explains the empirical analysis, and data set are discussed in Section 2.4. Section 2.5 presents the empirical results and Section 2.6 concludes the study.

2.2 Hybrid Vehicle Market

Honda Insight and Toyota Prius were the first HEVs sold in U.S. The first generation of Insight was available in the U.S. in December 1999, and a total of 13,889 units were sold until Honda introduced the second generation of Insight in February 2009. In June 2000, seven months after the Insight's introduction in the U.S., Toyota officially launched its first HEV model, the Prius, which was ranked as the top-selling HEV model since its debut.

The most attractive aspect of the HEV to consumers is its fuel efficiency. A HEV combines a gasoline engine with a battery-powered electric motor that provides improved fuel economy and performance. While average city/highway combined fuel economy of a new gasoline vehicle in 2001 was 22.1 MPG, the Insight and Prius earned combined fuel economy of 64.2 MPG and 48.9 MPG respectively, which is more than twice as much fuel economy compared to conventional gasoline vehicles. As gasoline prices started to increase at the beginning of 2002, consumers actively sought for more fuel efficient vehicles and started to show interest in HEVs.

The government also paid more attention to HEVs for environmental concern and energy security issues. Improved fuel economy decreases emissions from vehicles which in turn reduces total life-cycle greenhouse gas emissions, and also helps to mitigate foreign oil dependency. In order to facilitate the purchase of HEVs, the federal government began to offer tax credits up to $3,400 for HEV models that were purchased after December 31, 2005.

The amount of credits was planned to be phased out when cumulative sales of a HEV model reached 60,000 units. HEV models sold after December 31, 2010 did not qualify for the tax credit program. Table 2.1 presents the federal tax credits for selective HEVs between the years 2006 and 2010.

With the continuous rise in gasoline prices and the government's efforts to increase HEV sales, HEVs can achieve growing market share. Table 2.2 shows the total LDV and HEV sales from 2005 to 2013. A total of 472,597 of the 14,612,158 new LDVs sold in 2013 were HEVs and the corresponding market share was 3.23%. The market share of new hybrid cars and trucks in 2013 was 6.28% and 0.27% respectively.

As consumers have shown growing interests in HEVs, manufacturers such as GM, Ford, Nissan and Chrysler also began offering HEV models. In 2000, the Insight and Prius were the only available HEVs in the U.S., but by the end of 2013, there were 39 HEV models in the market. Toyota has a dominant position in the HEV market producing 9 HEV models and alone accounting for 63.90% of the HEV market share in 2013. Toyota is followed by Ford, GM and Honda with corresponding market shares of 16.90%, 5.28% and 4.13% respectively. See Tables 2.3 and 2.4.

2.3 Empirical Model

This section presents a structure model of new vehicle demand and supply, and explains how to identify price discrimination. Identifying price discrimination requires estimating consumers' demand for new vehicles and elasticities for each vehicle model. After obtaining demand side parameters, I solve for a firm's profit maximization problem assuming that firms are engaged in Bertrand-Pricing behavior, and recover marginal costs. Finally, price discrimination is measured by comparing markups between HEVs and gasoline vehicles.

Table 2.1: Federal Tax Credit for Qualified HEVs

	2006	2007	2008	2009	2010
BMW ActiveHybrid 7					$900
BMW X6 Hybrid					$1550
Cadillac Escalade Hybrid			$2,200	$2,200	$2,200
Chevrolet Malibu Hybrid		$1,300	$1,550	$1,550	$1,550
Chevrolet Tahoe Hybrid		$2,200	$2,200	$2,200	$2,200
Chevrolet Silverado Hybrid	$650	$650		$2,200	$2,200
Chrysler Aspen Hybrid			$2,200	$2,200	
Dodge Durango Hybrid			$2,200	$2,200	
Ford Escape Hybrid	$2,600	$3,000	$3,000	$1,688	$750
Ford Fusion Hybrid				$1,913	$850
GMC Yukon		$2,200	$2,200	$2,200	$2,200
GMC Sierra Hybrid	$650	$650			$2,200
Honda Accord Hybrid	$1,300	$1,300	$488		
Honda Civic Hybrid	$2,100	$2,100	$788		
Honda Insight	$1,450				
Lexus GS 450h	$1,356	$388			
Lexus LS 600h		$488			
Lexus RX 400h/450h	$1,925	$550			
Mazda Tribute Hybrid		$3,000	$3,000		$3,000
Mercedes Bentz S400 Hybrid					$1,150
Mercedes Bentz ML 450h					$2,200
Mercury Mariner Hybrid	$1,950	$3,000	$3,000	$1688	$750
Mercury Milan Hybrid				$1,913	$850
Nissan Altima Hybrid	$2,350	$2,350	$2,350	$2,350	$2,350
Porsche Cayenne Hybrid					$1,800
Saturn Vue Hybrid	$650	$1,550	$1,550		
Saturn Aura Hybrid	$1,300	$1,300	$1,550		
Toyota Camry Hybrid	$2,275	$650			
Toyota Prius	$2,756	$788			
Toyota Highlander Hybrid	$2,275	$650			

Source: Internal Revenue Service

Table 2.2: Total Light-duty Vehicle (LDV) and HEV Sales

Year	LDV Sales	Hybrid LDV Sales	Hybrid LDV Shares	# of LDV Models	# of HEV Models
2005	16,179,364	205,459	1.27	240	7
2006	15,632,382	251,862	1.61	246	10
2007	15,609,701	352,401	2.26	260	13
2008	13,002,227	313,658	2.41	281	19
2009	10,283,123	290,604	2.83	294	23
2010	11,388,209	274,729	2.41	280	30
2011	12,656,723	268,785	2.12	279	32
2012	14,338,108	411,672	2.87	289	42
2013	14,612,158	472,597	3.23	270	39
	Car Sales	Hybrid Car Sales	Hybrid Car Shares	# of Car Models	# of Hybrid Car Models
2005	7,098,981	151,253	2.13	126	4
2006	7,295,908	177,667	2.44	128	6
2007	7,595,921	283,547	3.73	138	8
2008	6,858,904	249,773	3.64	145	9
2009	5,536,770	237,086	4.28	156	12
2010	5,726,386	231,809	4.05	143	16
2011	6,108,983	237,833	3.89	147	19
2012	7,203,422	387,527	5.38	154	28
2013	7,203,195	452,483	6.28	152	28
	Truck Sales	Hybrid Truck Sales	Hybrid Truck Shares	# of Truck Models	of Hybrid Truck Models
2005	9,080,383	54,206	0.60	114	3
2006	8,336,474	74,195	0.89	118	4
2007	8,013,780	68,854	0.86	122	5
2008	6,143,323	63,885	1.04	136	10
2009	4,746,353	53,518	1.13	138	11
2010	5,661,823	42,920	0.76	137	14
2011	6,547,740	30,952	0.47	132	13
2012	7,134,686	24,145	0.34	135	14
2013	7,408,963	20,114	0.27	118	11

Table 2.3: Number of HEV Models, HEV Sales and HEV Market Shares by Manufacturers

Year	TOYOTA	HONDA	FORD	GM	NISSAN	CHRYSLER	BMW	DAIMLER	PORSCHE	MAZDA	HYUNDAI	VW	AUDI	KIA	Total
2005	3	3	1												7
2006	5	3	2												10
2007	6	2	2	2	1										13
2008	6	2	2	6	1	2									19
2009	7	2	4	7	1	2									23
2010	7	3	5	8	1		2	2	1	1					30
2011	8	3	3	7	2		2	2	2	1	1	1			32
2012	10	4	4	8	2		4	2	2	1	1	2	1	1	42
2013	9	5	3	7	4		3	1	2		1	2	1	1	39
2005	146,512	43,356	15,591												205,459
2006	191,742	37,571	22,549												251,862
2007	277,750	35,980	25,108	5,175	8,388										352,401
2008	241,401	31,495	19,522	12,340	8,819	81									313,658
2009	195,545	36,023	33,502	16,135	9,357	42									290,064
2010	189,147	33,547	35,496	6,760	6,710		349	1,721	344	655					274,729
2011	178,588	31,582	27,114	5,025	3,614		382	310	1,623	484	19,673	390			268,785
2012	291,482	18,166	32,543	33,979	794		1,044	143	1,750	90	20,754	412	270	10,245	411,672
2013	301,812	19,528	79,949	24,945	1,792		1,456	282	728		21,559	5,773	854	13,919	472,597
2005	71.30%	21.10%	7.59%												100%
2006	76.10%	14.90%	8.95%												100%
2007	78.80%	10.20%	7.12%	1.47%	2.38%										100%
2008	77.00%	10.00%	6.22%	3.93%	2.81%	0.03%									100%
2009	67.30%	12.40%	11.50%	5.55%	3.22%	0.01%									100%
2010	68.80%	12.20%	12.90%	2.46%	2.44%		0.13%	0.63%	0.13%	0.24%					100%
2011	66.40%	11.70%	10.10%	1.87%	1.34%		0.14%	0.12%	0.60%	0.18%	7.32%	0.15%			100%
2012	70.80%	4.41%	7.91%	8.25%	0.19%		0.25%	0.03%	0.43%	0.02%	5.04%	0.10%	0.07%	2.49%	100%
2013	63.90%	4.13%	16.90%	5.28%	0.38%		0.31%	0.06%	0.15%	0.00%	4.56%	1.22%	0.18%	2.95%	100%

Table 2.4: HEV Models Produced by Manufacturers in 2013: 39 Models

TOYOTA		GM		HONDA		NISSAN	
Avalon	(0.21%)	Escalade	(0.08%)	Accord	(0.21%)	M35	(0.10%)
CT 200h	(3.19%)	LaCrosse	(1.51%)	CR-Z	(0.96%)	Pathfinder	(0.07%)
Camry	(9.41%)	Malibu	(2.92%)	Civic	(1.63%)	Q50	(0.07%)
ES 300h	(3.50%)	Regal	(0.61%)	ILX	(0.31%)	QX60	(0.14%)
GS 450h	(0.11%)	Silverado	(0.02%)	Insight	(1.02%)		
Highlander	(1.07%)	Tahoe	(0.08%)				
LS 600h	(0.02%)	Yukon	(0.06%)				
Prius	(40.68%)						
RX 450h	(2.39%)						
BMW		**FORD**		**PORSCHE**		**VOLKSWAGEN**	
ActiveHybrid 3	(0.19%)	C-Max	(7.45%)	Cayenne S	(9.41%)	Jetta	(1.20%)
ActiveHybrid 5	(0.11%)	Fusion	(7.89%)	Panamera	(0.02%)	Touareg	(0.03%)
ActiveHybrid 7	(0.01%)	MKZ	(1.58%)				
AUDI		**DAIMLER**		**HYUNDAI**		**KIA**	
Q5	(0.18%)	BENZ E400	(0.06%)	Sonata	(4.56%)	Optima	(2.95%)

Note: Market shares in parentheses

2.3.1 Demand Specification

I employ the random coefficients logit model for new vehicle demand estimation.

A utility maximizing consumer i's indirect utility from purchasing a new vehicle model j in period t is defined as follows:

$$\begin{gathered} u_{ijt} = \alpha_i p_{jt} + X_{jt}\beta_i + \xi_{jt} + \epsilon_{ijt}, \\ j = 1, ..., J, \quad t = 1, ..., T \end{gathered} \tag{2.1}$$

where p_{jt} is the price of vehicle model j, X_{jt} is a K-dimensional vector of observable vehicle attributes, ξ_{jt} is the unobservable vehicle attributes such as style, quality, brand reputation and loyalty. ϵ_{ijt} is an idiosyncratic taste for product j and assumed to be distributed $i.i.d.$ with a Type I extreme value. Finally, α_i and β_i are individual specific coefficients that can be decomposed into mean preference common to all consumers and a deviation from the mean. α_i is consumer i's preference for price and consists of mean preference ($\overline{\alpha}$), observed income (y_i) and unobserved preferences for vehicle price ($v_{i\alpha}$): $\alpha_i = \overline{\alpha} + \sigma_y y_i + \sigma_\alpha v_{i\alpha}$. A sample of household income is obtained from the Current Population Survey conducted jointly by the Census Bureau and the Bureau of Labor Statistics. Mean and standard deviation of household income are estimated under the assumption of a log-normal distribution, and 100 individuals were randomly drawn in each year for the estimation. $v_{i\alpha}$ represents unobserved consumer characteristics and assumed to follow a standard normal distribution. σ_y and σ_α are parameters measuring preference variation with y_i and $v_{i\alpha}$.

Consumer i's preference for vehicle attributes, β_i is formed as $\beta_i = \overline{\beta}_k + \sigma_k v_{ik}$ where $\overline{\beta}_k$ is the mean preference and $\sigma_k v_{ik}$ is each consumer's deviation from the mean. $v_{ik} = (v_{i1}, \ldots, v_{iK})$ is a vector of random variables that represents the idiosyncratic preferences of consumer i for the K observed vehicle attributes, which are assumed to follow a standard normal distribution. σ_k can be interpreted as the standard deviation of preference for vehicle attribute k in the population that needs to be estimated. v_{ik} is interacted with σ_k and forms consumer i's personal preferences for vehicle attribute k, $\sigma_{ik} = \sigma_k v_{ik}$. This term helps to understand why some consumers show strong preference for a certain attribute over others.

The indirect utility function can be decomposed as follows:

$$\begin{aligned} u_{ijt} &= \left(\overline{\alpha} p_{jt} + X_{jt}\overline{\beta}_k + \xi_{jt}\right) + (\sigma_y y_i + \sigma_\alpha v_{i\alpha}) p_{jt} + \left(\sum_k^K \sigma_k v_{ik} x_{jkt}\right) + \epsilon_{ijt} \\ &= \delta_{jt}(X_{jt}, p_{jt}, \xi_{jt}; \theta_1) + \mu_{ijt}(X_{jt}, p_{jt}, y_i, v_i; \theta_2) + \epsilon_{ijt} \\ &= \delta_{jt} + \mu_{ijt} + \epsilon_{ijt} \end{aligned}$$

where δ_{jt} is the mean utility from the purchase of vehicle j that is the same for all consumers and $\mu_{ijt} + \epsilon_{ijt}$ represents the deviation from the mean utility that captures random coefficients effect. Parameters to be estimated are mean tastes coefficients common to all consumers, $\theta_1 = \{\overline{\alpha}, \overline{\beta}\}$ and deviation from the mean, $\theta_2 = \{\sigma_y, \sigma_\alpha, \sigma_k\}$.

The specification of the demand system is completed by introducing the indirect utility for the outside good which measures the consumer's utility that earns from the purchase of goods other than a new car:

$$u_{i0t} = \xi_{0t} + \sigma_0 y_i + \sigma_0 v_{i0} + \epsilon_{i0t}$$

Consumers are assumed to buy one unit of product that gives the highest utility level. The probability that consumer i chooses product j in period t gives

$$P_{ijt} = Prob(u_{ijt} > u_{ilt}, \forall l \neq j, l = 0, 1, \ldots, J \mid y_i, v_i, \epsilon_{ijt}) \tag{2.2}$$

As assumed, ϵ_{ijt} follows $i.i.d$ with Type I extreme value. If we normalize the mean utility of outside good to be zero, then market share of product j for consumer i in period t becomes

$$s_{ijt} = \frac{\exp(\delta_{jt} + \mu_{ijt})}{1 + \sum_{l=1}^{J} \exp(\delta_{lt} + \mu_{ilt})} \tag{2.3}$$

Overall Market share can be calculated by integrating the individual market share:

$$\begin{aligned} s_{jt} &= \int\int s_{ijt} dF_y(y_i) dF_v(v_i) \\ &= \int\int \left[\frac{exp(\delta_{jt} + \mu_{ijt})}{1 + \sum_{l=1}^{J} exp(\delta_{lt} + \mu_{ilt})} \right] dF_y(y_i) dF_v(v_i) \end{aligned} \tag{2.4}$$

where $F_y(y_i)$ and $F_v(v_i)$ are distributions of y_i and $v_i = (v_{i\alpha}, v_{i1}, \ldots, v_{iK})$.

The own and cross price elasticities of the market share of product j with respect to the price of product g are

$$\eta_{jgt} \equiv \frac{\partial s_{jt}}{\partial p_{gt}} \cdot \frac{p_{gt}}{s_{jt}} = \begin{cases} -\frac{p_{jt}}{s_{jt}} \int\int \alpha_i s_{ijt}(1 - s_{ijt}) dF_y(y_i) dF_v(v_i) & if \quad j = g \\ \frac{p_{gt}}{s_{jt}} \int\int \alpha_i s_{ijt} s_{igt} dF_y(y_i) dF_v(v_i) & \text{otherwise.} \end{cases}$$

Since BLP allows for consumers' heterogeneity in the preference for vehicle attributes, it shows larger substitution effects compared to the simple multinomial logit model.

2.3.2 Demand Estimation

This section discusses the demand side estimation procedure. Parameters that need to be estimated are $\theta_1 = \{\overline{\alpha}, \overline{\beta}\}$ and $\theta_2 = \{\sigma_y, \sigma_\alpha, \sigma_k\}$. Generalized Method of Moments (GMM) is used for the estimation.

2.3.2.1 Moment Conditions

We need to solve "Moment conditions" that match the market share equation s_j to actual market share S_j:

$$\underset{\theta}{\text{Min}} \parallel s_j(x, p, \delta(x, p, \xi; \theta_1); \theta_2) - S_j \parallel \tag{2.5}$$

where $s_j()$ is the market share that is defined by Equation (2.5) and S_j is the actual observed market shares from the data.

Let $Z = [z_1, \ldots, z_M]$ be a set of instrument variables and ω is a function of model parameter, an error term:

$$G(\theta) \equiv E[Z_m \cdot \omega(\theta^*)] = 0, \qquad m = 1, \ldots, M \tag{2.6}$$

where θ^* refers the true value of the parameters and the error term is defined as the unobservable vehicle attributes:

$$\xi_{jt} \equiv \delta_{jt}(x, p, S_t; \theta_2) - (\alpha p_{jt} + X_{jt}\beta) = \omega_{jt}$$

Computing unobservable vehicle attributes, ξ_{jt}, requires solving mean utility level $\delta_{.t}$ from the system of market equations:

$$s(x, p, \delta_t; \theta_2) = S_t \quad t = 1, ..., T \tag{2.7}$$

where $s(\cdot)$ are market shares given by Equation (2.5) and S_t is the actual observed market share from the data. Recall market share Equation (2.5):

$$\begin{aligned} s_{jt} &= \int\int s_{ijt} dF_y(y_i) dF_v(v_i) \\ &= \int\int \left[\frac{exp(\delta_{jt} + \mu_{ijt})}{1 + \sum_{l=1}^{J} exp(\delta_{lt} + \mu_{ilt})} \right] dF_y(y_i) dF_v(v_i) \end{aligned} \tag{2.5}$$

Once we draw random variables for y_i and υ_i for $i = 1, \ldots, R$ from the distributions $F_y(y_i)$ and $F_v(\upsilon_i)$ for sample size of R, we can approximate integral for market share that results from aggregating across i by the use of Monte Carlo simulation:

$$\begin{aligned} s_{jt}(p_t, x_t, \delta_t, F_R; \theta_2) &= (\frac{1}{R}) \sum_{i=1}^{R} s_{ijt} \\ &= (\frac{1}{R}) \sum_{i=1}^{R} \frac{\exp[\delta_{jt} + \mu(x_{jt}, p_{jt}, y_i, \upsilon_i; \theta_2)]}{1 + \sum_{m=1}^{J} \exp[\delta_{mt} + \mu(x_{mt}, p_{mt}, y_i, \upsilon_i; \theta_2)]} \end{aligned} \tag{2.8}$$

From this, we can obtain predicted market shares for given individual parameters (σ_y, σ_α, σ_k) and mean utilities, δ. For full random coefficients model, however, the system of Equation (2.8) is non-linear and δ_t does not have an analytical solution. Instead, it can be solved numerically using contraction mapping suggested by BLP (1995). Contraction mapping finds values of δ by the following interactive process keeping individual parameters (σ_y, σ_α, σ_k) fixed at starting points:

$$\delta_t^{h+1} = \delta_t^h + \ln(S_t) - \ln(s(p_t, x_t, \delta_t, F_R; \theta_2)), \quad t = 1, ...T \text{ and } h = 0, ..., H \tag{2.9}$$

where s_t are computed market shares that simulated from Equation (2.9). The contraction mapping process stops once the observed market share is equal to the computed market share. H is the smallest integer such that $\|\delta_t^H - \delta_t^{H-1}\|$ is smaller than some tolerance level, and δ_t^H is approximation to δ_t.

After solving δ_t, the error term can be defined as

$$\xi_{jt}(\theta_2) \equiv \delta_{jt}(x, p, S_t; \theta_2) - (\alpha p_{jt} + X_{jt}\beta) \tag{2.10}$$

2.3.2.2 The Objective Function

The population moment condition that enters GMM objective functions is

$$G(\theta) \equiv E[Z_m \cdot \xi(\theta_2)] = 0, \qquad m = 1, \ldots, M$$

where Z is the set of instrument variables. Then, GMM estimate is

$$\hat{\theta}_2 = \underset{\theta_2}{argmin}\ \xi(\theta_2)' Z \Phi^{-1} Z' \xi(\theta_2)$$

where Φ^{-1} is the optimal weight matrix which can be defined as

$$\Phi^{-1} = (E(Z'\xi'\xi Z))^{-1}$$

Using GMM, mean taste coefficients $\overline{\alpha}$ and $\overline{\beta}$ are estimated by regressing mean utility on observable vehicle attributes with the use of IVs:

$$(\widehat{\alpha}, \widehat{\beta}) = (X'Z\Phi^{-1}Z'ZX)^{-1}X'Z'Z\Phi^{-1}Z'\delta$$

2.3.2.3 Instrument Variables

Valid instrument variables are required for consistent and efficient estimation of the model. Price is most likely to be correlated with unobserved vehicle attributes in the demand equation which causes an endogeneity problem (e.g. Unobserved higher quality is positively correlated with price). If we fail to correct for the endogeneity of prices, the price coefficient will be biased toward zero which makes consumers appear to be less sensitive to the price than they really are. Valid IVs should satisfy the following two conditions. First, they should be uncorrelated with the error term.

Table 2.5: Vehicle Segmentation Criteria

Segment	**Typical Price Range**	**Typical Length**
Lower Small Car	Under $16,500	Under 170 ins.
Upper Small Car	$16,501 to $21,000	Under 185 ins.
Small Specialty Car	Under $25,000	Under 185 ins.
Lower Middle Car	$21,001 to $25,000	185 to 195 ins.
Upper Middle Car	$25,001 to $32,000	185 to 195 ins.
Middle Specialty Car	$25,000 to $32,000	Under 200 ins.
Large Car	$23,000 to $32,000	Over 195 ins.
Lower Luxury Car	$32,001 to $42,000	
Middle Luxury Car	$42,001 to $65,000	
Upper Luxury Car	Over $65,000	
Luxury Specialty Car	Over $32,000	
Luxury Sports Car	Over $32,000	
Small Cross Utility Vehicle	Under $25,000	Under 180 ins.
Small Luxury Cross Utility Vehicle	Over $32,000	Under 180 ins.
Middle Cross Utility Vehicle	$20,000 to $34,000	180 to 195 ins.
Middle Luxury Cross Utility Vehicle	Over $34,000	180 to 195 ins.
Large Cross Utility Vehicle	Under $40,000	Over 195 ins.
Large Luxury Cross Utility Vehicle	Over $40,000	Over 195 ins.
Small Sport Utility Vehicle	Under $25,000	Under 180 ins.
Middle Sport Utility Vehicle	$25,001 to $34,000	180 to 200 ins.
Middle Luxury Sport Utility Vehicle	Over $34,000	180 to 195 ins.
Large Sport Utility Vehicle	Under $49,000	Over 200 ins.
Large Luxury Sport Utility Vehicle	Over $49,000	Over 195 ins.
Small Van	Under $34,000	Under 210 ins.
Large Van	Over $26,000	Over 210 ins.
Small Pickups		Under 210 ins.
Large Pickups		Over 205 ins.

Source: WardsAuto Data Center.

Second, they should be highly correlated with the endogenous variable, the price. Followed by Bresnahan (1987), BLP (1995) and Furlong (2012), I constructed the following IV sets for the model. First, observed vehicle attributes, X_{jt} themselves are used for IVs. The second set of IVs are based on the price competition faced by vehicle j in the market. The logic implies that products with closer substitutes are more likely to have lower prices due to competitiveness. It includes the sum of the each vehicle attribute of other vehicles produced by the same firm $\sum_{l \neq j, l \in F_j}^{j} x_{lk}$, and the sum of the each vehicle attribute of other vehicles produced by other firms $\sum_{l \neq j, l \notin F_j}^{j} x_{lk}$ where F_j is the set of vehicle models produced by firm F. The third set of IVs is the sum of each vehicle attribute of other vehicles produced by the same firm and the same vehicle type (e.g. Car, Truck, SUV etc.) $\sum_{l \neq j, l \neq F_j, l \in G_t}^{j} x_{lk}$, and other firms and other vehicle types $\sum_{l \neq j, l \neq F_j, l \notin G_t}^{j} x_{lk}$ where G_t is the group of vehicle types. The last IV set is the sum of vehicle attributes of other vehicles in the same vehicle segment (e.g. Large, Large Van etc.) $\sum_{l \neq j, l \in G_s}^{j} x_{lk}$ where G_s is the group of vehicle segment class. Each vehicle segment class and its criteria are listed in Table 2.5. Among them, I include 8 IVs into the estimation that are highly correlated with the price.

2.3.3 Supply Side

Supply side model is required to recover marginal costs. I assume that automobile manufacturers engage in Bertrand-Nash competition to maximize the profit. Suppose there are F multiproduct firms in the market and each firm f sells subset, $F_{(f)}$ of the J products in the market. The profit function of a multiproduct firm f is

$$\Pi_f = \sum_{j \in F_{(f)}} (p_j - mc_j) M s_j(p) - FC_f \tag{2.11}$$

where $F_{(f)}$ is the subset of products produced by firm f, mc_j is the marginal cost of producing product j, M is the market size, $s_j(p)$ is the market share of product j and FC_f is the fixed cost for firm f. Solving the firm f's profit maximization problem yields the following first order condition:

$$\frac{\partial \Pi_f}{\partial p_j} = s_j(p) + \sum_{r \in F_f} (P_r - mc_r) \frac{\partial s_r(p)}{\partial P_j} = 0 \ \ \forall j \in J_f$$

If we further define the matrix:

$$\Omega_{jr}(p) = -\frac{\partial s_j(p)}{\partial p_r} \qquad j, r \in J$$

and the market structure matrix

$$\Lambda_{jr} = \begin{cases} 1 & \text{if } j \text{ and } r \text{ are produced by the same firm} \\ 0 & \text{otherwise} \end{cases}$$

then, the first order condition can be be written as following matrix form:

$$s(p) - \Omega(p) * \Lambda(p - mc) = 0$$

Finally markup and marginal cost are computed using the following equations:

$$\begin{aligned} p - mc &= (\Omega(p) * \Lambda)^{-1} s(p) \\ mc &= p - (\Omega(p) * \Lambda)^{-1} s(p) \end{aligned} \tag{2.12}$$

Equation (2.12) clearly shows that markups are affected by following three factors: 1) price elasticities (η_{jr}) which determines partial derivative matrix ($\Omega_{jr}(p) = -\eta_{jr}\frac{s_j}{p_r}$), 2) market structure matrix (Λ), and 3) market share of the vehicle model ($s(p)$).

2.3.4 Identifying Price Discrimination

The previous section provides markups for each vehicle that are required for measuring price discrimination. Comparing average markups and percentage markups for all HEV models and all gasoline vehicle models is an effective measure of price discrimination. If the average markup for HEVs exceeds gasoline vehicles, automobile manufacturers do engage in price discrimination against HEV consumers. Average markup and percentage markup are calculated by

$$\begin{aligned} &\frac{1}{H}\frac{1}{T}\sum_{h=1}^{H}\sum_{t=1}^{T}(p_{ht}-mc_{ht}) \qquad \frac{1}{G}\frac{1}{T}\sum_{g=1}^{G}\sum_{t=1}^{T}(p_{gt}-mc_{gt}) \\ &\frac{1}{H}\frac{1}{T}\sum_{h=1}^{H}\sum_{t=1}^{T}\left(\frac{p_{ht}-mc_{ht}}{p_{ht}}\right) \qquad \frac{1}{G}\frac{1}{T}\sum_{g=1}^{G}\sum_{t=1}^{T}\left(\frac{p_{gt}-mc_{gt}}{p_{gt}}\right) \end{aligned} \tag{2.13}$$

where H and G are numbers of hybrid and gasoline vehicles in period t, and $(p_{ht} - mc_{ht})$ and $(p_{gt} - mc_{gt})$ are markups for all hybrid and gasoline vehicle models in period t respectively. Percentage markup is calculated markup divide by the price.

Note that Equation (2.13) calculates average markups and percentage markups based on all HEV models and gasoline vehicle models in the market. Another way of measuring discrimination is comparing average markups between HEV models with their straight gasoline counterparts (e.g., Toyota Camry and Camry Hybrid). These vehicles are almost identical except that HEVs have electric powertrain that enables hybrid models to have better fuel economy than non-hybrid models:

$$\frac{1}{T}\sum_{t=1}^{T}(p_{jht}-mc_{jht}) \qquad \frac{1}{T}\sum_{t=1}^{T}(p_{jgt}-mc_{jgt}) \tag{2.14}$$

where jh and jg indicate the hybrid and non-hybrid vehicle model j. $(p_{jht} - mc_{jht})$ is the markup of HEV model j and $(p_{jgt} - mc_{jgt})$ is the markup of the non-hybrid counterpart gasoline vehicle model j in time t.

2.4 Data

This section explains data sets used in demand estimation. Four main data sets are used in this study: 1) new vehicle sales, vehicle attributes and incentives, 2) monthly regular retail gasoline prices, 3) federal tax credit for HEVs, and 4) total household income.

The primary data set in this study is monthly new car and light truck sales in the U.S. market. New vehicle sales data are collected from the Automotive News Data Center and the WardsAuto Data Center between January 2000 to December 2013. Monthly HEV sales data are separately collected from the Hybrid Market Dashboard provided by Hybridcars.com. All vehicle sales data are collected monthly then aggregated to yearly. In each year, more than 200 vehicle models are in the market which comprise 3,565 observations in the sample period.

Vehicle prices and attributes data are obtained from WardsAuto Data Center. New car incentives and cash rebates offered by manufacturers are separately collected from Automotive News Data Center. Actual vehicle transaction prices are the most suitable for this study but such data is difficult to obtain. While some studies use actual transaction level purchase data from the individual survey (BLP 2004; Langer 2012) or local car dealers (Copeland et al. 2011; Gujarado et al. 2014; Murry 2014), most of the earlier studies on the automobile industry use listed Manufacturer Suggested Retail Price (MSRP) because of the data unavailability (BLP 1995; Verboven 1996: Sudhir 2001; Petrin 2002; Thomassen 2010). I augment MSRP with monthly cash rebates and HEV tax credits to make vehicle price data as close to transaction level as possible.

The following vehicle attribute variables are included for demand specification: dollars per mile (DPM), the ratio of horsepower to curb weight (HPW), Size, Hybrid dummy, vehicle type dummies (Truck, SUV, Specialty, Luxury)[2] and 23 manufacturer (e.g., Toyota, BMW, GM, etc.) dummies. DPM measures the fuel cost per mile and is calculated gasoline prices divided by miles per gallon (MPG). Size is a proxy for both comfort and safety and calculated as length multiplied by width and height. A set of dummy variables account for unobservable vehicle attributes and fixed effects.

Yearly average gasoline prices are required to calculate fuel cost per mile (DPM). I collected this data from the Energy Information Administration (EIA) between the years 2000 to 2013.

[2] See Table 2.5 for details on vehicle type segmentation criteria.

As discussed in section 2.2, the federal government provides tax credits for eligible HEV models. Therefore, additional federal tax credits are subtracted from the MSRP. HEV tax credit information is available at the Internal Revenue Service (IRS).

Individual preference for the price, α_i, is interacted with a demographic variable, total household income, and forms a random coefficient. Total household income data are collected from the Current Population Survey Annual Social and Economic Supplements (CPS ASEC) provided by U.S. Census Bureau and Bureau of Labor Statistics. Each year, 100 individuals were randomly drawn and used for the demand estimation.

Not only vehicle attribute variables but macroeconomic indicators also have significant effects on consumers' vehicle choice. To address this issue, I include unemployment rate (Unemp) obtained from the Bureau of Labor Statistics, and a quadratic time trend (Trend and Trend2) during sample period.

Total market size, M_t, is required to calculate market share of each vehicle model, s_{jt}, and outside market share, s_0. I define total market size as the total number of households in the U.S. Then, market share of each vehicle model j in year t is calculated by $s_{jt} = \frac{q_{jt}}{M_t}$ where q_{jt} is the total yearly sales of each vehicle model, and outside market share is defined by the subtracting sum of all vehicle market shares from 1:

$$s_{0t} = 1 - \sum_{j=1}^{J} s_{jt}$$

Finally, vehicle prices, gasoline prices and household income are shown in 2012 dollars using consumer price index (CPI) which is available at U.S. Department of Labor, Bureau of Labor Statistics.

2.5 Results

This section presents the results of empirical analysis as follows: descriptive statistics of variables used in the demand estimation, followed by the parameter estimates and elasticities, and concluded with a comparison of markups and percentage markups between HEVs and gasoline vehicles to measure price discrimination.

2.5.1 Descriptive Statistics

Tables 2.6, 2.7 and 2.8 respectively report descriptive statistics of vehicle attributes for all LDVs, gasoline LDVs and hybrid LDVs that are used in the estimation. These variables include vehicle Price, HPW, DPM and Size.[3] The sales weighted average price of gasoline LDV is \$27,137 with a standard deviation of \$10,533 (Table 2.7). The sales weighted average price of HEVs after adjusting for cash rebates and HEV tax credits is slightly more expensive due to the hybrid premium, \$27,992. However, MPG and DPM variables in Table 2.8 clearly show better fuel efficiency of HEVs.

Table 2.6: Descriptive Statistics of Vehicle Attributes: All LDVs (2000 - 2013)

Variable	Mean	Std. Dev.	Mean[1]	Std. Dev.[1]	Min	Max
Price ($1,000s)	37.155	23.711	27.149	10.502	11.277	540.460
HPW	0.059	0.016	0.054	0.010	0.024	0.174
MPG	22.946	5.671	23.599	5.441	12.400	64.200
DPM	0.129	0.041	0.120	0.038	0.028	0.285
Size	0.872	0.197	0.902	0.199	0.395	1.486
Length (ins.)	187.93	15.20	190.37	13.81	106.1	230.0
Width (ins.)	73.122	4.034	73.227	4.201	61.4	89.0
Height (ins.)	62.701	7.904	63.912	7.453	44.0	83.7
# of Observations			3,565			

Notes:
1. Sales Weighted
2. Price = MSRP-Cash Rebate-HEV Tax Credit (In case of a HEV)
3. DPM = Gas Price($) / MPG
4. HPW = HP / Curb Weight(lbs.)
5. Size = (Length×Width×Height) / 1,000,000

[3] MPG, Length, Width and Height variables are included in the descriptive statistic table, but not used in the estimation.

Table 2.7: Descriptive Statistics of Vehicle Attributes: All Gasoline LDVs (2000 - 2013)

Variable	Mean	Std. Dev.	Mean[1]	Std. Dev.[1]	Min	Max
Price ($1,000s)	36.731	23.706	27.137	10.533	11.277	540.460
HPW	0.059	0.016	0.054	0.010	0.033	0.174
MPG	22.278	4.440	23.307	4.796	12.400	38.700
DPM	0.130	0.040	0.121	0.038	0.046	0.285
Size	0.872	0.198	0.904	0.200	0.395	1.486
Length (ins.)	187.92	15.28	190.52	13.81	106.1	228.9
Width (ins.)	73.153	4.066	73.276	4.203	61.40	89.0
Height (ins.)	62.727	7.963	63.975	7.475	44.0	83.7
# of Observations			3,340			

Notes:
1. Sales Weighted
2. Price = MSRP-Cash Rebate-HEV Tax Credit (In case of a HEV)
3. DPM = Gas Price($) / MPG
4. HPW = HP / Curb Weight(lbs.)
5. Size = (Length×Width×Height) / 1,000,000

Table 2.8: Descriptive Statistics of Vehicle Attributes: All Hybrid LDVs (2000 - 2013)

Variable	Mean	Std. Dev.	Mean[1]	Std. Dev.[1]	Min	Max
Price ($1,000s)	43.434	22.929	27.992	8.071	19.290	120.805
HPW	0.050	0.014	0.037	0.009	0.024	0.090
MPG	32.863	10.605	43.469	8.864	17.900	64.200
DPM	0.109	0.037	0.077	0.022	0.028	0.205
Size	0.861	0.183	0.752	0.091	0.551	1.358
Length (ins.)	188.08	14.02	179.84	7.860	155.1	230.0
Width (ins.)	72.663	3.510	69.908	2.262	66.70	80.0
Height (ins.)	62.316	6.974	59.610	3.881	53.3	76.9
# of Observations			225			

Notes:
1. Sales Weighted
2. Price = MSRP-Cash Rebate-HEV Tax Credit (In case of a HEV)
3. DPM = Gas Price($) / MPG
4. HPW = HP / Curb Weight(lbs.)
5. Size = (Length×Width×Height) / 1,000,000

While sales weighted average MPG and DPM of gasoline vehicles are 23.31 and \$0.12, HEVs have much higher fuel economy of 43.47 and lower DPM of \$0.08 respectively. Though HEVs are more fuel efficient, they are smaller in size and less powerful than gasoline LDVs. HEVs have an average size of 0.752 and gasoline vehicles have a slightly larger size at 0.904. HEVs are less powerful than gasoline vehicles in terms of HPW. This can be attributed to the fact that most HEV models belong to the midsize class, and HEV models are base or lower trim level of their counterpart gasoline vehicle models. Summary statistics of total household income for sample years are shown in Table 2.9.

Table 2.9: Descriptive Statistics of Total Household Income

Year	Median	Mean	Std. Dev.	Min	Max
2000	\$64,601	\$81,904	\$71,008	\$1.38	\$1,059,337
2001	\$65,676	\$83,641	\$79,332	\$1.27	\$993,956
2002	\$68,031	\$87,354	\$82,926	\$1.30	\$1,101,176
2003	\$66,904	\$85,658	\$82,898	\$1.28	\$1,260,408
2004	\$67,415	\$86,208	\$82,503	\$1.25	\$1,344,271
2005	\$67,012	\$85,939	\$82,981	\$1.22	\$1,368,000
2006	\$67,569	\$87,214	\$85,396	\$1.18	\$1,315,798
2007	\$68,328	\$89,065	\$88,948	\$1.14	\$1,369,756
2008	\$68,769	\$87,908	\$82,355	\$1.11	\$1,166,724
2009	\$67,183	\$86,013	\$80,496	\$1.07	\$1,077,188
2010	\$65,299	\$85,182	\$81,924	\$1.07	\$1,260,789
2011	\$64,283	\$83,549	\$83,718	\$1.05	\$2,064,059
2012	\$63,842	\$83,960	\$89,334	\$1.02	\$2,143,868
2013	\$64,200	\$84,390	\$91,583	\$1.00	\$2,742,997

Note: Data are obtained from CPS Annual Social and Economic Supplement

2.5.2 Parameter Estimates

Demand estimation results from the OLS logit and IV logit regression are presented in Table 2.10. Several interesting points are worth discussing. The first column of the table displays the OLS results without 23 manufacturer dummies and the second and third columns respectively show estimation results including manufacturer dummies. Most of the coefficient estimates have expected signs and are statistically significant. The price coefficient has a negative sign and is significant for all three specifications. Comparing the magnitude of estimated price coefficients between OLS logit with manufacturer dummies (-0.0273) and IV logit (-0.0993), models clearly shows the importance of introducing IVs when the endogeneity of price exists. Consumers are more price sensitive once the endogenous problem is corrected for. As a result, price sensitivity of consumers increases almost four times in IV logit regression. Vehicle attribute coefficients reveal the consumer's preference on vehicle choices. It turns out that, on average, consumers like powerful, fuel efficient and comfortable cars. The coefficient estimates on HPW, DPM and Size have expected signs and significantly different from zero in both the OLS and IV logit models. The negative and significant coefficient of hybrid dummy variable suggests that average consumers dislike HEVs compared to gasoline vehicles. It seems that average consumers are suspicious about novel fuel efficient HEV technology, which can partly explain why the hybrid car market share still remains at 6%. I also interact hybrid dummy variable with a quadratic time trend (Hytrend and Hytrend2) to track down the adoption of HEVs during the sample time period.Hybrid time trend variable is estimated to be positive in all demand specifications, which implies consumers' preference on HEVs has been growing over time. According to the coefficient estimates on vehicle type dummy variables, consumers prefer SUVs but do not like pickup trucks, specialties (coupe and convertible) and luxury vehicles. As expected, unemployment rate is negatively associated with vehicle market shares.

Table 2.10: OLS and IV Logit Model Estimation Results

Dependent variable: $\ln(s_j) - \ln(s_0)$						
	(1)		(2)		(3)	
Variable	OLS Logit		OLS Logit		IV Logit	
Price	-0.0259***	(0.002)	-0.0273***	(0.002)	-0.0993***	(0.011)
HPW	7.135***	(1.883)	2.422	(1.836)	40.34***	(6.224)
DPM	-12.64***	(1.073)	-10.56***	(0.944)	-7.126***	(1.304)
Size	1.754***	(0.154)	0.815***	(0.156)	2.790***	(0.359)
Hybrid	-2.631***	(0.590)	-3.454***	(0.510)	-2.161***	(0.553)
Hytrend	0.344**	(0.136)	0.393***	(0.117)	0.331***	(0.120)
Hytrend2	-0.0192**	(0.0075)	-0.0203***	(0.0065)	-0.0168**	(0.007)
Truck	0.371***	(0.0799)	0.199***	(0.0707)	-0.183*	(0.104)
SUV	0.167***	(0.0595)	0.213***	(0.0587)	0.598***	(0.0956)
Specialty	-0.552***	(0.0625)	-0.714***	(0.0573)	-0.463***	(0.0784)
Luxury	-0.236***	(0.0434)	-0.169***	(0.0459)	-0.560***	(0.0809)
Trend	0.0416*	(0.0248)	0.04*	(0.0217)	-0.108***	(0.0350)
Trend2	0.0019	(0.0013)	0.00112	(0.0012)	0.0052***	(0.0015)
Unemp	-0.181***	(0.0163)	-0.172***	(0.0141)	-0.133***	(0.0174)
Constant	-6.682***	(0.157)	-5.796***	(0.182)	-6.590***	(0.247)
R-Squared	0.352		0.530		0.334	
Manufacturer Dummies	NO		YES		YES	

Notes:
1. Standard errors in parentheses
2. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
3. Parameter estimates of manufacturer dummy variables are excluded from the table.

Table 2.11 compares demand estimate results from the IV logit model and Random coefficients logit model.[4] Column (1) is simply copied from column (3) in Table 2.10 for comparison purpose. The first panel of column (2) reports estimates of mean

[4]Knittel and Metaxoglou (2013) point out that BLP demand estimation results are sensitive to the choice of starting values and optimization algorithm. To overcome this issue, I use multiple sets of starting values, and employ derivative-based algorithm (SOLVOPT) that lead to the minimum GMM objective function value.

taste coefficients and the second panel provides estimates of heterogeneity taste parameters for three vehicle attributes (HPW, DPM, Size) as well as Price, all of

Table 2.11: Random Coefficients Logit Model Estimation Results

Dependent variable: $\ln(s_j) - \ln(s_0)$				
Variable	(1) IV Logit		(2) Random Coefficients Logit	
Price	-0.0993***	(0.0113)	-0.289*	(0.169)
HPW	40.34***	(6.224)	14.322	(33.335)
DPM	-7.126***	(1.304)	-58.153*	(32.211)
Size	2.790***	(0.359)	0.822**	(2.298)
Hybrid	-2.161***	(0.553)	-5.440**	(2.538)
Hytrend	0.331***	(0.120)	0.612*	(0.361)
Hytrend2	-0.0168**	(0.0067)	-0.027*	(0.017)
Pickup	-0.183*	(0.104)	-0.424	(0.663)
SUV	0.598***	(0.0956)	0.611**	(0.311)
Specialty	-0.463***	(0.0784)	-0.782***	(0.231)
Luxury	-0.560***	(0.0809)	-0.845*	(0.487)
Trend	-0.108***	(0.0350)	-0.160	(0.366)
Trend2	0.0052***	(0.0015)	0.017	(0.016)
Unemp	-0.133***	(0.0174)	-0.403*	(0.232)
Constant	-6.590***	(0.247)	-1.622	(-2.565)
Heterogeneity Parameters (σ)				
Constant			1.469	(2.64)
Price			0.121**	(0.054)
HPW			10.081	(21.64)
DPM			35.013	(24.189)
Size			4.21***	(1.394)
Income			0.085*	(0.046)
Manufacturer Dummies	YES		YES	
J statistic (D.F.)	1.08 (2)			

Notes:
1. Standard errors in parentheses
2. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
3. Parameter estimates of manufacturer dummy variables are excluded from the table.

which are normally distributed. Price coefficient, marginal utility of income, varies with household income.[5] Estimated mean taste coefficients in random coefficients models have same signs with IV logit model estimates. Consumers have significant heterogeneous tastes on price and size. Income heterogeneity coefficient is positive and significant indicating that higher income consumers are less sensitive to price than average consumers. In addition to demand side parameters, I also estimate cost side parameters and report the results in Table 2.12. These parameters are obtained by regressing estimated marginal cost (MC) on the cost side variables, Size, HPW, Hybrid as well as time trend dummy variable (Equation (2.15)):

$$\ln(MC_{jt}) = \delta_0 + \delta_1 \ln(Size_{jt}) + \delta_2 \ln(HPW_{jt}) + \delta_3 Hybrid_{jt} + \delta_4 Trend_t + \omega_{jt} \quad (2.15)$$

In order to capture the effect of returns to scale, a separate regression model including logarithm of cumulative vehicle sales ($\ln(Sales)$) is estimated and the results are reported in the second column of Table 2.12. Coefficients on Size and HPW are

Table 2.12: Cost Side Parameters Estimation Results

Dependent variable: ln(MC)				
Variable	Estimate	Std. Err.	Estimate	Std. Err.
ln(Size)	0.713***	(0.043)	0.746***	(0.043)
ln(HPW)	0.461***	(0.022)	0.466***	(0.022)
Hybrid	0.306***	(0.019)	0.307***	(0.019)
Trend	-0.015***	(0.000)	-0.002***	(0.002)
ln(Sales)			-0.078***	(0.012)
Constant	4.838***	(0.075)	6.200***	(0.215)
R-Squared	0.883		0.885	

Notes:
1. OLS regression of log of estimated marginal cost on cost side variables
2. Standard errors in parentheses
3. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
4. Parameter estimates of manufacturer and vehicle segment dummy variables are excluded from the table.

[5] I use demeaned value of household income for calculation purpose.

positive and significant which make sense because it costs more to produce bigger, more comfortable and more powerful vehicles. HEVs, on average, are estimated to cost 30.6% more than conventional gasoline vehicles.

2.5.3 Elasticities

In this section, I discuss estimated own and cross price elasticties for selective vehicle models. Since the random coefficients logit model has systematic heterogeneity among consumers, it provides a much larger flexible substitution patterns than a simple logit model. Table 2.13 displays the estimated own and cross price elasticities for selective vehicle models in 2013. Both own and cross elasticities explain percentage changes of market share with respect to the 1% increase in the vehicle price. For example, 1% increase in the price of the BMW 750i leads to the market share of the BMW X3 and the Ford Mustang to increase by 0.08% and 0.002% respectively. The more close substitutes, the higher cross price elasticity in magnitude we would expect. Honda civic has higher cross price elasticity than BENZ SL550 since it has more substitutes. Not surprisingly, vehicles within the same segment that have similar price range and attributes have larger cross price elasticities. BMW 750i is the closest substitute to the Benz SL 550 in that the SL 550 has the largest cross price elasticities of 0.011. Similarly, the Toyota Prius is the closest substitute for the Honda Civic Hybrid (0.042).

2.5.4 Marginal Costs, Markups and Price Discrimination

This section presents estimated marginal costs, markups and percentage markups derived from the demand side parameters in Table 2.11. I then compare markups and percentage markups between gasoline vehicles and HEVs to investigate the evidence of price discrimination against HEV consumers. Descriptive statistics of marginal costs,markups and percentage markups are summarized in Table 2.14 and are compared across vehicle types in the sample period. The first panel compares the

Table 2.13: A sample of Estimated Mean Own and Cross Price Elasticities (2013)

Vehicle Model	Own Elasticity	750i	X3	Malibu	Mustang	Escape	Civic	Civic Hybrid
BMW 7 Series 750i	-5.257	-5.257	0.010	0.011	0.004	0.020	0.013	0.001
BMW X3	-4.502	0.008	-4.502	0.025	0.011	0.043	0.031	0.001
CHEVROLET Malibu	-4.351	0.002	0.007	-4.351	0.016	0.062	0.055	0.001
FORD Mustang	-4.872	0.002	0.007	0.039	-4.872	0.069	0.058	0.001
FORD Escape	-4.604	0.003	0.007	0.038	0.017	-4.604	0.054	0.001
HONDA Civic	-3.904	0.002	0.006	0.038	0.017	0.061	-3.904	0.001
HONDA Civic Hybrid	-3.232	0.004	0.006	0.029	0.008	0.038	0.036	-3.232
HONDA CR-Z	-3.622	0.003	0.006	0.032	0.013	0.051	0.046	0.001
HYUNDAI Sonata	-4.384	0.002	0.007	0.040	0.017	0.064	0.057	0.001
BENZ SL550	-5.514	0.011	0.008	0.008	0.003	0.015	0.010	0.001
NISSAN Maxima	-5.080	0.005	0.010	0.032	0.018	0.059	0.043	0.001
TOYOTA Prius	-3.098	0.003	0.006	0.030	0.007	0.037	0.037	0.002
VOLKSWAGEN Jetta	-3.976	0.002	0.005	0.037	0.018	0.066	0.060	0.001
VOLKSWAGEN Tiguan	-4.916	0.002	0.007	0.035	0.021	0.070	0.054	0.001
Vehicle Model	Own Elasticity	CR-Z	Sonata	SL 550	Maxima	Prius	Jetta	Tiguan
BMW 7 series 750 i	-5.257	0.000	0.009	0.009	0.009	0.015	0.005	0.002
BMW X3 28i	-4.502	0.000	0.023	0.005	0.014	0.022	0.012	0.004
CHEVROLET Malibu	-4.351	0.001	0.038	0.001	0.013	0.032	0.024	0.006
FORD Mustang	-4.872	0.001	0.039	0.001	0.017	0.019	0.028	0.008
FORD Escape	-4.604	0.001	0.037	0.002	0.014	0.024	0.026	0.007
HONDA Civic	-3.904	0.001	0.036	0.001	0.012	0.027	0.026	0.006
HONDA Civic Hybrid	-3.232	0.001	0.025	0.003	0.007	0.042	0.013	0.002
HONDA CR-Z	-3.622	-3.622	0.030	0.002	0.011	0.027	0.021	0.005
HYUNDAI Sonata	-4.384	0.001	-4.384	0.001	0.013	0.029	0.026	0.006
BENZ SL550	-5.514	0.000	0.007	-5.514	0.006	0.014	0.003	0.001
NISSAN Maxima	-5.080	0.001	0.031	0.003	-5.080	0.017	0.020	0.007
TOYOTA Prius	-3.098	0.001	0.025	0.002	0.006	-3.098	0.012	0.002
VOLKSWAGEN Jetta	-3.976	0.001	0.037	0.001	0.012	0.021	-3.976	0.007
VOLKSWAGEN Tiguan	-4.916	0.001	0.036	0.001	0.017	0.014	0.029	-4.916

Note: The table shows the elasticity of demand of the row entry, i, with respect to the price of the column entry j, which can be interpreted as the percentage change in market share of vehicle model i with respect to one percent change in price of vehicle model j.

Table 2.14: Sales Weighted Average Price, Implied Marginal Cost, Markup and Markup(%) Estimates across Vehicle Types (2000 - 2013)

	All Cars					All Light Trucks			
	Price	MC	Markup	Markup(%)		Price	MC	Markup	Markup(%)
Mean	$25,597	$21,068	$4,529	19.42%	Mean	$28,449	$23,777	$4,672	17.30%
95% CI	[$25,030 $26,164]	[$20,527 $21,609]	[$4,481 $4,578]	[19.17% 19.66%]	95% CI	[$27,997 $28,902]	[$23,344 $24,211]	[$4,628 $4,716]	[17.10% 17.50%]
Min	$11,277	$7,211	$2,856	3.50%	Min	$16,000	$11,911	$2,946	4.30%
Max	$118,814	$114,635	$13,831	36.90%	Max	$113,974	$107,591	$13,230	29.30%

	Regular LDVs					Luxury LDVs			
	Price	MC	Markup	Markup(%)		Price	MC	Markup	Markup(%)
Mean	$23,198	$18,797	$4,401	19.59%	Mean	$43,386	$37,930	$5,456	13.05%
95% CI	[$22,985 $23,411]	[$18,592 $19,003]	[$4,374 $4,427]	[19.40% 19.77%]	95% CI	[$42,727 $44,045]	[$37,289 $38,570]	[$5,374 $5,538]	[12.86% 13.24%]
Min	$11,277	$7,211	$2,856	11.40%	Min	$28,922	$23,697	$3,426	3.50%
Max	$35,386	$31,081	$8,001	36.90%	Max	$118,814	$114,635	$13,381	27.50%

	Gasoline LDVs					Hybrid LDVs			
	Price	MC	Markup	Markup(%)		Price	MC	Markup	Markup(%)
Mean	$27,050	$22,455	$4,595	18.33%	Mean	$27,074	$22,003	$5,071	19.19%
95% CI	[$26,674 $27,426]	[$22,095 $22,815]	[$4,562 $4,628]	[18.16% 18.49%]	95% CI	[$25,965 $28,184]	[$20,949 $23,058]	[$4,888 $5,253]	[18.46% 19.93%]
Min	$11,277	$7,211	$2,856	3.50%	Min	$19,290	$14,644	$3,689	10.70%
Max	$118,814	$114,635	$13,831	36.90%	Max	$52,933	$47,246	$11,234	27.60%

	Gasoline Cars					Hybrid Cars			
	Price	MC	Markup	Markup(%)		Price	MC	Markup	Markup(%)
Mean	$25,600	$21,082	$4,518	19.41%	Mean	$25,480	$20,528	$4,952	19.69%
95% CI	[$25,012 $26,189]	[$20,520 $21,644]	[$4,468 $4,568]	[19.16% 19.67%]	95% CI	[$24,743 $26,216]	[$19,782 $21,273]	[$4,786 $5,119]	[18.88% 20.50%]
Min	$11,277	$7,211	$2,856	3.50%	Min	$19,290	$14,644	$3,689	12.30%
Max	$118,814	$114,635	$13,831	36.90%	Max	$40,145	$34,940	$6,909	27.60%

	Gasoline Light Trucks					Hybrid Light Trucks			
	Price	MC	Markup	Markup(%)		Price	MC	Markup	Markup(%)
Mean	$28,415	$23,748	$4,668	17.31%	Mean	$38,006	$32,120	$5,885	15.76%
95% CI	[$27,959 $28,871]	[$23,310 $24,185]	[$4,624 $4,711]	[17.10% 17.51%]	95% CI	[$35,092 $40,920]	[$29,423 $34,818]	[$5,259 $6,512]	[14.32% 17.20%]
Min	$16,000	$11,911	$2,946	4.30%	Min	$25,913	$20,101	$3,921	10.07%
Max	$113,974	$107,591	$13,230	29.30%	Max	$52,933	$47,246	$11,234	24.5%

Note: Marginal cost, markups and markups(%) are derived from the demand side parameters.

statistics between all cars and light trucks, and the second panel compares the statistics between regular LDVs and luxury LDVs.[6] On average, light trucks and luxury LDVs have higher markups but have lower percentage markups than cars and regular LDVs. Since light trucks and luxury LDVs are more expensive than cars and regular LDVs, markups are greater for light trucks and luxury LDVs but manufacturers cannot charge markups proportionally as they do for cars and regular LDVs. Panels 3-5 in Table 2.14 show markup and percentage markup comparisons between HEVs and gasoline vehicles. It turns out that hybrid LDVs have both higher markups and percentage markups than gasoline LDVs. The average markups for gasoline gasoline and hybrid LDVs are $4,595 and $5,071, corresponding to 18.33% and 19.19% of percentage markups. Though hybrid vehicles are more expensive than gasoline vehicles due to hybrid premium, manufacturers charge both higher markups and percentage markups for their hybrid vehicles. I then separate total LDVs by cars and light trucks, and compare markup and percentage markup differences. Hybrid cars have both higher markups and percentage markups than gasoline cars. Average gasoline car markup and hybrid car markup respectively averaged $4,518 and $4,952 and corresponding average percentage markups are 19.41% and 19.69%. In light trucks, hybrid light trucks have far greater markups ($5,885) than gasoline light trucks ($4,668) but have smaller percentage markups of 15.76% than gasoline trucks, %17.31. This can be partly explained by huge price differences between hybrid and non-hybrid light trucks.

In addition, I carry out an auxiliary regression of estimated markups and percentage markups on Hybrid and Hybrid-Trend interaction dummy variables (Hytrend). Results are shown in Tables 2.15 and 2.16. It is estimated that HEVs have 11.09% higher markups than gasoline vehicles, on average. The coefficient of Hytrend variable implies that HEV markups decrease during the time period with an approximate 3.5% per year due to increased competition in HEV market. I find the

[6] T-test results reject the null hypothesis of no statistically significant difference in average markups between gasoline LDVs and Hybrid LDVs. However, I do not find an evidence of significant difference in average percentage markups between two vehicle types.

similar result for percentage markups. On average, there is no significant percentage markup differences between HEVs and gasoline vehicles. However, Hytrend coefficient in Table 2.16 implies that percentage markups of HEVs are also greater than gasoline vehicles and decrease at the rate of 3.7%.

Table 2.15: Regression Result of Estimated Markup on HEVs

Dependent variable: ln(Markup)				
Variable	Estimate	Std. Err.	Estimate	Std. Err.
Hybrid	0.1109***	(0.029)	0.4739***	(0.090)
Hytrend			-0.0354***	(0.008)
Constant	1.6804***	(0.058)	1.6778***	(0.058)
R-Squared	0.278		0.282	

Notes:
1. Standard errors in parentheses
2. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
3. Parameter estimates of manufacturer and vehicle segment dummy variables are excluded from the table.

Table 2.16: Regression Result of Estimated Markup(%) on HEVs

Dependent variable: ln(Markup(%))				
Variable	Estimate	Std. Err.	Estimate	Std. Err.
Hybrid	-0.0079	(0.029)	0.3761***	(0.093)
Hytrend			-0.0374***	(0.009)
Constant	-1.9214***	(0.060)	-1.9243***	(0.060)
R-Squared	0.435		0.438	

Notes:
1. Standard errors in parentheses
2. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
3. Parameter estimates of manufacturer and vehicle segment dummy variables are excluded from the table.

We discuss in section 2.3.3 that markups are primarily determined by price elasticities and market structure, i.e., number of vehicle models produced by the manufacturer, which in turn determines market share. Higher market share enables a firm to have a stronger market position that allows a firm to have an ability to charge higher markups leveraging their dominant position in the market. I report this relationship in Table 2.17. Table 2.17 presents average market share, price, marginal cost, markups and percentage markups of all LDVs by manufacturers. During the time period, General Motors (GM) gains the most market share of 21.06% and has the highest estimated markup ($5,024), and the big three manufacturers (GM, Toyota, Ford) have similar percentage markups of (19%). Table 2.18 replicates Table 2.17 but I include only HEVs. The table confirms the fact that Toyota is the top HEV manufacturer in that Toyota alone accounts for approximately 70.0% of total HEV market share over the sample period. As we would expect from the observed market share, Toyota charges the highest average markup of $4,412 for their HEV models among other HEV manufacturers in 2013. Toyota, Ford and Volkswagen have similar HEV average prices but Toyota has the both highest markups and percentage markups than other manufacturers.[7] I also find in Table 2.18 that markups and percentage markups of HEVs kept decreasing over the sample period. Two competition effects can explain this phenomenon. First, competition between gasoline vehicles and HEVs. As gasoline vehicles become more fuel efficient, manufacturers hesitate to charge higher markups for their HEVs to compete with gasoline vehicles. In addition, competition between HEVs has been increased as more HEV models are introduced in the market. In order to compute the extent of price discrimination, I then directly compare average markup and percentage markup differences between HEV models with comparable non-hybrid counterpart gasoline models manufactured

[7] I test if average markups and percentage markups for HEVs are statistically different across manufacturers. The results show that there is no statistically significant difference in average markups for HEVs across major automobile manufacturers, Toyota, Honda, Ford, GM and Nissan. However, I find a statistically significant difference in average markups of these manufacturers with those of new HEV market entrants, Hyundai, KIA and Volkswagen. Hyundai, KIA and Volkswagen have smaller average markups for their HEVs than other major manufactures. I also find average percentage markups of Toyota's HEVs are statistically different from each manufacturer except for Nissan.

by Toyota. Table 2.19 displays average marginal cost, markup and percentage markup for Toyota's HEV models, and Table 2.20 reports the comparison results. Among 9

Table 2.17: Average Market Share, Price, Marginal Cost, Markup and Markup(%) Estimates by Manufacturers: All LDVs (2000 - 2013)

Manufacturer	Market Share	Price	Marginal Cost	Markup	Markup(%)
GM	21.06%	$27,091	$22,067	$5,024	19.61%
TOYOTA	15.62%	$25,445	$20,723	$4,722	19.74%
FORD	15.50%	$25,336	$20,697	$4,639	19.03%
CHRYSLER	11.54%	$24,462	$20,061	$4,400	18.41%
HONDA	10.23%	$24,885	$20,385	$4,499	18.93%
NISSAN	7.52%	$25,024	$20,587	$4,437	19.24%
HYUNDAI	4.26%	$20,643	$16,521	$4,123	20.78%
KIA	2.97%	$19,394	$15,366	$4,028	21.60%
VOLKSWAGEN	2.41%	$23,927	$19,546	$4,381	19.26%
BMW	2.29%	$44,995	$38,768	$6,227	14.53%
SUBARU	2.12%	$22,760	$18,648	$4,112	18.28%
DAIMLER	1.99%	$49,381	$42,830	$4,042	14.35%
MAZDA	1.90%	$20,774	$16,732	$6,551	20.15%
MERCEDES	1.60%	$57,831	$51,760	$4,055	11.17%
AUDI	0.92%	$41,880	$36,674	$5,206	12.74%
MITSUBISHI	0.62%	$21,917	$17,862	$6,071	19.06%
SUZUKI	0.53%	$19,110	$15,357	$3,753	20.27%
GEELY[1]	0.42%	$35,943	$30,999	$6,760	13.89%
TATA[1]	0.38%	$62,536	$55,775	$4,944	11.16%
PORSCHE	0.22%	$64,761	$58,031	$6,730	10.87%
SAAB	0.05%	$24,437	$20,720	$3,717	16.13%
ISUZU	0.05%	$33,815	$28,379	$5,437	15.86%

Note: Both Volvo and Jaguar LandRover were subsidiaries of Ford company. Ford decided to sell Volvo to Chinese automotive company, Geely, in 2009 and sell Jaguar LandRover to Indian automotive company, Tata Motors in 2008.

Table 2.18: Average Market Share, Price, Marginal Cost, Markup and Markup(%) Estimates by Manufacturers: All HEVs (2009 - 2013)

	Manufacturer	Market Share	Price	Marginal Cost	Markup	Markup(%)
2009	TOYOTA	69.41%	$28,005	$22,045	$5,959	21.92%
	HONDA	12.84%	$23,782	$18,210	$5,572	23.60%
	FORD	10.81%	$29,752	$24,312	$5,439	18.33%
	GM	3.61%	$36,231	$30,628	$5,603	16.87%
	NISSAN	3.33%	$26,911	$21,825	$5,085	18.90%
2010	TOYOTA	72.31%	$27,208	$22,167	$5,040	19.41%
	HONDA	12.85%	$21,382	$16,639	$4,743	22.39%
	FORD	12.26%	$29,734	$24,674	$5,059	17.05%
	NISSAN	2.57%	$26,439	$21,607	$4,832	18.30%
2011	TOYOTA	68.59%	$26,915	$22,001	$4,914	18.74%
	HONDA	12.16%	$20,805	$15,864	$4,941	23.92%
	FORD	10.44%	$32,088	$26,977	$5,111	16.05%
	HYUNDAI	7.57%	$27,142	$22,281	$4,861	17.90%
	NISSAN	1.25%	$28,081	$23,117	$4,964	17.70%
2012	TOYOTA	72.36%	$26,703	$22,086	$4,617	17.72%
	GM	7.81%	$29,016	$24,235	$4,781	16.61%
	FORD	7.78%	$29,009	$24,256	$4,754	16.57%
	HYUNDAI	5.19%	$26,445	$22,184	$4,261	16.10%
	HONDA	4.30%	$22,088	$17,746	$4,343	19.86%
	KIA	2.56%	$26,700	$22,460	$4,240	15.90%
2013	TOYOTA	65.03%	$27,456	$23,044	$4,412	16.60%
	FORD	17.26%	$27,268	$23,069	$4,199	15.54%
	GM	5.14%	$29,081	$24,758	$4,323	15.00%
	HYUNDAI	4.66%	$26,542	$22,418	$4,124	15.50%
	HONDA	3.69%	$22,301	$18,198	$4,103	18.55%
	KIA	3.01%	$26,433	$22,354	$4,079	15.40%
	VOLKSWAGEN	1.22%	$27,799	$23,544	$4,255	15.30%

Table 2.19: Average Markup Comparison of Toyota's HEV Models (2000 - 2013)

HEV Model	Price	Marginal Cost	Markup	Markup(%)
Avalon Hybrid	$36,001	$31,154	$4,847	13.50%
Camry Hybrid	$27,772	$22,577	$5,195	18.68%
CT 200h Hybrid	$32,062	$27,076	$4,985	15.58%
ES 300h Hybrid	$39,943	$34,938	$5,006	12.51%
Highlander Hybrid	$37,822	$32,129	$5,693	15.09%
HS 250h Hybrid	$37,819	$32,125	$5,694	15.06%
Prius	$24,002	$19,027	$4,975	20.76%
RX 400h Hybrid	$45,744	$39,262	$6,483	14.17%
RX 450h Hybrid	$46,357	$39,567	$6,789	14.68%

Table 2.20: Average Markup Comparison between TOYOTA's HEV Models and Gasoline Counterparts (2000 - 2013)

Model	Price	Marginal Cost	Markup	Markup(%)	Price Premium	Marginal Cost Difference	Markup Difference
Avalon	$31,829	$27,371	$4,458	14.00%	$4,172	$3,783	$389
Avalon Hybrid	$36,001	$31,154	$4,847	13.46%			
Camry	$21,974	$17,501	$4,473	20.36%	$5,798	$5,076	$722
Camry Hybrid	$27,772	$22,577	$5,195	18.70%			
Corolla	$17,210	$13,014	$4,196	24.38%	$6,792	$6,013	$779
Prius	$24,002	$19,027	$4,975	20.72%			
Lexus ES 350	$37,127	$32,248	$4,879	13.14%	$6,608	$6,311	$297
Lexus ES 300h	$43,735	$38,559	$5,176	11.83%			
Highlander	$29,503	$24,705	$4,798	16.26%	$8,319	$7,424	$895
Highlander Hybrid	$37,822	$32,129	$5,693	15.05%			
Lexus RX 350	$41,251	$35,288	$5,963	14.45%	$4,909	$4,181	$728
Lexus RX 400h	$46,160	$39,469	$6,691	14.49%			

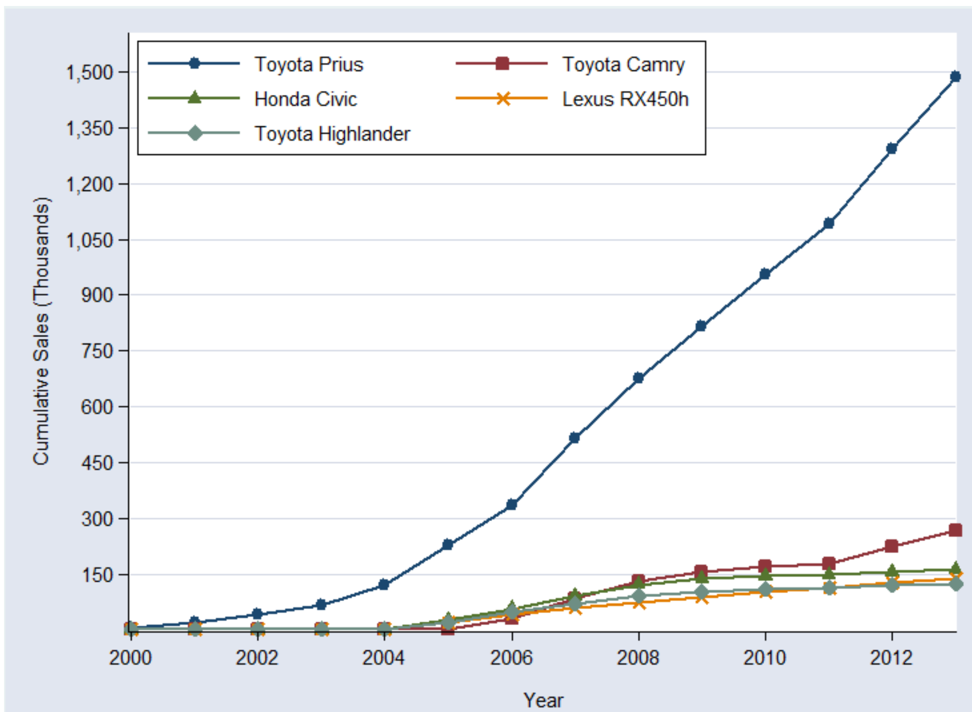

Figure 2.1: Cumulative Sales of Top 5 Best-Selling HEV Models

Table 2.21: Markup Comparison: Prius vs. Other LDVs (2013)

Manufacturer	Model	Segmentation	Price	Marginal Cost	Markup	Markup (%)	Hybrid
DODGE	Avenger	Lower Middle	$21,374	$17,577	$3,797	17.77%	NO
VOLKSWAGEN	Passat	Lower Middle	$21,424	$17,699	$3,725	17.39%	NO
HYUNDAI	Tucson	Small Cross Utility	$22,102	$18,332	$3,770	17.06%	NO
RAM	Ram Tradesman	Small Van	$22,131	$18,738	$3,394	15.33%	NO
NISSAN	Altima	Lower Middle	$22,592	$18,777	$3,815	16.88%	NO
TOYOTA	**Prius**	**Upper Middle**	**$23,785**	**$19,510**	**$4,275**	**17.97%**	**YES**
CHEVROLET	Camaro	Middle Specialty	$24,305	$20,329	$3,976	16.36%	NO
BUICK	Verano	Lower Middle	$24,379	$20,258	$4,121	16.90%	NO
BUICK	Encore	Small Cross Utility	$24,834	$20,624	$4,210	16.95%	NO
HONDA	Civic Hybrid	Upper Small	$25,171	$20,907	$4,264	16.94%	YES
FORD	C-Max Hybrid	Upper Middle	$25,735	$21,604	$4,131	16.05%	YES
CHEVROLET	Malibu Hybrid	Upper Middle	$25,834	$21,719	$4,115	15.93%	YES

Toyota's HEV models, I pair 6 models with their gasoline counterparts except for CT 200h and HS 250h.[8] All Toyota HEV models have higher markups than their gasoline pairs, and markup differences vary by model. However, percentage markups for HEVs are similar or slightly smaller than gasoline counterparts. For example, markup and percentage markup differences of Lexus RX series pairs are $728 and 0.05%.

Finally, I compare average markup and percentage markup of Toyota Prius with competing vehicle models in terms of price and segmentation. As shown in table 2.4, the Toyota Prius is the top-selling HEV model in the U.S. market in that the Prius alone accounts for 40% of total HEV market share in 2013 and it has been sold 1,485,076 units by the end of 2013 since its debut in 2000 (Figure 2.1). The comparison results are presented in Table 2.21. The Prius enjoys larger markups and percentage markups than other gasoline vehicles that belong to middle class. In addition, the Prius turns out to have greater markup than other middle class HEV models. For example, the Prius markup ($4,275) is greater than the Ford C-Max Hybrid ($4,131) and Chevrolet Malibu hybrid ($4,115) although the price of Prius is lower than these two HEV models.

2.6 Conclusion

This study explores the evidence of quality-based price discrimination in the automobile industry that arises from the fuel savings benefit of HEV technology. Using a structural estimation of differentiated product model of new vehicle demand and supply, I estimate marginal costs, markups and percentage markups for all vehicle models, and analyze the extent of quality-based price discrimination by comparing markup and percentage markup differences between HEVs and conventional gasoline vehicles.

[8]There is no exact comparable gasoline counterpart for Toyota's Prius. Instead, I can pair Prius with Corolla in terms of attributes and amenities by following suggestion from the Fuel Economy Guide.

The results show that HEVs, on average, have larger markups than gasoline vehicles, but have similar or smaller percentage markups than gasoline vehicles. Further analysis on the relationship between market power and markups reveal that firms with higher market power are associated with higher markups and percentage markups. Average markups and percentage markups of HEVs produced by major automobile manufacturers (Toyota, Honda, Ford, GM and Nissan) are higher than those of new HEV market entrants (Hyundai, KIA and Volkswagen). I also find that the Toyota Prius, the top-selling HEV model in the U.S. particularly enjoys larger markups and percentage markups than its competitors.

While this study employs the structural model of demand and supply to overcome drawbacks of a simple discrete choice model of demand, the results I present here still have room for discussion and improvement. Estimated marginal costs, markups are computed using parameter estimates from the demand side model. The simultaneous estimation of parameters from both demand and cost side models would allow us to have more precise and realistic parameter estimates for the analysis (BLP 1995; Sudhir 2001). In addition, marginal utility of income, α_i, is interacted with only the observed household income variable. Interacting with additional demographic variables such as education level, family size and age would help to understand how consumer heterogeneity in vehicle choice varies with demographics, though it requires increased parameter estimation space. The estimation results are derived from market-level data. As Petrin (2002) and BLP (2004) show, combining market-level data with supplemental consumer-level data would improve the identification of the parameter estimates by adding extra moment conditions in the objective function. Finally, this study does not take into account dynamics in market environment that have significant impacts on HEV premiums. On the demand side, consumers' willingness-to-pay for HEVs varies over time as the number of innovators or environmentally friendly consumers changes. Production costs are also characterized dynamically rather than statically and those costs evolves over time via scale and learning effects. These issues are left for future studies.

Chapter 3

Adoption of an Environmentally Friendly Product with Heterogeneous Environmental Concerns

3.1 Introduction

It is a well-known fact that firms offer different qualities of the same or similar products to appeal to consumers with different preferences. This practice is known as product differentiation. One reason for product differentiation is the phenomenon of heterogeneous preferences among consumers (Belleflamme and Peitz 2010). The concepts of product differentiation and heterogeneous preferences are relevant to automobile manufacturers who produce both conventional gasoline vehicles and environmentally friendly fuel-efficient hybrid electric vehicles (HEVs) for consumers with heterogeneous preferences for environmentally-friendly technologies. Although HEVs provide higher fuel economy than conventional gasoline vehicles, the empirical literature on HEVs has shown that fuel economy is generally not consumers' sole reason for purchasing them (Heffner et al. 2007; Kahn 2007; Klein 2007; Sexton 2011). For consumers with environmental concerns (so-called green consumers), the fact that the HEVs emit fewer pollutants than conventional gasoline vehicles may be what motivates their purchase of an HEV, and such consumers may be willing to pay more for HEVs because of their quality of environmental friendliness. In this paper, we provide a model of the automobile market where consumers choose between gasoline vehicles and hybrid vehicles and consumers have heterogeneous preferences, caring about both the environment and the physical quality of the product–specifically its fuel economy.

Our model examines three consumer groups according to their environmental concerns: 1) gasoline vehicle consumers, 2) HEV consumers, and 3) consumers who decide not to buy any vehicles because of their concern for environmental protection. Many of our findings are to be expected. Demand for each vehicle type is negatively associated not only with increases in the price of the vehicles but also with increases in consumers' concerns about environmental damage (specifically emissions); demand for both vehicle-types increases when vehicles are equipped with better fuel economy technology; and, conversely, demand for both vehicle-types falls as consumers become more pro-environmental. In addition to these expected findings, we also make one interesting finding with respect to environmental protection policies. By taking into account the heterogeneity of consumer preferences, we show that a tax on gasoline vehicles will always generate a decrease in total emissions, while a subsidy for the adoption of environmentally friendly HEVs may not.

This paper is structured as follows: Section 3.2 reviews literature on product differentiation. Section 3.3 describes the model, Sections 3.4 and 3.5 discuss market outcomes under two different assumptions-first, a perfectly competitive automobile market and second, a hybrid vehicle monopoly market, and Section 3.6 presents conclusions based on the model.

3.2 Literature Review

The pioneer study of the literature on quality-based product differentiation by a monopolist is Mussa and Rosen (1978). The study shows that imperfect quality discrimination by a monopolist results in optimal level of quality of products for high willingness to pay consumers but degrading quality of products for low willingness to pay consumers.[1] This quality distortion makes the monopolist to have higher profits by segmenting markets, and preventing higher willingness to pay consumers from switching to low quality products that give lower profits. The primary reason for quality distortion is threatening high willingness to pay consumers, not hurting low willingness to pay consumers. Contrary to the results from Mussa and Rosen (1978), Donnenfeld and White (1988) and Srinagesh and Bradburd (1989) demonstrate that quality distortion by a monopolist can actually lead to a form of quality improvement rather than quality degradation. The key difference between these studies from the model of Mussa and Rosen (1978) is the assumption of relationship between consumers' total and marginal valuations of product quality. Muss and Rosen (1978) assume the positive association between total and marginal valuation of the quality, which results in quality degradation of low quality products. However, when a negative relationship is assumed, quality distortion occurs as the form of quality enhancement for high quality products.

A sizable literature has extended the model of Mussa and Rosen (1978) to the duopoly or oligopoly competition. While there are mixed results among studies, the literature concludes that only a limited number of firms with positive market shares can survive at equilibrium as a result of price competition. Gabszewicz and Thisse (1979, 1980) first study the price competition in a vertically differentiated market. Gabszewicz and Thisse (1979) present a model of price competition in a differentiated duopoly. The non-cooperative market outcomes show that some

[1] Other studies that have similar conclusions include Maskin and Riley (1984), Cooper (1984), Phlips (1983), Itoh (1983) and Gabszewicz et al. (1986).

consumers do not buy anything or all consumers buy either of the two products. The likelihood of realization of each market outcome depends on the degree of product differentiation and income distribution. Gabszewicz and Thisse (1980) extend duopoly to oligopolistic competition. They find that a fixed number of firms can have positive market shares. Entry of a new firm into the market inevitably entails the exit of an existing firm, and this process forces the equilibrium prices to decrease to the competitive level. Shaked and Sutton (1982, 1983) discuss price competition under vertical differentiation. Shaked and Sutton (1982) present a game theoretical model that analyzes monopolistic competition in differentiated products market. The Perfect Nash Equilibrium is one in which only two firms enter the market and provide differentiated products with distinctive qualities, and make positive profits at equilibrium. Shaked and Sutton (1983) show that there exists an upper bound independent of product qualities, to the number of firms with positive market shares at a Nash Equilibrium in prices in the market with vertical differentiation. Low fixed costs, independent of optimal quality choice by a firm and price competition guarantee a limited number of firms at equilibrium.

While most of the theoretical literature on product differentiation in oligopoly assumes that each firm provides a single quality, there are studies that demonstrate the idea that duopolists offer multiple qualities rather than a single quality. Champsaur and Rochet (1989) develops a model where two firms compete with each other by offering a range of product qualities. They assume that given quality level is purchased by different type of consumers, and find the existence of unique price equilibria where firms' quality range is an interval. They also show that the Chamberlinian incentive for product differentiation dominates for intermediate qualities so that there is always a subset of intermediate qualities that are not offered to consumers. Cheng et al. (2011) find that each duopolist produces single quality for any concave cost function of quality improvement. However, when strictly convex cost function is assumed and the market coverage is endogenously determined by firms, each firm offers a disconnected continuum of multiple qualities. They also show that consumer surplus and social welfare are greater under multi-qualities than single-quality duopoly.

Products are differentiated not only by qualities but also by brand names. Katz (1984) assumes positive correlation between brand sensitivity and quality sensitivity across consumers, which implies consumers become more brand sensitive as one moves up the quality level. He argues that a firm with good reputation or strong brand image sells products only to the brand-sensitive consumers in order to maximize the profits at the upper end of the quality spectrum, whereas a firm with a low value of reputation would serve brand-insensitive consumers. Gilbert and Matutes (1993) show that the range of product lines depends on the degree of band-specific differentiation if differentiated products offered by rival firms are being treated as close substitutes by consumers. With a credible commitment on the restriction of product offerings, firms would specialize in products if brand-specific differentiation is small, but firms offer full product lines as brand-specific differentiation gets larger.

There is a branch of literature that analyzes the provisions of environmental quality when consumers have different awareness of environmental concern. Mahenc and Podesta (2012) examine the provision of environmental quality by a monopolist when environmental quality is a non-excludable vertical characteristic of monopolized good. They find similar results from Mussa and Rosen (1978) that the monopolist offers goods only to the high-demand consumers with efficient level of environmental quality when the group of high-demand consumers are large, and the monopolist provides the inefficiently low level of environmental quality when the group of low-demand consumers are large. Conard (2005) develops a duopoly model of vertical product differentiation incorporating the environmental awareness of the consumers. Nash-equilibria of prices, market shares and profits are affected by both consumer awareness about the environment and the higher production costs. Cremer and Thisse (1999) and Bansal and Gangopadhyay (2003) study the effects of environmental and tax-subsidy policies on the allocation of environmental quality in an imperfectly competitive market in the presence of environmentally aware consumers. A commodity tax and a discriminatory subsidy can results in welfare enhancing.

3.3 Model

3.3.1 The Utility

This model posits a consumer who considers purchasing either a conventional gasoline vehicle or an environmentally friendly hybrid vehicle. Each preference is represented thus:

$$u_i = \begin{cases} v_g - p_g - t\gamma d_g & \text{if buys a gasoline vehicle of quality } v_g \text{ at price } p_g, \\ v_h - p_h - t\gamma d_h & \text{if buys a hybrid vehicle of quality } v_h \text{ at price } p_h, \\ 0 & \text{if buys nothing.} \end{cases}$$

where u_i is the consumer i's indirect utility function. The two vehicle types are indexed by $j = \{g, h\}$ where g and h respectively refer to the gasoline vehicle and the hybrid vehicle. The variable v_j denotes the quality of each vehicle type measured in fuel economy. Since a hybrid vehicle has better fuel economy than a gasoline vehicle, we take $v_g < v_h$. γ to be the environmental concern parameter, which is distributed across consumers according to the cumulative distribution function, $F(\gamma)$. Consumers with higher γ attach more value to (i.e. care more about) environmental protection, so the higher the value of γ, the more pro-environmental the consumer is. The scalar variable t measures consumers' preference regarding the environment. As t increases, the distribution of environmental concerns increases to some extent. We assume that when consumers buy a vehicle, they perceive a disutility of environmental damage, d_j (emissions from a vehicle).[2] The environmental damage, d_j, is a decreasing function

[2]Air pollution from vehicles is negative externality, which imposes higher social costs. The utility function of a consumer i with negative externality can be written as $u_i = v_j - p_j - t\gamma d_j - \beta E$ where E is the total environmental damage from the vehicles. We can drop E from the model since an individual cannot control E, and it will not affect our main results significantly. Even though each individual's impact on the total emissions is small, our model assumes that each individual still

of vehicle quality and is greater for gasoline vehicles than for hybrid vehicles, $d_g > d_h$. Furthermore, we also assume that the unit cost of producing each vehicle type, $C(v_j)$ increases with quality, v_j, and that $C(v_g) = c_g$ and $C(v_h) = c_h$.

Assumption 3.1. *Let* $(v_j - c_j)$ *be the gross surplus from buying each type of vehicle, where* $j = \{g, h\}$*. The following condition then holds:*

$$(v_g - c_g) > (v_h - c_h) \text{ or } (v_h - v_g) < (c_h - c_g)$$

Assumption 3.1 implies that the additional cost of producing hybrid vehicles is greater than the fuel cost savings.

The following constraints must be satisfied for all consumers. First, in order for a consumer to be willing to buy a gasoline vehicle, the net surplus of buying a gasoline vehicle must be positive. This is the individual rationality constraint, or IR:

$$v_g - p_g - t\gamma_g^{IR} d_g > 0 \tag{3.1}$$

Rearranging Equation (3.1) yields

$$\gamma < \frac{v_g - p_g}{td_g} \equiv \gamma_g^{IR} \tag{3.2}$$

and $v_g - p_g > 0$. Therefore, consumers with an environmental concern parameter of less than γ_g^{IR} will buy a gasoline vehicle. The second constraint requires that the consumer of a gasoline vehicle will prefer to buy a gasoline vehicle but not a hybrid vehicle. This is the incentive compatibility constraint, or IC:

$$v_g - p_g - t\gamma^{IC} d_g > v_h - p_h - t\gamma^{IC} d_h \tag{3.3}$$

$$\gamma^{IC} t(d_g - d_h) < v_g - v_h - p_g + p_h \tag{3.4}$$

cares about the damage that they impose on the environment, which is captured by γ. γ can be interpreted as a negative felling of guilty or regret about the damage that the individual imposes on the environment by driving a car. In addition, the magnitude of γ may be bigger than β because it includes not only from the environmental effects but also social and psychological effects on the individual.

$$\gamma < \frac{(v_g - p_g) - (v_h - p_h)}{t(d_g - d_h)} \equiv \gamma^{IC} \tag{3.5}$$

The IR and IC constraints for the hybrid vehicle consumers can be written thus:

$$\gamma < \frac{v_h - p_h}{td_g} \equiv \gamma_h^{IR} \tag{3.6}$$

$$\gamma > \frac{(v_g - p_g) - (v_h - p_h)}{t(d_g - d_h)} \equiv \gamma^{IC} \tag{3.7}$$

3.4 A Perfectly Competitive Automobile Market

In this model, we initially suppose that both gasoline vehicles and hybrid vehicle are sold in a perfectly competitive automobile market so that the price for a vehicle is equal to its marginal cost, $p_g = c_g$ and $p_h = c_h$, which yields zero profit from selling any vehicle.

3.4.1 Demands

Under the assumption of a perfectly competitive automobile market, the IR and IC constraints for consumers of gasoline vehicles can be written thus:

$$\gamma < \frac{v_g - c_g}{td_g} \equiv \gamma_g^{IR} \tag{3.8}$$

$$\gamma < \frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)} \equiv \gamma^{IC} \tag{3.9}$$

Similarly, the IR and IC constraints for consumers of hybrid vehicles are

$$\gamma < \frac{v_h - c_h}{td_g} \equiv \gamma_h^{IR} \tag{3.10}$$

$$\gamma > \frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)} \equiv \gamma^{IC} \tag{3.11}$$

Lemma 3.1. *In a perfectly competitive automobile market assumption, we have*

$$\gamma^{IC} < \gamma_g^{IR} < \gamma_h^{IR} \tag{3.12}$$

as shown in Figure 3.1, implying that all consumers with $\gamma < \gamma^{IC}$ will drive gasoline vehicles, that consumers with $\gamma^{IC} < \gamma < \gamma_h^{IR}$ will be willing to drive hybrid vehicles and that consumers with $\gamma > \gamma_h^{IR}$ will walk rather than driving a car.

Proof. See Appendix A.1.

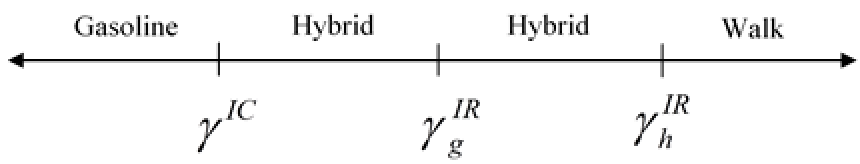

Figure 3.1: Vehicle Choices among Consumers with respect to Distribution of γ.

The demand for the gasoline vehicles, $D_g(v, c, t, d)$ and the demand for hybrid vehicles, $D_h(v, c, t, d)$ can now be derived under the assumption of a perfectly competitive automobile market:

$$D_g(v, c, t, d) = F(\gamma^{IC}) \tag{3.13}$$

$$D_h(v, c, t, d) = \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] \tag{3.14}$$

where $\gamma^{IC} \equiv \frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}$, $\gamma_h^{IR} \equiv \frac{v_h - c_h}{t d_h}$ and $F(\gamma)$ is CDF of γ.

3.4.2 Comparative Statics Analysis

Table 3.1 summarizes the comparative statics analysis of the demand for gasoline vehicles and the demand for hybrid vehicles. The full comparative statics analysis is provided in the Appendix A.2.

Table 3.1: Comparative Statics Analysis of a Perfectly Competitive Automobile Market

	dd_g	dd_h	dc_g	dc_h	dv_g	dv_h	dt
$dD_g(d,c,v,t)$	$-$	$+$	$-$	$+$	$+$	$-$	$-$
$dD_h(d,c,v,t)$	$+$	$-$	$+$	$-$	$-$	$+$	$-$

Proposition 3.1.

(i) *The demand for gasoline vehicles increases in response to an increase in d_h, c_h, v_g, and the demand for gasoline vehicles decreases in response to an increase in d_g, c_g, v_h.*

(ii) *The demand for hybrid vehicles increases in response to an increase in d_g, c_g, v_h, and the demand for gasoline vehicles decreases in response to an increase in d_h, c_h, v_g.*

(iii) *Other things being equal, an increase in t decreases the both demand for gasoline vehicles and the demand for hybrid vehicles.*

Increases in d_j and c_j make each vehicle type less attractive ($j = \{g, h\}$). Consumers who are indifferent between buying a gasoline vehicle and buying a hybrid vehicle will switch to the other vehicle types. In the case of hybrid vehicles, consumers who are indifferent between buying a hybrid vehicle and walking (buying no vehicle) will decide against buying a vehicle as c_h rises, which will generate a further decrease in the demand for hybrid vehicles. The demand for each vehicle type, $D_j(d, c, v, t)$, increases as vehicles are equipped with better fuel economy technology, v_j. As consumers become more pro-environmental, t, consumers of gasoline vehicles with higher γ will decide to buy hybrid vehicles, thereby decreasing the demand for gasoline vehicles and increasing the demand for hybrid vehicles. At the same time, however, consumers of hybrid vehicles who have higher environmental concerns will decide not to buy any kind of vehicle as their environmental concerns grow, thereby decreasing the demand for hybrid vehicles. The net effect of increases in t on the demand for hybrid vehicles is negative by Lemma 3.1. See Appendix A.2 for details.

3.4.3 Policy Implications

This section examines two important policy implications: 1) the effects of the model parameters on the total environmental damage, and 2) the effect of a government subsidy of hybrid vehicles on the total environmental damage.

3.4.3.1 Environmental Damage

Aggregate environmental damage, E, is defined as the sum of vehicle emissions from gasoline vehicles and hybrid vehicles:

$$E = \int_{0}^{\gamma^{IC}} [f(\gamma) \cdot d_g] d\gamma + \int_{\gamma^{IC}}^{\gamma_h^{IR}} [f(\gamma) \cdot d_h] d\gamma \tag{3.15}$$

where d_g and d_h respectively represent emissions from gasoline vehicles and hybrid vehicles, and $\gamma^{IC} \equiv \frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}$, $\gamma_h^{IR} \equiv \frac{v_h - c_h}{t d_h}$ and $f(\gamma)$ is the probability density function of γ.

Table 3.2 provides the comparative statics analysis of total environmental damages, considering various functional forms of γ. Computational details of the comparative statics analysis are provided in the Appendix A.4.1.

Proposition 3.2.

(i) *Other things being equal, an increase in c_g decreases total emissions, as does an increase in t, while an increase in v_g increases total emissions.*

(ii) *If $f(\gamma_h^{IR}) > f(\gamma^{IC})$, then total emissions decrease in response to an increase in d_g, d_h and c_h, and total emissions increase in response to v_h and s_h.*

(iii) *If $f(\gamma_h^{IR}) < f(\gamma^{IC})$, then total emissions decrease in response to an increase in v_h and s_h, and total emissions increase in response to d_g, d_h and c_h.*

Table 3.2: Comparative Statics Analysis of the Total Environmental Damage in a Perfectly Competitive Automobile Market

		dd_g	dd_h	dc_g	dc_h	dv_g	dv_h	dt	$d\tau_g$	ds_h
General Case	dE	$\lesseqgtr$	$\lesseqgtr$	$-$	$\lesseqgtr$	$+$	$\lesseqgtr$	$-$	$-$	$\lesseqgtr$
Uniform Distribution $F(\gamma) = \gamma$	dE	0	0	$-$	0	$+$	0	$-$	$-$	0
Generalized Uniform Distribution (1) $F(\gamma) = \gamma^2$, $f(\gamma_h^{IR}) > f(\gamma^{IC})$	dE	$-$	$-$	$-$	$-$	$+$	$+$	$-$	$-$	$+$
Generalized Uniform Distribution (2) $F(\gamma) = \gamma^{1/2}$, $f(\gamma_h^{IR}) < f(\gamma^{IC})$	dE	$+$	$+$	$-$	$+$	$+$	$-$	$-$	$-$	$-$

When c_g and t increase, consumers will switch to hybrid vehicles, and total emissions will decrease. However, if gasoline vehicles are equipped with better fuel economy, v_g, consumers will decide to buy gasoline vehicles, with a resulting increase in total emissions.

d_g, d_h, c_h, v_h and s_h have two opposing effects on the total emissions, so that the net effect on total emissions is generally ambiguous and depends on the probability density function of γ, $f(\gamma)$. As d_g increases, consumers who are driving gasoline vehicles now do more damage to the environment. However, consumers who are indifferent between gasoline vehicles and hybrid vehicles will switch to hybrid vehicles, which will cause total emission to fall. Likewise, as d_h rises, drivers of hybrid vehicles will cause more environmental damage and consumers who are indifferent between gasoline vehicles and hybrid vehicles will switch to gasoline vehicles, thereby further increasing the total emissions. However, consumers who are indifferent between buying hybrid vehicles or walking will decide not to buy any vehicle at all, in order to protect the environment, thereby decreasing the total emissions. Changes in c_h and v_h also have mixed effects. As c_h increases, consumers who are indifferent between gasoline vehicles and hybrid vehicles will decide to buy gasoline vehicles, increasing the total emissions. However, consumers who are indifferent between buying hybrid vehicles and walking will decide to walk, so that and the total emissions decrease. As v_h increases, consumers who are indifferent between gasoline vehicles and hybrid vehicles will switch to hybrid vehicles, which will cause the total emissions to fall. At the same time, however, consumers who are indifferent between buying hybrid vehicles and walking will decide to buy hybrid vehicles as hybrid vehicles become more environmentally friendly, which will result in an increases in total emissions.

In light of Proposition 3.2, it follow immediately that $\frac{\partial E}{\partial \tau_g} = \frac{\partial E}{\partial c_g}$ and $\frac{\partial E}{\partial s_h} = -\frac{\partial E}{\partial c_h}$ where τ_g is a tax on gasoline vehicles, and s_h is a subsidy (e.g. a tax incentive or rebate) for consumers of hybrid vehicle.

Corollary 3.1 (to Proposition 3.2)**.** *A tax on gasoline vehicles will reduce total emissions, and a subsidy for HEVs has an ambiguous effect on total emissions.*

A subsidy will encourage gasoline vehicle consumers to switch to hybrid vehicles, which will cause total emissions to fall. At the same time, however, when offered a subsidy, consumers who have previously used to walk will decide to buy hybrid vehicles, which will increase the emissions from hybrid vehicles. The net effect depends on the probability density function of γ, $f(\gamma)$.

3.5 The Hybrid Vehicle Monopolist

The Hybrid Vehicle Monopolist Model relaxes the assumption of a perfectly competitive automobile market, assuming instead that an automobile manufacturer has a market power in the hybrid vehicle market and can charge a price for the hybrid vehicle above the marginal cost.

3.5.1 Demands

For any p_h such that $v_h \geq p_h \geq c_h$, we can write:

$$\gamma_h^{IR} \equiv \frac{v_h - p_h}{td_h} \tag{3.16}$$

$$\gamma^{IC} \equiv \frac{(v_g - c_g) - (v_h - p_h)}{t(d_g - d_h)} \tag{3.17}$$

$$\gamma^{IC} < \gamma_g^{IR} < \gamma_h^{IR} \tag{3.18}$$

The demand for the gasoline vehicle, $D_g(v, c, p, t, d)$, and the demand for the hybrid vehicle, $D_h(v, c, p, t, d)$, are

$$D_g(v, c, p, t, d) = F(\gamma^{IC}) \tag{13}$$

$$D_h(v, c, p, t, d) = \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] \tag{14}$$

where $\gamma^{IC} \equiv \frac{(v_g - c_g) - (v_h - p_h)}{t(d_g - d_h)}$ and $\gamma_h^{IR} \equiv \frac{v_h - p_h}{td_h}$.

3.5.2 Profit Maximization Problem for The Hybrid Vehicle Monopolist

The monopolist can find the profit maximizing price for the hybrid vehicle by solving the following profit function:

$$\begin{aligned} \max_{p_h} \Pi &= (p_h - c_h) D_h(v, c, p, t, d) \\ &= (p_h - c_h)\left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] \end{aligned} \tag{3.19}$$

The first order condition for the profit function with respect to p_h can be written as

$$\frac{\partial \Pi}{\partial p_h} \equiv \Pi_{p_h} = \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] + (p_h^* - c_h)\left[-\frac{f(\gamma_h^{IR})}{td_h} - \frac{f(\gamma^{IC})}{t(d_g - d_h)}\right] = 0 \quad (3.20)$$

And corresponding second order condition is given by

$$\frac{\partial^2 \Pi}{\partial {p_h}^2} \equiv \Pi_{p_h p_h} = -2\left[\frac{f(\gamma_h^{IR})}{td_h} + \frac{f(\gamma^{IC})}{t(d_g - d_h)}\right] + (p_h^* - c_h)\left[\frac{f'(\gamma_h^{IR})}{t^2 {d_h}^2} - \frac{f'(\gamma^{IC})}{t^2 (d_g - d_h)^2}\right] < 0 \quad (3.21)$$

Rearranging the FOC (3.20) yields

$$p_h^* = c_h + \frac{\left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right]}{\left[\frac{f(\gamma_h^{IR})\cdot(d_g - d_h) + f(\gamma^{IC})\cdot d_h}{td_h(d_g - d_h)}\right]} \quad (3.22)$$

and

$$p_h^* = c_h + \frac{t\left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right]}{\left[\frac{f(\gamma_h^{IR})\cdot(d_g - d_h) + f(\gamma^{IC})\cdot d_h}{d_h(d_g - d_h)}\right]} \quad (3.23)$$

where the monopoly price for the hybrid vehicle, p_h^*, is the sum of marginal cost (c_h) and the markup, the second term of the right-hand side of Equation (3.23). Other things being equal, the monopolist can increase p_h^* as consumers become more pro-environmental (t), and as the demand for hybrid vehicles $\left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right]$ increases.

However, Equation (3.23) does not provide a reduced form solution for p_h^*. Instead, we solve for p_h^* in Equation (3.24) assuming γ is uniformly distributed on [0,1]. See Appendix A.3 for details.

$$p_h^* = \frac{(v_h + c_h)}{2} - \frac{d_h(v_g - c_g)}{2d_g} \quad (3.24)$$

And corresponding $F(\gamma_h^{IR}*)$ and $F(\gamma^{IC}*)$ are respectively given by

$$F(\gamma_h^{IR}*) = \frac{d_h(v_g - c_g) + d_g(v_h - c_h)}{2td_g d_h} \quad (3.25)$$

$$F(\gamma^{IC}*) = \frac{(2d_g - d_h)(v_g - c_g) - d_g(v_h - c_h)}{2td_g(d_g - d_h)} \tag{3.26}$$

Finally, the demands for both gasoline vehicles and hybrid vehicles are provided respectively by

$$D_g^*(v, c, t, d) = F(\gamma^{IC}*) = \frac{(2d_g - d_h)(v_g - c_g) - d_g(v_h - c_h)}{2td_g(d_g - d_h)} \tag{3.27}$$

$$D_h^*(v, c, t, d) = \left[F(\gamma_h^{IR}*) - F(\gamma^{IC}*)\right] = \frac{d_g(v_h - c_h) - d_h(v_g - c_g)}{2td_h(d_g - d_h)} \tag{3.28}$$

For a numerical example, let $d_g = 3$, $d_h = 1$, $v_g = 5$, $c_g = 2$, $v_h = 6$, $c_h = 4$ and $t = 1$. Then, $F(\gamma^{IC}*) = 0.75$, $F(\gamma_h^{IR}*) = 1.5$, $p_h^* = 4.5$, $D_g^*(v, c, t, d) = 0.75$ and $D_h^*(v, c, t, d) = 0.75$.

3.5.3 Comparative Statics Analysis

Table 3.3 presents the comparative statics analysis of the Monopoly Hybrid Vehicle Price, p_h^*, in order to examine the effects of the model parameters on the monopoly price. The computational details of the comparative statics analysis are presented in the Appendix A.3.

Table 3.3: Comparative Statics Analysis of the Monopoly Hybrid Vehicle Price

	dd_g	dd_h	dc_g	dc_h	dv_g	dv_h
$dp_h(d, c, v)$	+	−	+	+	−	+

Proposition 3.3.

The monopoly hybrid vehicle price increases in response to an increase in d_g, c_g, c_h, v_h and the monopoly hybrid vehicle price decreases in response to an increase in d_h and v_g.

3.5.4 Policy Implications

We now turn our attention to the effects of the model parameters and the efficacy of a government subsidy of hybrid vehicles as a means of reducing total environmental damage.

3.5.4.1 Environmental Damage

Table 3.4 provides the comparative statics analysis of the total environmental damages for the Hybrid Vehicle Monopolist Model. The signs of comparative statics analysis are the same as in the model that assumes a perfectly competitive automobile market, but the magnitudes of the effects are different. Computational details of the comparative statics analysis are provided in the Appendix A.4.2.

Table 3.4: Comparative Statics Analysis of Total Environmental Damage in the Hybrid Vehicle Monopolist Model

		dd_g	dd_h	dc_g	dc_h	dv_g	dv_h	dt	$d\tau_g$	ds_h
General Case	dE	$\lesseqgtr$	$\lesseqgtr$	$-$	$\lesseqgtr$	$+$	$\lesseqgtr$	$-$	$-$	$\lesseqgtr$
Uniform Distribution $F(\gamma)=\gamma$	dE	0	0	$-$	0	$+$	0	$-$	$-$	0
Generalized Uniform Distribution (1) $F(\gamma)=\gamma^2$, $f(\gamma_h^{IR}) > f(\gamma^{IC})$	dE	$-$	$-$	$-$	$-$	$+$	$+$	$-$	$-$	$+$
Generalized Uniform Distribution (2) $F(\gamma)=\gamma^{1/2}$, $f(\gamma_h^{IR}) < f(\gamma^{IC})$	dE	$+$	$+$	$-$	$+$	$+$	$-$	$-$	$-$	$-$

3.6 Conclusion

The model developed in this study assumes that consumers are heterogeneous with respect to their preferences toward environmental concerns and also care about the physical quality of the product. It considers three consumer groups according to their environmental concerns. By applying this model to the automobile market, we show that heterogeneous environmental concerns have similar effects in both a perfectly competitive market and a hybrid vehicle monopoly market. Many of our results are to be expected: consumers buy fewer vehicles as environmental damages and prices of vehicles increase. More vehicles are sold when vehicles are equipped with better fuel economy technology. Consumers buy fewer vehicles as they become more concerned about the environment. In addition, we show that unintended consequences arise because of consumer heterogeneity with regard to environmental concerns. Specifically, taxing gasoline vehicles always improves environmental quality, while government supports for environmentally friendly HEV adoption do not always result in decrease in total emissions.

One underlying assumption of the model presented here is that it does not allow for implicit changes in driving patterns: consumers either buy a car or not. In future research, the model could be extended to incorporate consumers' choices about how much to drive based on the benefits and damages they experience from driving each type of a car. Another worthwhile direction for future research would be to analyze the simultaneous effects of product characteristics on the demand for each vehicle type as well as total emissions. A third direction for future research would be to use the model to find the optimal level of vehicle type for maximizing the social welfare: endogenous product choice.

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Appendix

Appendix A

Adoption of an Environmentally Friendly Product with Heterogeneous Environmental Concerns

A.1 Proof of Lemma 3.1

Since we don't know magnitudes of γ_g^{IR}, γ^{IC} and γ_h^{IR}, we need to consider following 6 cases and examine whether each case satisfies necessary conditions.
1) Case 1: $\gamma_g^{IR} < \gamma^{IC} < \gamma_h^{IR}$. In this case, the relationship should satisfies following three conditions.

1. $\gamma_g^{IR} - \gamma^{IC} \equiv \frac{-d_h(v_g-c_g)+d_g(v_h-c_h)}{td_g(d_g-d_h)} < 0$ which implies $d_g(v_h - c_h) < d_h(v_g - c_g)$
2. $\gamma^{IC} - \gamma_h^{IR} \equiv \frac{d_h(v_g-c_g)-d_g(v_h-c_h)}{td_h(d_g-d_h)} < 0$ which implies $d_h(v_g - c_g) < d_g(v_h - c_h)$
3. $\gamma_g^{IR} - \gamma_h^{IR} \equiv \frac{d_h(v_g-c_g)-d_g(v_h-c_h)}{td_g d_h} < 0$ which implies $d_h(v_g - c_g) < d_g(v_h - c_h)$

Comparing results in a contradiction since $d_g(v_h - c_h) < d_h(v_g - c_g)$ and $d_h(v_g - c_g) < d_g(v_h - c_h)$ are incompatible. Therefore, we can ignore case 1.

2) Case 2: $\gamma_g^{IR} < \gamma_h^{IR} < \gamma^{IC}$

1. $\gamma_g^{IR} - \gamma_h^{IR} \equiv \frac{d_h(v_g-c_g)-d_g(v_h-c_h)}{td_g d_h} < 0$ which implies $d_h(v_g - c_g) < d_g(v_h - c_h)$
2. $\gamma_h^{IR} - \gamma^{IC} \equiv \frac{-d_h(v_g-c_g)+d_g(v_h-c_h)}{td_h(d_g-d_h)} < 0$ which implies $d_g(v_h - c_h) < d_h(v_g - c_g)$
3. $\gamma_g^{IR} - \gamma^{IC} \equiv \frac{-d_h(v_g-c_g)+d_g(v_h-c_h)}{td_g(d_g-d_h)} < 0$ which implies $d_g(v_h - c_h) < d_h(v_g - c_g)$

Case 2 is also contradictory and we can ignore case 2 too.

3) Case 3: $\gamma^{IC} < \gamma_g^{IR} < \gamma_h^{IR}$

1. $\gamma^{IC} - \gamma_g^{IR} \equiv \frac{d_h(v_g-c_g)-d_g(v_h-c_h)}{td_g(d_g-d_h)} < 0$ which implies $d_h(v_g - c_g) < d_g(v_h - c_h)$
2. $\gamma_g^{IR} - \gamma_h^{IR} \equiv \frac{d_h(v_g-c_g)-d_g(v_h-c_h)}{td_g d_h} < 0$ which implies $d_h(v_g - c_g) < d_g(v_h - c_h)$
3. $\gamma^{IC} - \gamma_h^{IR} \equiv \frac{d_h(v_g-c_g)-d_g(v_h-c_h)}{td_h(d_g-d_h)} < 0$ which implies $d_h(v_g - c_g) < d_g(v_h - c_h)$

Case 3 satisfies all required conditions. A simple numerical example illustrates the relationship. Suppose $d_g = 3$, $d_h = 1$, $v_g = 5$, $c_g = 2$, $v_h = 6$, $c_h = 4$ and $t = 1$, then, $\gamma^{IC} = \frac{1}{2}$, $\gamma_g^{IR} = 1$ and $\gamma_h^{IR} = 2$. Figure A.1 shows the region of consumers' choice of each vehicle type according to γ.

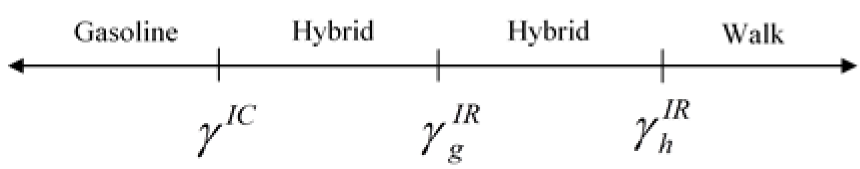

Figure A.1: Vehicle Choices among Consumers with respect to Distribution of γ (Case 3)

4) Case 4: $\gamma^{IC} < \gamma_h^{IR} < \gamma_g^{IR}$

1. $\gamma^{IC} - \gamma_h^{IR} \equiv \frac{d_h(v_g-c_g)-d_g(v_h-c_h)}{td_h(d_g-d_h)} < 0$ which implies $d_h(v_g - c_g) < d_g(v_h - c_h)$

2. $\gamma_h^{IR} - \gamma_g^{IR} \equiv \frac{-d_h(v_g-c_g)+d_g(v_h-c_h)}{td_gd_h} < 0$ which implies $d_g(v_h - c_h) < d_h(v_g - c_g)$

3. $\gamma^{IC} - \gamma_g^{IR} \equiv \frac{d_h(v_g-c_g)-d_g(v_h-c_h)}{td_g(d_g-d_h)} < 0$ which implies $d_h(v_g - c_g) < d_g(v_h - c_h)$

As a result, case 4 is also a contradiction.

5) Case 5: $\gamma_h^{IR} < \gamma_g^{IR} < \gamma^{IC}$

1. $\gamma_h^{IR} - \gamma_g^{IR} \equiv \frac{-d_h(v_g-c_g)+d_g(v_h-c_h)}{td_gd_h} < 0$ which implies $d_g(v_h - c_h) < d_h(v_g - c_g)$

2. $\gamma_g^{IR} - \gamma^{IC} \equiv \frac{-d_h(v_g-c_g)+d_g(v_h-c_h)}{td_g(d_g-d_h)} < 0$ which implies $d_g(v_h - c_h) < d_h(v_g - c_g)$

3. $\gamma_h^{IR} - \gamma^{IC} \equiv \frac{-d_h(v_g-c_g)+d_g(v_h-c_h)}{td_h(d_g-d_h)} < 0$ which implies $d_g(v_h - c_h) < d_h(v_g - c_g)$

Therefore, case 5 also satisfies necessary conditions. Let $d_g = 2$, $d_h = 1$, $v_g = 10$, $c_g = 2$, $v_h = 12$, $c_h = 10$ and $t = 1$. Then, $\gamma_h^{IR} = 2$, $\gamma_g^{IR} = 4$ and $\gamma^{IC} = 6$. As we can see in Figure A.2, no hybrid vehicles are sold in case 5), and we can remove this case too.

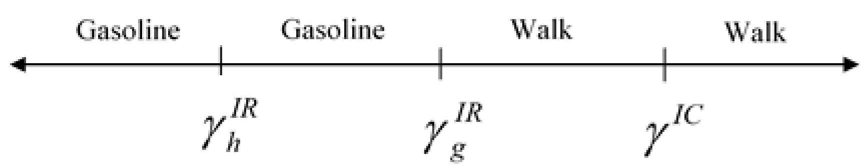

Figure A.2: Vehicle Choices among Consumers with respect to Distribution of γ (Case 5)

6) Case 6: $\gamma_h^{IR} < \gamma^{IC} < \gamma_g^{IR}$

1. $\gamma_h^{IR} - \gamma^{IC} \equiv \frac{-d_h(v_g-c_g)+d_g(v_h-c_h)}{td_h(d_g-d_h)} < 0$ which implies $d_g(v_h - c_h) < d_h(v_g - c_g)$

2. $\gamma^{IC} - \gamma_g^{IR} \equiv \frac{d_h(v_g-c_g)-d_g(v_h-c_h)}{td_g(d_g-d_h)} < 0$ which implies $d_h(v_g - c_g) < d_g(v_h - c_h)$

3. $\gamma_h^{IR} - \gamma_g^{IR} \equiv \frac{-d_h(v_g-c_g)+d_g(v_h-c_h)}{td_gd_h} < 0$ which implies $d_g(v_h - c_h) < d_h(v_g - c_g)$

Case 6 also results in a contradiction.

A.2 Comparative Statics Analysis of a Perfectly Competitive Automobile Market

Recall demand functions for the gasoline vehicle and the hybrid vehicle.

$$D_g(v, c, t, d) = F(\gamma^{IC})$$

$$D_h(v, c, t, d) = \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right]$$

$$\gamma^{IC} \equiv \frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}$$

$\gamma^{IC} \equiv \frac{(v_g-c_g)-(v_h-c_h)}{t(d_g-d_h)}$ and $\gamma_h^{IR} \equiv \frac{v_h-c_h}{td_h}$

First, we take partial derivatives of each demand with respect to d_g to get

$$\frac{\partial D_g(v, c, t, d)}{\partial d_g} = -f(\gamma^{IC}) \left[\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)^2}\right] < 0$$

$$\frac{\partial D_h(v, c, t, d)}{\partial d_g} = -f(\gamma^{IC}) \left[\frac{-\{(v_g - c_g) - (v_h - c_h)\}}{t(d_g - d_h)^2}\right] > 0$$

Partial derivatives with respect to d_h are given by

$$\frac{\partial D_g(v, c, t, d)}{\partial d_h} = -f(\gamma^{IC}) \left[\frac{(v_g - c_g) - (v_h - c_h)}{-t(d_g - d_h)^2}\right] > 0$$

$$\frac{\partial D_h(v, c, t, d)}{\partial d_h} = -f(\gamma_h^{IR}) \left(\frac{v_h - c_h}{t{d_h}^2}\right) - \left[f(\gamma^{IC}) \left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)^2}\right)\right] < 0$$

The signs of partial derivatives with respect to c_g are

$$\frac{\partial D_g(v, c, t, d)}{\partial c_g} = f(\gamma^{IC}) \left[\frac{-1}{t(d_g - d_h)}\right] < 0$$

$$\frac{\partial D_h(v,c,d)}{\partial c_g} = -f(\gamma^{IC}) \cdot \left[\frac{-1}{t(d_g - d_h)}\right] > 0$$

Similarly, the signs of partial derivatives with respect to c_h are given by

$$\frac{\partial D_g(v,c,t,d)}{\partial c_h} = f(\gamma^{IC}) \left[\frac{1}{t(d_g - d_h)}\right] > 0$$

$$\frac{\partial D_h(v,c,t,d)}{\partial c_h} = f(\gamma_h^{IR}) \left(\frac{-1}{td_h}\right) - f(\gamma^{IC}) \left[\frac{1}{t(d_g - d_h)}\right] < 0$$

We find the signs of partial derivatives with respect to v_g as

$$\frac{\partial D_g(v,c,t,d)}{\partial v_g} = f(\gamma^{IC}) \left[\frac{1}{t(d_g - d_h)}\right] > 0$$

$$\frac{\partial D_h(v,c,t,d)}{\partial v_g} = -f(\gamma^{IC}) \left[\frac{1}{t(d_g - d_h)}\right] < 0$$

Likewise, we find the signs of partial derivatives with respect to v_h as

$$\frac{\partial D_g(v,c,t,d)}{\partial v_h} = f(\gamma^{IC}) \left[\frac{-1}{t(d_g - d_h)}\right] < 0$$

$$\frac{\partial D_h(v,c,t,d)}{\partial v_h} = f(\gamma_h^{IR}) \frac{1}{td_h} - f(\gamma^{IC}) \left[\frac{-1}{t(d_g - d_h)}\right] > 0$$

Finally, taking partial derivatives with respect to t yields

$$\frac{\partial D_g(v,c,t,d)}{\partial t} = f(\gamma^{IC}) \left[\frac{(v_g - c_g) - (v_h - c_h)}{-t^2(d_g - d_h)}\right] < 0$$

$$\begin{aligned}\frac{\partial D_h(v,c,t,d)}{\partial t} &= f(\gamma_h^{IR}) \left[\frac{(v_h - c_h)}{-t^2 d_h}\right] + \left[f(\gamma^{IC}) \left(\frac{(v_g - c_g) - (v_h - c_h)}{t^2(d_g - d_h)}\right)\right] \\ &= \frac{f(\gamma^{IC})\gamma^{IC} - f(\gamma_h^{IR})\gamma_h^{IR}}{t} < 0\end{aligned}$$

and $\gamma_h^{IR} > \gamma^{IC}$ by Lemma 3.1.

For example, if we assume γ is uniformly distributed on [0,1] so that $F(\gamma) = \gamma$ and

$f(\gamma) = 1$. Then, $\frac{\partial D_h(v,c,t,d)}{\partial t} = \gamma^{IC} - \gamma_h^{IR} < 0$. Instead, if we use a generalized uniform distribution of $F(\gamma) = \gamma^2$ and $f(\gamma) = 2\gamma$. Then, $\frac{\partial D_h(v,c,t,d)}{\partial t} = -\frac{2}{t}\left((\gamma_h^{IR})^2 - (\gamma^{IC})^2\right) < 0$. Finally, if we use another generalized uniform distribution of $F(\gamma) = \gamma^{1/2}$ and $f(\gamma) = \frac{1}{2}\gamma^{-1/2}$. Then, $\frac{\partial D_h(v,c,t,d)}{\partial t} = -\frac{1}{2t}\left((\gamma_h^{IR})^{1/2} - (\gamma^{IC})^{1/2}\right) < 0$.

A.3 Comparative Statics Analysis of the Hybrid Vehicle Monopolist

For comparative statics analysis, we assume γ is uniformly distributed on [0,1] where $0 < \gamma^{IC} < \gamma_h^{IR} < 1$. Applying uniform distribution, demands can be rewritten as

$$D_g(v,c,p,t,d) = F(\gamma^{IC}) = \frac{(v_g - c_g) - (v_h - p_h)}{t(d_g - d_h)}$$

$$D_h(v,c,p,t,d) = \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] = \frac{(v_h - p_h)}{td_h} - \frac{((v_g - c_g) - (v_h - p_h))}{t(d_g - d_h)}$$

A.3.1 Profit Maximization Problem for the Hybrid Vehicle Monopolist

The monopolist needs to find the profit maximizing price for the hybrid vehicle by solving the following profit function:

$$\begin{aligned}
\max_{p_h} \Pi &= (p_h - c_h)D_h(v,c,p,t,d) \\
&= (p_h - c_h)\left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] \\
&= (p_h - c_h)\left[\frac{(v_h - p_h)}{td_h} - \frac{((v_g - c_g) - (v_h - p_h))}{t(d_g - d_h)}\right]
\end{aligned}$$

The first order condition for the profit function with respect to can be written as

$$\frac{\partial \Pi}{\partial p_h} \equiv \Pi_{p_h} = \left[\frac{(v_h - p_h)}{td_h} - \frac{((v_g - c_g) - (v_h - p_h))}{t(d_g - d_h)} \right] + (p_h^* - c_h) \left[-\frac{1}{td_h} - \frac{1}{t(d_g - d_h)} \right] = 0$$

And corresponding second order condition is given by

$$\frac{\partial^2 \Pi}{\partial {p_h}^2} \equiv \Pi_{p_h p_h} = -2 \left[\frac{1}{td_h} + \frac{1}{t(d_g - d_h)} \right] < 0$$

Rearranging the FOC to find profit maximizing monopoly price for the hybrid vehicle, p_h^*

$$\begin{aligned}
-2p_h^* \left(\frac{1}{td_h} + \frac{1}{t(d_g - d_h)} \right) &= \left[-\frac{(v_h + c_h)}{td_h} + \frac{((v_g - c_g) - (v_h + c_h)))}{t(d_g - d_h)} \right] \\
-2p_h^* \left(\frac{d_g}{td_h(d_g - d_h)} \right) &= \left[\frac{-(v_h + c_h)(d_g - d_h) + d_h((v_g - c_g) - (v_h + c_h))}{td_h(d_g - d_h)} \right] \\
-2p_h^* \left(\frac{d_g}{td_h(d_g - d_h)} \right) &= \left[\frac{-d_g (v_h + c_h) + d_h(v_g - c_g)}{td_h(d_g - d_h)} \right] \\
p_h^* &= \left[\frac{d_g (v_h + c_h) - d_h(v_g - c_g)}{2d_g} \right] \\
p_h^* &= \frac{(v_h + c_h)}{2} - \frac{d_h(v_g - c_g)}{2d_g}
\end{aligned}$$

A.3.2 Comparative Statics Analysis of the Monopoly Hybrid Vehicle Price

We take the partial derivative of p_h^* with respect to d_g to get

$$\frac{\partial p_h^*(v, c, d)}{\partial d_g} = \frac{d_h(v_g - c_g)}{2{d_g}^2} > 0$$

The partial derivative with respect to d_h is given by

$$\frac{\partial p_h^*(v,c,d)}{\partial d_h} = \frac{-(v_g - c_g)}{2d_g} < 0$$

The sign of partial derivative with respect to c_g is

$$\frac{\partial p_h^*(v,c,d)}{\partial d_h} = \frac{d_h}{2d_g} > 0$$

Similarly, the sign of partial derivative with respect to c_h is given by

$$\frac{\partial p_h^*(v,c,d)}{\partial c_h} = \frac{1}{2} > 0$$

We find the sign of partial derivative with respect to v_g as

$$\frac{\partial p_h^*(v,c,d)}{\partial v_g} = -\frac{d_h}{2d_g} < 0$$

We find the sign of partial derivative with respect to v_h as

$$\frac{\partial p_h^*(v,c,d)}{\partial v_h} = \frac{1}{2} > 0$$

A.4 Comparative Statics Analysis of the Total Environmental Damage

Three functional forms of are assumed. First, γ is uniformly distributed on [0,1] so that $F(\gamma) = \gamma$ and $f(\gamma) = 1$. Second, we use generalized uniform distribution: $F(\gamma) = \gamma^2$ and $f(\gamma) = 2\gamma$. Finally we use another generalized uniform distribution of $F(\gamma) = \gamma^{1/2}$ and $f(\gamma) = \frac{1}{2}\gamma^{-1/2}$.

A.4.1 A Perfectly Competitive Automobile Market Case

$$E = \int_{0}^{\gamma^{IC}} [f(\gamma) \cdot d_g] d\gamma + \int_{\gamma^{IC}}^{\gamma^{IRH}} [f(\gamma) \cdot d_h] d\gamma$$
$$= d_g F(\gamma^{IC}) + d_h \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right]$$

where $\gamma_h^{IR} \equiv \frac{v_h - c_h}{td_h}$ and $\gamma_h^{IR} \equiv \frac{v_h - c_h}{td_h}$

A.4.1.1 Environmental Damage from a Gasoline Vehicle: d_g

$$\frac{\partial E}{\partial d_g} = F(\gamma^{IC}) - d_g \left[f(\gamma^{IC}) \left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)^2} \right) \right]$$
$$+ d_h \left[f(\gamma^{IC}) \left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)^2} \right) \right]$$
$$= F(\gamma^{IC}) - (d_g - d_h) \left[f(\gamma^{IC}) \left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)^2} \right) \right]$$
$$= F(\gamma^{IC}) - \left[f(\gamma^{IC}) \left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)} \right) \right]$$

1) Uniform distribution: $F(\gamma) = \gamma$, $f(\gamma) = 1$ and $f(\gamma_h^{IR}) = f(\gamma^{IC}) = 1$

$$\frac{\partial E}{\partial d_g} = \gamma^{IC} - \left[\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)} \right) \right]$$
$$= \gamma^{IC} - \gamma^{IC} = 0$$

2) Generalized uniform distribution: $F(\gamma) = \gamma^2$, $f(\gamma) = 2\gamma$ and $f(\gamma_h^{IR}) > f(\gamma^{IC})$

$$\frac{\partial E}{\partial d_g} = (\gamma^{IC})^2 - 2(\gamma^{IC})^2$$
$$= -(\gamma^{IC})^2$$
$$= -\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)} \right)^2 < 0$$

3) Generalized uniform distribution: $F(\gamma) = \gamma^{1/2}$, $f(\gamma) = \frac{1}{2}\gamma^{-1/2}$ and $f(\gamma_h^{IR}) < f(\gamma^{IC})$

$$\begin{aligned}
\frac{\partial E}{\partial d_g} &= (\gamma^{IC})^{1/2} - \left[\frac{1}{2}(\gamma^{IC})^{-(1/2)}\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)\right] \\
&= (\gamma^{IC})^{1/2} - \left[\frac{1}{2}(\gamma^{IC})^{-(1/2)}(\gamma^{IC})\right] \\
&= (\gamma^{IC})^{1/2} - \left[\frac{1}{2}(\gamma^{IC})^{(1/2)}\right] \\
&= \frac{1}{2}(\gamma^{IC})^{(1/2)} = \frac{1}{2}\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)^{1/2} > 0
\end{aligned}$$

A.4.1.2 Environmental Damage from a Hybrid Vehicle: d_h

$$\begin{aligned}
\frac{\partial E}{\partial d_h} &= d_g\left[f(\gamma^{IC})\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)^2}\right)\right] + \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] \\
&\quad + d_h\left[-f(\gamma_h^{IR})\left(\frac{v_h - c_h}{t{d_h}^2}\right) - \left[f(\gamma^{IC})\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)^2}\right)\right]\right] \\
&= \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] + (d_g - d_h)\left[f(\gamma^{IC})\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)^2}\right)\right] \\
&\quad - d_h\left[f(\gamma_h^{IR})\left(\frac{v_h - c_h}{t{d_h}^2}\right)\right] \\
&= \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] + \left[f(\gamma^{IC})\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)\right] - \left[f(\gamma_h^{IR})\left(\frac{v_h - c_h}{t d_h}\right)\right]
\end{aligned}$$

1) Uniform distribution: $F(\gamma) = \gamma$, $f(\gamma) = 1$ and $f(\gamma_h^{IR}) = f(\gamma^{IC}) = 1$

$$\frac{\partial E}{\partial d_h} = \gamma_h^{IR} - \gamma^{IC} + \gamma^{IC} - \gamma_h^{IR} = 0$$

2) Generalized uniform distribution: $F(\gamma) = \gamma^2$, $f(\gamma) = 2\gamma$ and $f(\gamma_h^{IR}) > f(\gamma^{IC})$

$$\begin{aligned}\frac{\partial E}{\partial d_h} &= \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] + 2(\gamma^{IC})^2 - 2(\gamma_h^{IR})^2 \\ &= \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] + 2F(\gamma^{IC}) - 2F(\gamma_h^{IR}) \\ &= -\left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] = -\left[(\gamma_h^{IR})^2 - (\gamma^{IC})^2\right] \\ &= -\left[\left(\frac{v_h - c_h}{td_h}\right)^2 - \left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)^2\right] < 0\end{aligned}$$

3) Generalized uniform distribution: $F(\gamma) = \gamma^{1/2}$, $f(\gamma) = \frac{1}{2}\gamma^{-1/2}$ and $f(\gamma_h^{IR}) < f(\gamma^{IC})$

$$\begin{aligned}\frac{\partial E}{\partial d_h} &= (\gamma_h^{IR})^{1/2} - (\gamma^{IC})^{1/2} + \left(\frac{1}{2}(\gamma^{IC})^{-(1/2)}(\gamma^{IC})\right) - \left(\frac{1}{2}(\gamma_h^{IR})^{-(1/2)}(\gamma_h^{IR})\right) \\ &= (\gamma_h^{IR})^{1/2} - (\gamma^{IC})^{1/2} + \left(\frac{1}{2}(\gamma^{IC})^{1/2}\right) - \left(\frac{1}{2}(\gamma_h^{IR})^{1/2}\right) \\ &= \frac{1}{2}\left((\gamma_h^{IR})^{1/2} - (\gamma^{IC})^{1/2}\right) = \frac{1}{2}\left[\left(\frac{v_h - c_h}{td_h}\right)^{1/2} - \left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)^{1/2}\right] > 0\end{aligned}$$

A.4.1.3 Price of a Gasoline Vehicle: c_g

$$\begin{aligned}\frac{\partial E}{\partial c_g} &= d_g\left[f(\gamma^{IC})\left(\frac{-1}{t(d_g - d_h)}\right)\right] + d_h\left[f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right] \\ &= -(d_g - d_h)\left[f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right] \\ &= -\frac{f(\gamma^{IC})}{t} < 0\end{aligned}$$

1) Uniform distribution: $F(\gamma) = \gamma$, $f(\gamma) = 1$ and $f(\gamma_h^{IR}) = f(\gamma^{IC}) = 1$

$$\frac{\partial E}{\partial c_g} = -\frac{1}{t} < 0$$

2) Generalized uniform distribution: $F(\gamma) = \gamma^2$, $f(\gamma) = 2\gamma$ and $f(\gamma_h^{IR}) > f(\gamma^{IC})$

$$\frac{\partial E}{\partial c_g} = -\frac{2(\gamma^{IC})}{t} = -\frac{2}{t}\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right) < 0$$

3) Generalized uniform distribution: $F(\gamma) = \gamma^{1/2}$, $f(\gamma) = \frac{1}{2}\gamma^{-1/2}$ and $f(\gamma_h^{IR}) < f(\gamma^{IC})$

$$\frac{\partial E}{\partial c_g} = -\frac{(\gamma^{IC})^{-(1/2)}}{2t} = -\frac{1}{2t}\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)^{-(1/2)} < 0$$

A.4.1.4 Price of a Hybrid Vehicle: c_h

$$\begin{aligned}
\frac{\partial E}{\partial c_h} &= d_g\left[f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right] + d_h\left[f(\gamma_h^{IR})\left(\frac{-1}{td_h}\right) - f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right] \\
&= (d_g - d_h)\left[f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right] - d_h\left[f(\gamma_h^{IR})\left(\frac{1}{td_h}\right)\right] \\
&= -\left(\frac{f(\gamma_h^{IR}) - f(\gamma^{IC})}{t}\right)
\end{aligned}$$

1) Uniform distribution: $F(\gamma) = \gamma$, $f(\gamma) = 1$ and $f(\gamma_h^{IR}) = f(\gamma^{IC}) = 1$

$$\frac{\partial E}{\partial c_h} = -\left(\frac{f(\gamma_h^{IR}) - f(\gamma^{IC})}{t}\right) = 0$$

2) Generalized uniform distribution: $F(\gamma) = \gamma^2$, $f(\gamma) = 2\gamma$ and $f(\gamma_h^{IR}) > f(\gamma^{IC})$

$$\frac{\partial E}{\partial c_h} = -\frac{2}{t}\left((\gamma_h^{IR}) - (\gamma^{IC})\right) = -\frac{2}{t}\left[\left(\frac{v_h - c_h}{td_h}\right) - \left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)\right] < 0$$

3) Generalized uniform distribution: $F(\gamma) = \gamma^{1/2}$, $f(\gamma) = \frac{1}{2}\gamma^{-1/2}$ and $f(\gamma_h^{IR}) < f(\gamma^{IC})$

$$\begin{aligned}
\frac{\partial E}{\partial c_h} &= -\frac{1}{2t}\left((\gamma_h^{IR})^{-(1/2)} - (\gamma^{IC})^{-(1/2)}\right) \\
&= -\frac{1}{2t}\left[\left(\frac{v_h - c_h}{td_h}\right)^{-(1/2)} - \left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)^{-(1/2)}\right] > 0
\end{aligned}$$

A.4.1.5 Quality of a Gasoline Vehicle: v_g

$$\begin{aligned}\frac{\partial E}{\partial v_g} &= d_g\left[f(\gamma^{IC})\left(\frac{1}{t(d_g-d_h)}\right)\right] - d_h\left[f(\gamma^{IC})\left(\frac{1}{t(d_g-d_h)}\right)\right]\\ &= (d_g-d_h)\left[f(\gamma^{IC})\left(\frac{1}{t(d_g-d_h)}\right)\right]\\ &= \frac{f(\gamma^{IC})}{t} > 0\end{aligned}$$

1) Uniform distribution: $F(\gamma)=\gamma$, $f(\gamma)=1$ and $f(\gamma_h^{IR})=f(\gamma^{IC})=1$

$$\frac{\partial E}{\partial v_g} = \frac{1}{t} > 0$$

2) Generalized uniform distribution: $F(\gamma)=\gamma^2$, $f(\gamma)=2\gamma$ and $f(\gamma_h^{IR})>f(\gamma^{IC})$

$$\frac{\partial E}{\partial v_g} = \frac{2(\gamma^{IC})}{t} = \frac{2}{t}\left(\frac{(v_g-c_g)-(v_h-c_h)}{t(d_g-d_h)}\right) > 0$$

3) Generalized uniform distribution: $F(\gamma)=\gamma^{1/2}$, $f(\gamma)=\frac{1}{2}\gamma^{-1/2}$ and $f(\gamma_h^{IR}) < f(\gamma^{IC})$

$$\frac{\partial E}{\partial v_g} = \frac{(\gamma^{IC})^{-(1/2)}}{2t} = \frac{1}{2t}\left(\frac{(v_g-c_g)-(v_h-c_h)}{t(d_g-d_h)}\right)^{-(1/2)} > 0$$

A.4.1.6 Quality of a Hybrid Vehicle: v_h

$$\begin{aligned}\frac{\partial E}{\partial v_h} &= d_g\left[f(\gamma^{IC})\left(\frac{-1}{t(d_g-d_h)}\right)\right] + d_h\left[f(\gamma_h^{IR})\frac{1}{td_h} - f(\gamma^{IC})\left(\frac{-1}{t(d_g-d_h)}\right)\right]\\ &= -(d_g-d_h)\left[f(\gamma^{IC})\left(\frac{1}{t(d_g-d_h)}\right)\right] + d_h\left[f(\gamma_h^{IR})\frac{1}{td_h}\right]\\ &= \frac{-\left[f(\gamma^{IC})-f(\gamma_h^{IR})\right]}{t} = \frac{f(\gamma_h^{IR})-f(\gamma^{IC})}{t}\end{aligned}$$

1) Uniform distribution: $F(\gamma)=\gamma$, $f(\gamma)=1$ and $f(\gamma_h^{IR})=f(\gamma^{IC})=1$

$$\frac{\partial E}{\partial v_h} = \frac{f(\gamma_h^{IR})-f(\gamma^{IC})}{t} = 0$$

2) Generalized uniform distribution: $F(\gamma) = \gamma^2$, $f(\gamma) = 2\gamma$ and $f(\gamma_h^{IR}) > f(\gamma^{IC})$

$$\frac{\partial E}{\partial v_h} = \frac{2}{t}\left((\gamma_h^{IR}) - (\gamma^{IC})\right) = \frac{2}{t}\left[\left(\frac{v_h - c_h}{td_h}\right) - \left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)\right] > 0$$

3) Generalized uniform distribution: $F(\gamma) = \gamma^{1/2}$, $f(\gamma) = \frac{1}{2}\gamma^{-1/2}$ and $f(\gamma_h^{IR}) < f(\gamma^{IC})$

$$\begin{aligned}\frac{\partial E}{\partial v_h} &= \frac{1}{2t}\left((\gamma_h^{IR})^{-(1/2)} - (\gamma^{IC})^{-(1/2)}\right)\\ &= \frac{1}{2t}\left[\left(\frac{v_h - c_h}{td_h}\right)^{-(1/2)} - \left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)^{-(1/2)}\right] < 0\end{aligned}$$

A.4.1.7 Environmental Preference Scalar: t

$$\begin{aligned}\frac{\partial E}{\partial t} &= d_g\left[f(\gamma^{IC})\left(\frac{(v_g - c_g) - (v_h - c_h)}{-t^2(d_g - d_h)}\right)\right]\\ &\quad + d_h\left[f(\gamma_h^{IR})\left(\frac{(v_h - c_h)}{-t^2 d_h}\right) + \left[f(\gamma^{IC})\left(\frac{(v_g - c_g) - (v_h - c_h)}{t^2(d_g - d_h)}\right)\right]\right]\\ &= -(d_g - d_h)\left[f(\gamma^{IC})\left(\frac{(v_g - c_g) - (v_h - c_h)}{t^2(d_g - d_h)}\right)\right] - d_h\left[f(\gamma_h^{IR})\left(\frac{(v_h - c_h)}{t^2 d_h}\right)\right]\\ &= -\left[\frac{f(\gamma^{IC})\left((v_g - c_g) - (v_h - c_h)\right)}{t^2}\right] - \left[\frac{f(\gamma_h^{IR})(v_h - c_h)}{t^2}\right]\\ &= -\frac{1}{t^2}\left[f(\gamma^{IC})\left((v_g - c_g) - (v_h - c_h)\right) + f(\gamma_h^{IR})(v_h - c_h)\right]\end{aligned}$$

1) Uniform distribution: $F(\gamma) = \gamma$, $f(\gamma) = 1$ and $f(\gamma_h^{IR}) = f(\gamma^{IC}) = 1$

$$\frac{\partial E}{\partial t} = -\frac{(v_g - c_g)}{t^2} < 0$$

2) Generalized uniform distribution: $F(\gamma) = \gamma^2$, $f(\gamma) = 2\gamma$ and $f(\gamma_h^{IR}) > f(\gamma^{IC})$

$$\begin{aligned}\frac{\partial E}{\partial t} &= -\frac{1}{t^2}\left[2(\gamma^{IC})\left((v_g - c_g) - (v_h - c_h)\right) + 2(\gamma_h^{IR})(v_h - c_h)\right]\\ &= -\frac{2}{t^2}\left[\frac{\left((v_g - c_g) - (v_h - c_h)\right)^2}{t(d_g - d_h)} + \frac{(v_h - c_h)^2}{td_h}\right] < 0\end{aligned}$$

3) Generalized uniform distribution: $F(\gamma) = \gamma^{1/2}$, $f(\gamma) = \frac{1}{2}\gamma^{-1/2}$ and $f(\gamma_h^{IR}) < f(\gamma^{IC})$

$$\begin{aligned}\frac{\partial E}{\partial t} &= -\frac{1}{t^2}\left[\frac{1}{2}(\gamma^{IC})^{-(1/2)}\left((v_g - c_g) - (v_h - c_h)\right) + \frac{1}{2}(\gamma_h^{IR})^{-(1/2)}(v_h - c_h)\right] \\ &= -\frac{1}{2t^2}\left[\begin{array}{l}\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)^{-(1/2)}\left((v_g - c_g) - (v_h - c_h)\right) \\ +\left(\frac{(v_h - c_h)}{td_h}\right)^{-(1/2)}(v_h - c_h)\end{array}\right] < 0\end{aligned}$$

A.4.1.8 Government Subsidy: s_h

$$\begin{aligned}E &= \int_0^{\gamma^{IC}} [f(\gamma)\cdot d_g]d\gamma + \int_{\gamma^{IC}}^{\gamma^{IRH}} [f(\gamma)\cdot d_h]d\gamma \\ &= d_g F(\gamma^{IC}) + d_h\left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right]\end{aligned}$$

where $\gamma^{IC} \equiv \frac{(v_g - c_g) - (v_h - c_h + s_h)}{t(d_g - d_h)}$ and $\gamma_h^{IR} \equiv \frac{v_h - c_h + s_h}{td_h}$

$$\begin{aligned}\frac{\partial E}{\partial s_h} &= -d_g\left[f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right] + d_h\left[f(\gamma_h^{IR})\left(\frac{1}{td_h}\right) + f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right] \\ &= -(d_g - d_h)\left[f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right] + d_h\left[f(\gamma_h^{IR})\left(\frac{1}{td_h}\right)\right] \\ &= \left(\frac{f(\gamma_h^{IR}) - f(\gamma^{IC})}{t}\right)\end{aligned}$$

1) Uniform distribution: $F(\gamma) = \gamma$, $f(\gamma) = 1$ and $f(\gamma_h^{IR}) = f(\gamma^{IC}) = 1$

$$\frac{\partial E}{\partial s_h} = \left(\frac{f(\gamma_h^{IR}) - f(\gamma^{IC})}{t}\right) = 0$$

2) Generalized uniform distribution: $F(\gamma) = \gamma^2$, $f(\gamma) = 2\gamma$ and $f(\gamma_h^{IR}) > f(\gamma^{IC})$

$$\frac{\partial E}{\partial s_h} = \frac{2}{t}\left((\gamma_h^{IR}) - (\gamma^{IC})\right) = \frac{2}{t}\left[\left(\frac{v_h - c_h}{td_h}\right) - \left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)\right] > 0$$

3) Generalized uniform distribution: $F(\gamma) = \gamma^{1/2}$, $f(\gamma) = \frac{1}{2}\gamma^{-1/2}$ and $f(\gamma_h^{IR}) < f(\gamma^{IC})$

$$\frac{\partial E}{\partial s_h} = \frac{1}{2t}\left((\gamma_h^{IR})^{-(1/2)} - (\gamma^{IC})^{-(1/2)}\right)$$
$$= \frac{1}{2t}\left[\left(\frac{v_h - c_h}{td_h}\right)^{-(1/2)} - \left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)^{-(1/2)}\right] < 0$$

A.4.2 The Hybrid Vehicle Monopolist Case

$$E = \int_0^{\gamma^{IC}} [f(\gamma) \cdot d_g] d\gamma + \int_{\gamma^{IC}}^{\gamma^{IRH}} [f(\gamma) \cdot d_h] d\gamma$$
$$= d_g F(\gamma^{IC}) + d_h \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right]$$

where $\gamma_h^{IR} = \frac{d_h(v_g - c_g) + d_g(v_h - c_h)}{2td_g d_h}$ and $\gamma^{IC} = \frac{(2d_g - d_h)(v_g - c_g) - d_g(v_h - c_h)}{2td_g(d_g - d_h)}$

A.4.2.1 Environmental Damage from a Gasoline Vehicle: d_g

$$\frac{\partial E}{\partial d_g} = F(\gamma^{IC}) - d_g\left[f(\gamma^{IC})\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)^2}\right)\right]$$
$$+ d_h\left[f(\gamma^{IC})\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)^2}\right)\right]$$
$$= F(\gamma^{IC}) - (d_g - d_h)\left[f(\gamma^{IC})\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)^2}\right)\right]$$
$$= F(\gamma^{IC}) - \left[f(\gamma^{IC})\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)\right]$$

1) Uniform distribution: $F(\gamma) = \gamma$, $f(\gamma) = 1$ and $f(\gamma_h^{IR}) = f(\gamma^{IC}) = 1$

$$\frac{\partial E}{\partial d_g} = \gamma^{IC} - \left[\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)\right]$$
$$= \gamma^{IC} - \gamma^{IC} = 0$$

2) Generalized uniform distribution: $F(\gamma) = \gamma^2$, $f(\gamma) = 2\gamma$ and $f(\gamma_h^{IR}) > f(\gamma^{IC})$

$$\begin{aligned}\frac{\partial E}{\partial d_g} &= (\gamma^{IC})^2 - 2(\gamma^{IC})^2 \\ &= -(\gamma^{IC})^2 \\ &= -\left(\frac{(2d_g - d_h)(v_g - c_g) - d_g(v_h - c_h)}{2td_g(d_g - d_h)}\right)^2 < 0\end{aligned}$$

3) Generalized uniform distribution: $F(\gamma) = \gamma^{1/2}$, $f(\gamma) = \frac{1}{2}\gamma^{-1/2}$ and $f(\gamma_h^{IR}) < f(\gamma^{IC})$

$$\begin{aligned}\frac{\partial E}{\partial d_g} &= (\gamma^{IC})^{1/2} - \left[\frac{1}{2}(\gamma^{IC})^{-(1/2)}\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)\right] \\ &= (\gamma^{IC})^{1/2} - \left[\frac{1}{2}(\gamma^{IC})^{-(1/2)}(\gamma^{IC})\right] \\ &= (\gamma^{IC})^{1/2} - \left[\frac{1}{2}(\gamma^{IC})^{(1/2)}\right] \\ &= \frac{1}{2}(\gamma^{IC})^{(1/2)} = \frac{1}{2}\left(\frac{(2d_g - d_h)(v_g - c_g) - d_g(v_h - c_h)}{2td_g(d_g - d_h)}\right)^{1/2} > 0\end{aligned}$$

A.4.2.2 Environmental Damage from a Hybrid Vehicle: d_h

$$\begin{aligned}\frac{\partial E}{\partial d_h} &= d_g\left[f(\gamma^{IC})\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)^2}\right)\right] + \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] \\ &\quad + d_h\left[-f(\gamma_h^{IR})\left(\frac{v_h - c_h}{td_h^2}\right) - \left[f(\gamma^{IC})\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)^2}\right)\right]\right] \\ &= \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] + (d_g - d_h)\left[f(\gamma^{IC})\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)^2}\right)\right] \\ &\quad - d_h\left[f(\gamma_h^{IR})\left(\frac{v_h - c_h}{td_h^2}\right)\right] \\ &= \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] + \left[f(\gamma^{IC})\left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)\right] - \left[f(\gamma_h^{IR})\left(\frac{v_h - c_h}{td_h}\right)\right]\end{aligned}$$

1) Uniform distribution: $F(\gamma) = \gamma$, $f(\gamma) = 1$ and $f(\gamma_h^{IR}) = f(\gamma^{IC}) = 1$

$$\frac{\partial E}{\partial d_h} = \gamma_h^{IR} - \gamma^{IC} + \gamma^{IC} - \gamma_h^{IR} = 0$$

2) Generalized uniform distribution: $F(\gamma) = \gamma^2$, $f(\gamma) = 2\gamma$ and $f(\gamma_h^{IR}) > f(\gamma^{IC})$

$$\begin{aligned}
\frac{\partial E}{\partial d_h} &= \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] + 2(\gamma^{IC})^2 - 2(\gamma_h^{IR})^2 \\
&= \left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] + 2F(\gamma^{IC}) - 2F(\gamma_h^{IR}) \\
&= -\left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right] = -\left[(\gamma_h^{IR})^2 - (\gamma^{IC})^2\right] \\
&= -\left[\left(\frac{v_h - c_h}{td_h}\right)^2 - \left(\frac{(v_g - c_g) - (v_h - c_h)}{t(d_g - d_h)}\right)^2\right] < 0
\end{aligned}$$

3) Generalized uniform distribution: $F(\gamma) = \gamma^{1/2}$, $f(\gamma) = \frac{1}{2}\gamma^{-1/2}$ and $f(\gamma_h^{IR}) < f(\gamma^{IC})$

$$\begin{aligned}
\frac{\partial E}{\partial d_h} &= (\gamma_h^{IR})^{1/2} - (\gamma^{IC})^{1/2} + \left(\frac{1}{2}(\gamma^{IC})^{-(1/2)}(\gamma^{IC})\right) - \left(\frac{1}{2}(\gamma_h^{IR})^{-(1/2)}(\gamma_h^{IR})\right) \\
&= (\gamma_h^{IR})^{1/2} - (\gamma^{IC})^{1/2} + \left(\frac{1}{2}(\gamma^{IC})^{1/2}\right) - \left(\frac{1}{2}(\gamma_h^{IR})^{1/2}\right) \\
&= \frac{1}{2}\left((\gamma_h^{IR})^{1/2} - (\gamma^{IC})^{1/2}\right) \\
&= \frac{1}{2}\left[\left(\frac{d_h(v_g - c_g) + d_g(v_h - c_h)}{2td_gd_h}\right)^2 - \left(\frac{(2d_g - d_h)(v_g - c_g) - d_g(v_h - c_h)}{2td_g(d_g - d_h)}\right)^2\right] > 0
\end{aligned}$$

A.4.2.3 Price of a Gasoline Vehicle: c_g

$$\begin{aligned}
\frac{\partial E}{\partial c_g} &= d_g\left[f(\gamma^{IC})\left(\frac{-1}{t(d_g - d_h)}\right)\right] + d_h\left[f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right] \\
&= -(d_g - d_h)\left[f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right] \\
&= -\frac{f(\gamma^{IC})}{t} < 0
\end{aligned}$$

1) Uniform distribution: $F(\gamma) = \gamma$, $f(\gamma) = 1$ and $f(\gamma_h^{IR}) = f(\gamma^{IC}) = 1$

$$\frac{\partial E}{\partial c_g} = -\frac{1}{t} < 0$$

2) Generalized uniform distribution: $F(\gamma) = \gamma^2$, $f(\gamma) = 2\gamma$ and $f(\gamma_h^{IR}) > f(\gamma^{IC})$

$$\frac{\partial E}{\partial c_g} = -\frac{2(\gamma^{IC})}{t} = -\frac{2}{t}\left(\frac{(2d_g - d_h)(v_g - c_g) - d_g(v_h - c_h)}{2td_g(d_g - d_h)}\right) < 0$$

3) Generalized uniform distribution: $F(\gamma) = \gamma^{1/2}$, $f(\gamma) = \frac{1}{2}\gamma^{-1/2}$ and $f(\gamma_h^{IR}) < f(\gamma^{IC})$

$$\frac{\partial E}{\partial c_g} = -\frac{2(\gamma^{IC})}{t} = -\frac{2}{t}\left(\frac{(2d_g - d_h)(v_g - c_g) - d_g(v_h - c_h)}{2td_g(d_g - d_h)}\right) < 0$$

A.4.2.4 Cost of a Hybrid Vehicle: c_h

$$\begin{aligned}\frac{\partial E}{\partial c_h} &= d_g\left[f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right] + d_h\left[f(\gamma_h^{IR})\left(\frac{-1}{td_h}\right) - f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right] \\ &= (d_g - d_h)\left[f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right] - d_h\left[f(\gamma_h^{IR})\left(\frac{1}{td_h}\right)\right] \\ &= -\left(\frac{f(\gamma_h^{IR}) - f(\gamma^{IC})}{t}\right)\end{aligned}$$

1) Uniform distribution: $F(\gamma) = \gamma$, $f(\gamma) = 1$ and $f(\gamma_h^{IR}) = f(\gamma^{IC}) = 1$

$$\frac{\partial E}{\partial c_h} = -\left(\frac{f(\gamma_h^{IR}) - f(\gamma^{IC})}{t}\right) = 0$$

2) Generalized uniform distribution: $F(\gamma) = \gamma^2$, $f(\gamma) = 2\gamma$ and $f(\gamma_h^{IR}) > f(\gamma^{IC})$

$$\begin{aligned}\frac{\partial E}{\partial c_h} &= -\frac{2}{t}\left((\gamma_h^{IR}) - (\gamma^{IC})\right) \\ &= -\frac{2}{t}\begin{bmatrix}\left(\frac{d_h(v_g - c_g) + d_g(v_h - c_h)}{2td_gd_h}\right) \\ -\left(\frac{(2d_g - d_h)(v_g - c_g) - d_g(v_h - c_h)}{2td_g(d_g - d_h)}\right)^{-(1/2)}\end{bmatrix} < 0\end{aligned}$$

3) Generalized uniform distribution: $F(\gamma) = \gamma^{1/2}$, $f(\gamma) = \frac{1}{2}\gamma^{-1/2}$ and $f(\gamma_h^{IR}) < f(\gamma^{IC})$

$$\begin{aligned}\frac{\partial E}{\partial c_h} &= -\frac{1}{2t}\left((\gamma_h^{IR})^{-(1/2)} - (\gamma^{IC})^{-(1/2)}\right)\\ &= -\frac{1}{2t}\left[\begin{array}{l}\left(\dfrac{d_h(v_g - c_g) + d_g(v_h - c_h)}{2td_g d_h}\right)^{-(1/2)}\\ -\left(\dfrac{(2d_g - d_h)(v_g - c_g) - d_g(v_h - c_h)}{2td_g(d_g - d_h)}\right)^{-(1/2)}\end{array}\right] > 0\end{aligned}$$

A.4.2.5 Quality of a Gasoline Vehicle: v_g

$$\begin{aligned}\frac{\partial E}{\partial v_g} &= d_g\left[f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right] - d_h\left[f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right]\\ &= (d_g - d_h)\left[f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right]\\ &= \frac{f(\gamma^{IC})}{t} > 0\end{aligned}$$

1) Uniform distribution: $F(\gamma) = \gamma$, $f(\gamma) = 1$ and $f(\gamma_h^{IR}) = f(\gamma^{IC}) = 1$

$$\frac{\partial E}{\partial v_g} = \frac{1}{t} > 0$$

2) Generalized uniform distribution: $F(\gamma) = \gamma^2$, $f(\gamma) = 2\gamma$ and $f(\gamma_h^{IR}) > f(\gamma^{IC})$

$$\frac{\partial E}{\partial v_g} = \frac{2(\gamma^{IC})}{t} = \frac{2}{t}\left(\frac{(2d_g - d_h)(v_g - c_g) - d_g(v_h - c_h)}{2td_g(d_g - d_h)}\right) > 0$$

3) Generalized uniform distribution: $F(\gamma) = \gamma^{1/2}$, $f(\gamma) = \frac{1}{2}\gamma^{-1/2}$ and $f(\gamma_h^{IR}) < f(\gamma^{IC})$

$$\frac{\partial E}{\partial v_g} = \frac{(\gamma^{IC})^{-(1/2)}}{2t} = \frac{1}{2t}\left(\frac{(2d_g - d_h)(v_g - c_g) - d_g(v_h - c_h)}{2td_g(d_g - d_h)}\right)^{-(1/2)} > 0$$

A.4.2.6 Quality of a Hybrid Vehicle: v_h

$$\begin{aligned}\frac{\partial E}{\partial v_h} &= d_g\left[f(\gamma^{IC})\left(\frac{-1}{t(d_g-d_h)}\right)\right] + d_h\left[f(\gamma_h^{IR})\frac{1}{td_h} - f(\gamma^{IC})\left(\frac{-1}{t(d_g-d_h)}\right)\right]\\ &= -(d_g-d_h)\left[f(\gamma^{IC})\left(\frac{1}{t(d_g-d_h)}\right)\right] + d_h\left[f(\gamma_h^{IR})\frac{1}{td_h}\right]\\ &= \frac{-\left[f(\gamma^{IC}) - f(\gamma_h^{IR})\right]}{t} = \frac{f(\gamma_h^{IR}) - f(\gamma^{IC})}{t}\end{aligned}$$

1) Uniform distribution: $F(\gamma)=\gamma$, $f(\gamma)=1$ and $f(\gamma_h^{IR}) = f(\gamma^{IC}) = 1$

$$\frac{\partial E}{\partial v_h} = \frac{f(\gamma_h^{IR}) - f(\gamma^{IC})}{t} = 0$$

2) Generalized uniform distribution: $F(\gamma)=\gamma^2$, $f(\gamma)=2\gamma$ and $f(\gamma_h^{IR}) > f(\gamma^{IC})$

$$\begin{aligned}\frac{\partial E}{\partial v_h} &= \frac{2}{t}\left((\gamma_h^{IR}) - (\gamma^{IC})\right)\\ &= \frac{2}{t}\left[\left(\frac{d_h(v_g-c_g)+d_g(v_h-c_h)}{2td_gd_h}\right) - \left(\frac{(2d_g-d_h)(v_g-c_g)-d_g(v_h-c_h)}{2td_g(d_g-d_h)}\right)\right] > 0\end{aligned}$$

3) Generalized uniform distribution: $F(\gamma)=\gamma^{1/2}$, $f(\gamma)=\frac{1}{2}\gamma^{-1/2}$ and $f(\gamma_h^{IR}) < f(\gamma^{IC})$

$$\begin{aligned}\frac{\partial E}{\partial v_h} &= \frac{1}{2t}\left((\gamma_h^{IR})^{-(1/2)} - (\gamma^{IC})^{-(1/2)}\right)\\ &= \frac{1}{2t}\left[\begin{array}{l}\left(\frac{d_h(v_g-c_g)+d_g(v_h-c_h)}{2td_gd_h}\right)^{-(1/2)}\\ -\left(\frac{(2d_g-d_h)(v_g-c_g)-d_g(v_h-c_h)}{2td_g(d_g-d_h)}\right)^{-(1/2)}\end{array}\right] < 0\end{aligned}$$

A.4.2.7 Environmental Preference Scalar: t

$$\begin{aligned}
\frac{\partial E}{\partial t} &= d_g\left[f(\gamma^{IC})\left(\frac{(v_g-c_g)-(v_h-c_h)}{-t^2(d_g-d_h)}\right)\right] \\
&+ d_h\left[f(\gamma_h^{IR})\left(\frac{(v_h-c_h)}{-t^2 d_h}\right)+\left[f(\gamma^{IC})\left(\frac{(v_g-c_g)-(v_h-c_h)}{t^2(d_g-d_h)}\right)\right]\right] \\
&= -(d_g-d_h)\left[f(\gamma^{IC})\left(\frac{(v_g-c_g)-(v_h-c_h)}{t^2(d_g-d_h)}\right)\right]-d_h\left[f(\gamma_h^{IR})\left(\frac{(v_h-c_h)}{t^2 d_h}\right)\right] \\
&= -\left[\frac{f(\gamma^{IC})\left((v_g-c_g)-(v_h-c_h)\right)}{t^2}\right]-\left[\frac{f(\gamma_h^{IR})(v_h-c_h)}{t^2}\right] \\
&= -\frac{1}{t^2}\left[f(\gamma^{IC})\left((v_g-c_g)-(v_h-c_h)\right)+f(\gamma_h^{IR})(v_h-c_h)\right]
\end{aligned}$$

1) Uniform distribution: $F(\gamma)=\gamma$, $f(\gamma)=1$ and $f(\gamma_h^{IR})=f(\gamma^{IC})=1$

$$\frac{\partial E}{\partial t} = -\frac{(v_g-c_g)}{t^2} < 0$$

2) Generalized uniform distribution: $F(\gamma)=\gamma^2$, $f(\gamma)=2\gamma$ and $f(\gamma_h^{IR}) > f(\gamma^{IC})$

$$\begin{aligned}
\frac{\partial E}{\partial t} &= -\frac{1}{t^2}\left[2(\gamma^{IC})\left((v_g-c_g)-(v_h-c_h)\right)+2(\gamma_h^{IR})(v_h-c_h)\right] \\
&= -\frac{2}{t^2}\left[\begin{array}{l}\left(\frac{(2d_g-d_h)(v_g-c_g)-d_g(v_h-c_h)}{2td_g(d_g-d_h)}\right)\left((v_g-c_g)-(v_h-c_h)\right) \\ +\left(\frac{d_h(v_g-c_g)+d_g(v_h-c_h)}{2td_g d_h}\right)(v_h-c_h)\end{array}\right] \\
&= -\frac{1}{t^2}\left[\begin{array}{l}\left(\frac{(2d_g-d_h)(v_g-c_g)-d_g(v_h-c_h)}{td_g(d_g-d_h)}\right)\left((v_g-c_g)-(v_h-c_h)\right) \\ +\left(\frac{d_h(v_g-c_g)+d_g(v_h-c_h)}{td_g d_h}\right)(v_h-c_h)\end{array}\right] < 0
\end{aligned}$$

3) Generalized uniform distribution: $F(\gamma) = \gamma^{1/2}$, $f(\gamma) = \frac{1}{2}\gamma^{-1/2}$ and $f(\gamma_h^{IR}) < f(\gamma^{IC})$

$$\frac{\partial E}{\partial t} = -\frac{1}{t^2}\left[\frac{1}{2}(\gamma^{IC})^{-(1/2)}\left((v_g - c_g) - (v_h - c_h)\right) + \frac{1}{2}(\gamma_h^{IR})^{-(1/2)}(v_h - c_h)\right]$$
$$= -\frac{1}{2t^2}\left[\begin{array}{l}\left(\frac{(2d_g - d_h)(v_g - c_g) - d_g(v_h - c_h)}{2td_g(d_g - d_h)}\right)^{-(1/2)}\left((v_g - c_g) - (v_h - c_h)\right) \\ + \left(\frac{d_h(v_g - c_g) + d_g(v_h - c_h)}{2td_g d_h}\right)^{-(1/2)}(v_h - c_h)\end{array}\right] < 0$$

A.4.2.8 Government Subsidy: s_h

$$E = \int_0^{\gamma^{IC}} [f(\gamma) \cdot d_g] d\gamma + \int_{\gamma^{IC}}^{\gamma^{IRH}} [f(\gamma) \cdot d_h] d\gamma$$
$$= d_g F(\gamma^{IC}) + d_h\left[F(\gamma_h^{IR}) - F(\gamma^{IC})\right]$$

where $\gamma^{IC} = \frac{(2d_g - d_h)(v_g - c_g) - d_g(v_h - c_h + s_h)}{2td_g(d_g - d_h)}$ and $\gamma_h^{IR} = \frac{d_h(v_g - c_g) + d_g(v_h - c_h + s_h)}{2td_g d_h}$

$$\frac{\partial E}{\partial s_h} = -d_g\left[f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right] + d_h\left[f(\gamma_h^{IR})\left(\frac{1}{td_h}\right) + f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right]$$
$$= -(d_g - d_h)\left[f(\gamma^{IC})\left(\frac{1}{t(d_g - d_h)}\right)\right] + d_h\left[f(\gamma_h^{IR})\left(\frac{1}{td_h}\right)\right]$$
$$= \left(\frac{f(\gamma_h^{IR}) - f(\gamma^{IC})}{t}\right)$$

1) Uniform distribution: $F(\gamma) = \gamma$, $f(\gamma) = 1$ and $f(\gamma_h^{IR}) = f(\gamma^{IC}) = 1$

$$\frac{\partial E}{\partial s_h} = \left(\frac{f(\gamma_h^{IR}) - f(\gamma^{IC})}{t}\right) = 0$$

2) Generalized uniform distribution: $F(\gamma) = \gamma^2$, $f(\gamma) = 2\gamma$ and $f(\gamma_h^{IR}) > f(\gamma^{IC})$

$$\frac{\partial E}{\partial s_h} = \frac{2}{t}\left((\gamma_h^{IR}) - (\gamma^{IC})\right)$$
$$= \frac{2}{t}\left[\left(\frac{d_h(v_g - c_g) + d_g(v_h - c_h)}{2td_g d_h}\right) - \left(\frac{(2d_g - d_h)(v_g - c_g) - d_g(v_h - c_h)}{2td_g(d_g - d_h)}\right)\right] > 0$$

3) Generalized uniform distribution: $F(\gamma) = \gamma^{1/2}$, $f(\gamma) = \frac{1}{2}\gamma^{-1/2}$ and $f(\gamma_h^{IR}) < f(\gamma^{IC})$

$$\frac{\partial E}{\partial s_h} = \frac{1}{2t}\left((\gamma_h^{IR})^{-(1/2)} - (\gamma^{IC})^{-(1/2)}\right)$$
$$= \frac{1}{2t}\left[\begin{array}{l}\left(\dfrac{d_h(v_g - c_g) + d_g(v_h - c_h)}{2td_g d_h}\right)^{-(1/2)} \\ -\left(\dfrac{(2d_g - d_h)(v_g - c_g) - d_g(v_h - c_h)}{2td_g(d_g - d_h)}\right)^{-(1/2)}\end{array}\right] < 0$$

Vita

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