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by

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Committee in charge:

Professor David Zilberman, Chair
Professor Maximilian Auffhammer
Professor Lee Friedman

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Abstract

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In an era of fluctuating energy costs where we observe increasing concerns for environmental protection, energy sources and energy efficiency, it is of great importance to understand the mechanisms underlying consumer vehicle choices. This dissertation develops a theoretical model of vehicle choice by embedding the disaggregate indirect utility function model of household choice in the aggregate framework of the threshold model of adoption/diffusion. This approach incorporates multiple sources of heterogeneity including household income levels, household structure, comfort/quality levels and attitudes towards environmental awareness. Then, we examine the diffusion of vehicle adoption through dynamic processes such as learning-by-doing (Arrow 1962 [4]). In addition, the simulation model based on this theoretical model enables forecasts particularly suited for examining both household level adoption as well as overall diffusion of different vehicle technologies with relatively few calibrated parameters, especially in dynamic economies such as China or India.

First, this dissertation starts out with the threshold model of diffusion introduced by David (1969) [25] and Sunding and Zilberman (2001) [82], applying the theoretical foundation commonly used in analyzing modern irrigation technology adoption to household vehicle adoption. Households are assumed to be heterogeneous and utility-maximizing through a discrete vehicle choice and a continuous choices of miles traveled, and they adopt the technology that provides the highest utility given the optimal number of miles chosen for that particular technology. Then, the theoretical model is extended to include both parameters of vehicle comfort/quality and environmental awareness in the choice process. Another extension

of the theoretical model includes household heterogeneity through the inclusion of household structures where each household structure may have their own preference set for vehicle comfort/quality. On the aggregate level, the aggregate flow demand of vehicles at time t ($Q_j(t)$) is derived and determined to be a combination of these effects: the population growth rate (Population Effect), the shift of income distribution within the population (Income Distribution Effect) and the movement of the critical income levels for each type of vehicle (affected by characteristics of each vehicle technology as well as preferences of households including the Variable Cost Effect and Fixed Cost Effect).

Next, we develop a computer simulation model with the theoretical household vehicle choice threshold model as foundation. Utilizing a CES utility functional form as the starting point, we calibrate the simulation model using data from various sources, including data of income distribution, vehicle attributes and pricing, vehicle sales data in the U.S. and environmental awareness factors. The final calibrated specification yields an R^2 equal to 0.9595, indicating the simulated results explains approximately 95.95% of the variance in historical vehicle sales data. Using this simulation model, we forecast the influence of various factors on vehicle adoption patterns and optimal miles traveled by households. We find that changes in the fixed cost of vehicles (influenced through government policies regarding rebates or through learning-by-doing) and shifts in income distribution (including both income distribution shifts and shape changes) present particularly dominant effects on vehicle adoption compared to changes in energy price, environmental awareness or vehicle comfort/quality. The main conclusion here is that as parameters are changing, households are not only changing what type of vehicle they prefer to purchase, they also adjust how much they would like to travel.

The theoretical model and the simulation model culminate in Chapter 5 where three very different case studies illustrating potential scenarios in emerging markets, ageing economies and public transportation are presented. Case Study I presents the scenarios of rapidly growing economies with rapidly changing population dynamics such as China or India. The results from this case study illustrate the potential trend towards the adoption of bigger, better (more comfortable) and newer vehicles which are less fuel-efficient and more polluting as the economy experiences high income growth and increases in inequality. The extended scenarios presented in Case Study I incorporates the increasing trend of transportation infrastructure construction. Two effects are hypothesized in this extension: increasing comfort levels due to better roadways and networks of roadways, and decreasing comfort levels due to increasing congestion or pollution caused by the increasing stock of vehicles and miles traveled. The other extension in this portion proposes increasing environmental awareness in a developing economy as it is growing, possibly due to the Environmental Kuznets Curve. Both increasing overall comfort levels and increasing environmental awareness lead to the high rates of adoption of energy-efficient vehicles such as the new hybrid vehicle or the new compact vehicle.

Case Study II of Chapter 5 examines the ageing economies of Japan and Europe. The population dynamics are also shifting in these regions, although at a slower rate, towards a larger percentage of childless households and senior households. The substitution towards energy-efficient vehicles is driven by a combination of increased environmental concern, increasing energy prices, decreasing cost of new hybrid vehicle technology as well as increasing income levels. The effects caused by the larger percentage of childless households and senior households depend on the magnitude of each as well as on the income distribution shape within each household structure.

Case Study III takes the simulation model one step further by introducing public transportation as an alternative travel mode. Public transportation is unique because it entails zero private fixed cost but with the tradeoff of higher variable cost per mile traveled compared to driving a private vehicle. In addition, public transportation provides lower levels of comfort/quality/convenience as well as higher utility from environmental awareness. Unsurprisingly, we find that public transportation ridership benefits from high energy price increases and low public transit fares. We also observe that increasing public transit fares not only decreases the overall number of households who ride public transit, but also induces them to ride less. This case study is extended to incorporate the income distribution shifts in economies such as China. We find that public transportation usage declines and new SUV adoption rapidly increases as the population experiences income increases, demonstrating the dominant effect of the income distribution shift on the adoption of vehicle technologies.

To Mom and Dad

Contents

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Chapter 1

Introduction

In an era of fluctuating energy costs where we observe increasing concerns for environmental protection, energy sources and energy efficiency, it is of great importance to understand the mechanisms underlying consumer vehicle choices. Although econometric models provide perspective for marginal effects, the simulation model presented here will complement econometric studies and provide a novel framework in which we are able to simulate consumer purchasing and adoption patterns. For example, how would dramatically decreasing energy costs much like the scenario in the latter portion of 2008 affect purchases of hybrid vehicles? If it results in lower adoption of hybrid vehicles, how large of a consumer incentive would offset that effect? On the other hand, how would the changing dynamics of a developing country like China affect the technology diffusion process? What role would a dramatic shift in the population income distribution in such a place play? These are the type of questions we seek to answer through the simulation process.

Numerous vehicle ownership and choice models have been developed over the years to forecast vehicle sales for car manufacturers, to provide guidance for policy planning, or to predict vehicle/gasoline usage for environmental conditions and energy consumption forecasts. De Jong et al. (2004) [27], Potoglou and Kanaroglou (2008) [66] and De Jong and Kitamura (2009) [28] offer critical reviews of the current vehicle ownership models that can be generally segregated into levels of aggregation, dynamic or static modeling, different levels of data requirements and various other criteria. Aggregate level studies look at the overall development of car ownership, or what we call diffusion of vehicle technology, and often assume an S-shaped diffusion curve which we discuss in Chapter 2. Ingram and Liu (1999) [42] and Dargay and Gately (1999) [23] are two recent papers that take this approach in estimating the aggregate diffusion patterns of vehicles.

On the disaggregate level, studies involve examining the determinants of household or individual choice of vehicle ownership: whether to own a vehicle, how many vehicles to own, what type of vehicle to own, how much to drive each vehicle, etc. These studies are further separated into dynamic vehicle holding models or dynamic vehicle transactions models. The studies by Mannering and Winston (1985) [54], Train (1986) [83] and Hensher et al. (1992) [41] develop vehicle choice models that are quite influential. For example, Mannering and Winston (1985) [54] analyze how attributes such as brand loyalty or price contribute to the household's choice of vehicle quantity, type and utilization. On the other hand, Train (1986) [83] and Hensher et al. (1992) [41] utilize a microeconomic framework of the 'indirect utility function' where households "compare combinations of car ownership and car use with each other and choose the combination that gives then the highest utility" (De Jong et al. 2004 [27]). We will follow along the same model of indirect utility function in Chapter 2 for the disaggregate portion of the model developed in this dissertation. Dynamic vehicle transaction models attempt to explain the choices of replacing or disposing vehicles within the current fleet of household vehicles, taking into account that vehicle transactions do not occur as often as the transactions of other goods given the high transaction costs (De Jong and Kitamura 2009 [28]). Although our model does not deal with forecasting the changes in household vehicle fleets in its current state, we suggest possible future expansion in this area in Chapter 6.

One of the limitations of current disaggregate vehicle choice and demand models is the reliance on revealed preference data. This limits the ability of these models to forecast the adoption and diffusion patterns of new alternative technologies of which many parameters may be unknown or uncertain. Several recent studies have used experiments or surveys to extract stated preferences regarding new vehicle alternatives (Potoglou and Kanaroglou 2008 [66]; Louviere et al. 2000 [51]), but these types of studies suffer from common surveying problems and biases. Our computer simulation model enables us to look at the introduction of any number of new vehicle type alternatives or changes in vehicle attributes which may provide a way around the stated preference problems. It also allows us to closely examine the disaggregate vehicle choices of individual households as well as the aggregate patterns of vehicle diffusion within an economy.

Adoption and diffusion of goods has been studied intensively in the literature starting from David (1969) [25] and Griliches (1957) [38], and further developed over the years by Bass (1969 and 1980) [6] [7], Davies (1979) [26], Feder et al. (1985) [33], Karshenas and Stoneman (1993) [43], Mahajan et al. (1990) [52], Mansfield (1961) [56], Rogers (1962) [68], Stoneman (1980 and 1983) [78] [80], Sunding and Zilberman (2001) [82] among many others. Two types of adoption models arise from this literature: the threshold model and the imitation model. Our model follows the threshold model of adoption and diffusion which incorporates heterogeneity amongst potential adopters as well as a microeconomic theoretical basis for consumer behavior (through utility maximization). An extended discussion of the differences between the threshold model and the imitation model is presented in Chapter 2.

The main contribution of the model presented in this dissertation is developing the disaggregate indirect utility function model of household choice in the aggregate framework of the threshold model of adoption/diffusion within the context of vehicle choice. This approach incorporates multiple sources of heterogeneity including household income levels, household structure, comfort/quality levels and attitudes towards environmental awareness, and examines the diffusion of vehicle adoption through dynamic processes such as learning-by-doing (Arrow 1962 [4]). In addition, the simulation model based on this theoretical model enables forecasts particularly suited for examining both household level adoption as well as overall diffusion of different vehicle technologies with relatively few calibrated parameters, especially in dynamic economies such as China or India. Although most predictive models are econometrics-based (Bhat and Sen (2006) [11], Bhat and Pulugurta (1998) [10], Rich and Nielsen (2001) [67], Hensher et al. (1992) [41], Mannering and Winston (1985) [54], Train (1986) [83], Brownstone et al. (2000) [18], Birkeland and Jordal-Jørgensen (2001) [13]), simulations such as the computational general equilibrium (CGE) model commonly use optimization to provide some order of magnitude predictions that are consistent in theory. Simulation models are prevalent in climate change modeling. For example, Schneider and McCarl (2002 and 2005) [72] [73] use mathematical-programming-based simulation models to forecast the effects of policies on climate change and agricultural production. These types of models generally assume homogeneity and look at the equilibrium as an interaction of supply and demand using some estimations of elasticities. In this dissertation, we take a deeper look at adoption and diffusion without assuming homogeneity and develop the simulation model based on the threshold model to understand the basic forces that shape household behaviors and overall outcomes.

The main idea is that we apply a theoretical model of diffusion (the threshold model) using a computerized simulation model assuming continuous heterogeneity and contains three main elements: micro-level behavior of household vehicle choice (adoption), aggregation (diffusion) and dynamic assumptions that generate the adoption and diffusion behavior. There are two essential components of our framework: the household theoretical model and the simulation. First, the household model depicts household decisions through standard microeconomic utility maximization. In the baseline model, we assume that the household obtains utility through miles traveled and a composite good. The household maximizes utility by jointly choosing how to fulfill their demand for travel (by purchasing a certain type of vehicle) and how many miles to travel. To account for distributional differences within the population and consumer heterogeneity, we take on an adoption/diffusion modeling approach and use a threshold model to analyze the "adoption" of vehicles. The main feature of such an approach involves analyzing the effects of fixed and variable costs on adoption, which is parallel to modeling the purchase of an automobile. We further extend the framework by incorporating not only fixed and variable costs of vehicles, but comfort and environmental awareness factors as characteristics. Household heterogeneity is incorporated through both differences in income levels and differences in household structures. Through this model, we can observe the basic elements that affect energy demand, as part of the larger picture of vehicle adoption.

Second, the simulation uses calibrated parameters to develop a pattern of vehicle adoption. Aside from the marginal effects we observe from existing econometric models, we can predict and forecast the performance of different policies with this simulation. This tool enables us to project the sensitivity and adoption patterns of consumers to taxation, public transportation policies, fuel efficiency changes, price of vehicles and price of gasoline. In addition, using the same basic model, the simulation allows us to evaluate the effects for different population compositions and varying market conditions. For example, by choosing different parameterizations of the model, we can compare the effects of a gasoline tax in San Francisco versus Shanghai where the income distribution, household characteristics and even vehicle choices vary greatly. In addition, the simulation model may afford us a preview of the dramatic patterns of adoption in developing countries where the shift of income distribution and household structures play important roles in characterizing the societal structure. The applications and possibilities of the simulation framework are endless with simple re-calibrations and adjustments.

In essence, each household is faced with the decision of which vehicle to purchase (or in terms of adoption, which type of technology to adopt) and how much to utilize it. The choice is dependent on a multitude of variables related to the household's demographics, vehicle characteristics as well as input costs such as energy costs and taxation. In this paper, a conceptual framework recognizing heterogeneous consumers, discrete choices associated with the adoption of different technologies, and continuous choices associated with utilization of the technologies is introduced. We are able to compare attributes and costs of different types of vehicles (including varying sizes, different levels of fuel efficiencies), and develop conditions at which consumers switch from one type of vehicle to another. Within this framework based on the adoption threshold model, we can observe the effects of energy costs, vehicle costs, public policy and dynamic economic transitions (such as income distributional shifts) on adoption of fuel-efficient vehicles, adoption of alternative fuel vehicles, demand for transportation and demand for energy. Chapter 2 introduces the theoretical model that is the framework for our analysis of household vehicle choice. Chapter 3 extends the theoretical framework to the simulation model and utilizes data from multiple sources to calibrate it. Next, in Chapter 4, we use the simulation model to examine several hypothetical scenarios. In Chapter 5, we take the simulation a few steps further, looking in depth at three case studies related to emerging economies, ageing economies and public transportation. Finally, we present the conclusions as well as suggested future research directions in Chapter 6.

Chapter 2

The Model

We can look at the overall picture of household vehicle choice as a picture of the adoption and diffusion of technology (in our case, vehicles). In this model, the micro-decision rule of the household is determined by utility maximization characterized by a combination of Mussa and Rosen's (1978) [60] hedonic pricing model and Lancaster's (1966) [47] characteristics model approach to consumer theory. Then, in the aggregate scenario, we incorporate household heterogeneity and dynamic forces through the threshold model of diffusion introduced by David (1969) [25].

In this model, we consider the household as the decision unit. Within the framework of household vehicle choice, it is intuitive to follow adoption models to examine the factors that influence the discrete choice of adopting and the continuous choice of utilization of the technology. The choice to purchase an automobile for transportation can be viewed within the adoption literature as the choice of a household durable good. For example, within the household, we might make a decision whether to purchase a washing machine which would incur a fixed cost and lower variable costs compared to washing laundry in a laundromat. In essence, adoption is about a trade-off between fixed and variable costs, depending on available options. The same concept can be applied directly to the decision of which type of vehicle to purchase to fulfill the need of transportation.

In addition, the adoption behavior can be analyzed in aggregate through diffusion. Diffusion can be evaluated by the percentage of population adopting the alternative fuel vehicle or by the share of transportation utilizing the new technology (Sunding and Zilberman 2001 [82]). The S-shaped diffusion curve developed in the seminal papers by Rogers (1962) [68] and Griliches (1957) [38] studying the adoption of hybrid corn in Iowa is critical to understanding diffusion. Under the S-shaped diffusion curve, early adoption is characterized by "a relatively low adoption rate but with a high rate of change in adoption" followed by takeoff during which the market experiences a high adoption rate (Sunding and Zilberman 2001 [82]). After the takeoff period, the technology adoption slows down reaching a saturation point and eventually declines when a newer technology appears and replaces the current one.

One of the most prominent models of diffusion is the threshold model introduced by David (1969) [25] to study the adoption of grain harvesting machinery. I illustrate the model here using the example in Sunding and Zilberman (2001) [82] of a simple case where the source of heterogeneity is farm size, denoted by L. Notation is as follows: the density of farm sized is denoted by $g(L)$, total number of farms is N and the total acreage is $\bar{L}$, the profit from technology i is $\pi_i(t)$ (where $i = 0$ denotes the traditional technology and $i = 1$ is the new technology) and $\Delta\pi$ is the per acre profit differential. The two measures of diffusion are

$$Y_t^1 = \frac{\int_{L_t^C}^{\infty} g(L)dL}{N}$$
$$Y_t^2 = \frac{\int_{L_t^C}^{\infty} Lg(L)dL}{\bar{L}}$$

where Y_t^1 is the share of farms which adopt and Y_t^2 is the percentage of land with the adopted technology at time t. L_t^C is the critical farm size at which farms switch from traditional to modern technology and it is determined by $L_t^C = \frac{F_t}{\Delta\pi_t}$ where F_t is the fixed cost of adoption. The critical farm size is determined by when the marginal costs of adoption are equal to the marginal benefits of adoption. In our model of vehicle choice, the main heterogeneity in the population is the income level of households denoted by I, and we are able to derive the critical income levels (I_c) at which households switch between vehicle technologies.

One dominant thread in the diffusion and adoption literature is pioneered by Griliches (1957) [38], Mansfield (1961) [56], Bass (1969 and 1980) [6] [7], Mahajan et al. (1990) [52] and is commonly known as the "imitation" model or the "epidemic" model. The imitation model stresses the role of communication and the relationship between "innovators" who are early adopters of technology and "imitators" who observe the behavior of innovators and imitate their behavior. This thread of work has been criticized by Davies (1979) [26], Stoneman (1981 and 1983) [79] [80] and others for the assumed homogeneity between adopters and the lack of theoretical linkage to the firm's profit-maximizing behavior.

Critics of the imitation model developed the threshold model of adoption and diffusion. It was introduced by David (1969) [25] and further explored Feder et al. (1985) [33], Sunding and Zilberman (2001) [82] and Stoneman (1980 and 1983) [78] [80] among others is theoretically based upon the micro-level firm behavior of profit-maximization or the consumer behavior of utility-maximization which determines adoption amongst those within the critical range (i.e. critical income range if income levels are the source of heterogeneity). The source of heterogeneity may include firm/farm size, human capital, search costs, beliefs about returns on new technology, factor productivity, vintage of current capital or input prices (Blackman 1999 [14]). Technology diffusion occurs through dynamic processes such as learning-by-doing (Arrow 1962 [4]), Bayesian learning or information gathering (Feder et al. 1985 [33]). Suppose that we have two firms with different production capabilities, the big firm and the small firm, deciding whether to adopt a costly new technology. After some evaluation, the big firm decides to adopt the technology because the cost-savings are large (allowing the firm to break-even on its investment sooner) due to its large production level. The small firm chooses not to adopt because their production level is too low to justify the cost of the new technology. Therefore, we can say that the small firm has a production level that is below the critical level of adoption. Through some process of innovation over time, the new technology becomes cheaper (or better, leading to larger cost-savings for the adopting firm) and the critical level of adoption will drop. Eventually, the small firm will fall within the critical range of adoption and choose to adopt the new technology.

Our model departs from the imitation model and follows the threshold model because of the limitations caused by the assumption of a homogeneous population and the usage of aggregate adoption data in the imitation literature. Assuming a homogeneous population may not present severe problems for predicting short-term adoption and diffusion behavior, but may not be suitable for long-term forecasts, especially when one considers dynamic economies that consists of both heterogeneity and dramatic shifts in income or other characteristics such as China or India. In addition, the threshold model may be used in conjunction with disaggregate individual data through logit, mixed logit, multinomial logit and various other econometric specifications studied in Bhat and Sen (2006) [11], Bhat and Pulugurta (1998) [10], Rich and Nielsen (2001) [67], Hensher et al. (1992) [41], Mannering and Winston (1985) [54], Train (1986) [83], Brownstone et al. (2000) [18], Birkeland and Jordal-Jørgensen (2001) [13] to further identify household/individual characteristics of those who choose to adopt the new technology.

The threshold model has been extended and applied to various other technology adoption scenarios, such as the Caswell and Zilberman (1986) [20] and the Shah, Zilberman and Chakravorty (1995) [74] papers that study the adoption of modern irrigation technologies in light of an exhaustible resource. The threshold model of adoption and diffusion is not uniquely used for agricultural technologies, it has been applied in numerous contexts such as the adoption of broadband technology in Majumdar et al. (2010) [53], the adoption of NO_X control technologies in coal-fired power plants in Popp (2010) [65] which follows an extension of David's (1969) [25] model by Karshenas and Stoneman (1993) [43] and the relationship between technology adoption and productivity in Hellegers et al. (2010) [40]. Diffusion, as described in the threshold model, may follow the S-shaped diffusion curve over time depending on the distribution on the heterogeneous parameter.

In our threshold adoption/diffusion model of vehicle choice, we assume that the decision-making agents (households) with numerous sources of heterogeneity including income levels, household structure, comfort/quality requirements and are engaging in profit-maximizing (or in our case, utility-maximizing) behavior. Over time, we can derive the critical income levels at which households choose to adopt certain vehicle technologies which is induced by dynamic changes such as learning-by-doing. With the simulation model that is based on this theoretical framework, we are able to forecast far into the future with relatively few calibrated parameters, identifying the dynamic processes that cause different patterns of diffusion. Therefore, using a threshold model framework and previous consumer choice models as our theoretical foundation, we will examine the choice of adopting private automobiles and of adopting alternative fuel vehicles incorporating household and consumer heterogeneity.

2.1 The Baseline Model

Within the household, utility is provided by two components: miles traveled and a composite good of everything else consumed. Assuming that the household resides in an area where public transportation does not exist as an option, the household can decide to fulfill the need for travel through the purchase of a vehicle.

For simplicity, the household's decision space consists of several types of vehicles denoted by j, which could be new or used vehicles of varying sizes using conventional or alternative energy sources where $j \epsilon \{1, 2, ..., J\}$, ranked in ascending order of annual fixed cost. A smaller vehicle is assumed to have lowering purchasing cost and higher level of energy efficiency than a larger vehicle. In addition, the fixed cost of purchasing a used vehicle may be a fraction of the cost of a comparable new vehicle, but energy efficiency may also be only a fraction of the new vehicle. In other words, each type of vehicle is characterized by its annual fixed cost (F_j) and variable cost or energy efficiency (e_j). Choosing to buy a particular type of vehicle incurs an annual fixed cost (including depreciation of the vehicle and other fixed costs of owning such as insurance or registration) to the household, but provides travel with varying levels of variable costs (i.e. cost of energy which varies with the amount of travel). Although the following model specification assumes a single vehicle household, it is easily extended to a multiple-vehicle model with greater variety of vehicle choices without much change to the analysis and interpretations.

Following the utility formulation in the hedonic pricing model of Mussa and Rosen (1978) [60], let $U(x_j, z)$ denote the utility of the household and we assume that the utility-maximizing household optimizes by jointly choosing the type of vehicle to purchase (j) and the optimal level of transportation on vehicle type j where z is a composite good other than miles traveled (numeraire good) with price equal to one. Households maximize utility given the household budget constraint of $F_j + e_j x_j + z \leq I$ where I is the household income level, F_j is the annual fixed cost of owning vehicle type j, e_j is the variable cost per mile traveled and x_j is the number of miles traveled on the chosen vehicle. Therefore, the indirect utility given vehicle type j is as follows

$$V_j \equiv \max_{x_j} U(x_j, I - F_j - e_j x_j) \tag{1}$$

Each household gains utility from miles traveled (assuming all miles are equivalent in value to the household) and a composite good. The magnitudes of fixed cost (F_j) and variable cost (e_j) may be obtained from current statistics of the automobile industry.

With each vehicle choice j, an indirect utility curve V_j can be derived from the maximization. When these indirect utility curves cross, they indicate a switch from one type of vehicle to another. These points are called critical income points (I_c^j), the income at which the household switches from $j-1$ to j (i.e. I_c^2 is the critical income at which households below this income level will choose to purchase vehicle type 1, and households at and above this critical income will choose to purchase vehicle type 2). Because $V_j(I_c^j) = V_{j-1}(I_c^j)$, we are able to derive the level of critical income I_c^j given the functional form of the household utility function and the fixed and variable costs. The outermost envelope formed by the highest utility curves is the utility frontier from which we can observe consumer behavior.

In this model, the household maximizes utility by choosing how many miles to travel (x_j) given technology j. Then, the household will maximize utility by choosing the technology that provides the highest utility (given the optimal miles for each technology).

Through aggregation, we are able to determine the demand for travel as well as the demand for gasoline since it is "a derived demand that has its source in the demand for travel services" (Blair et al. 1984 [15]). Gasoline is only consumed by the consumer when traveling in a private vehicle, and therefore the amount of travel determines the amount of gasoline demanded.

> [T]his derived demand contains certain technological components that relate to the size and potential fuel efficiency ofet. In the short run, these technological components are fixed. Consequently, individuals are able to alter their gasoline consumption in response to price changes only through reductions in total travel miles and/or altered driving and maintenance habits (frequency of tune-ups, etc.) that result in improved attained efficiency of the existing vehicle fleet. (Blair et al. 1984 [15])

Therefore, we will assume that gasoline/energy demand is linearly related to travel demand in this paper.

2.1.1 Baseline Model Analysis

The first and second order conditions of the maximization problem are

$$FOC: \quad \frac{\partial U}{\partial(x_j)} + \frac{\partial U}{\partial(z)}[-e_j] = 0 \tag{2}$$

$$SOC: \quad \frac{\partial^2 U}{\partial(x_j^2)} + \frac{\partial^2 U}{\partial(z)\partial(x_j)}[-e_j] < 0 \tag{3}$$

These conditions yield intuitive results. We observe that the optimal miles traveled on a vehicle of type j is decided when the marginal utility of a mile is equal to the change in utility when income is decreased by the per mile variable cost of e_j (when the marginal benefit of travel is equal to the marginal cost of travel). Next, the second-order condition is met when the functional form of the utility function is concave (i.e. Cobb-Douglas utility). We can obtain further comparative static results that represent the response of optimal miles traveled to a change in energy costs.

$$\begin{aligned}
\frac{dx_j}{de_j} &= \frac{\frac{\partial^2 U}{\partial x_j \partial z}[x_j] + \frac{\partial^2 U}{\partial z^2}[-e_j x_j] + \frac{\partial U}{\partial z}}{SOC} \\
&= \frac{\frac{\partial^2 U}{\partial z^2}[-e_j x_j] + \frac{\partial U}{\partial z}}{SOC} < 0 \qquad (4) \\
\frac{dx_j}{dI} &= \frac{-\frac{\partial^2 U}{\partial x_j \partial z} + \frac{\partial^2 U}{\partial z^2}[e_j]}{SOC} \\
&= \frac{\frac{\partial^2 U}{\partial z^2}[e_j]}{SOC} > 0 \qquad (5) \\
\frac{dx_j}{dF_j} &= \frac{\frac{\partial^2 U}{\partial x_j \partial z} - \frac{\partial^2 U}{\partial z^2}[e_j]}{SOC} \\
&= \frac{-\frac{\partial^2 U}{\partial z^2}[e_j]}{SOC} < 0 \qquad (6)
\end{aligned}$$

For the remainder of the analysis in this paper, we will assume that the marginal utility of travel is constant across all income levels for simplicity $\left(\frac{\partial^2 U}{\partial x_j \partial z} = 0\right)$. It could be a future source of extension if consumers with differing income levels have some disparity in the marginal utility of travel large enough to offset the other effects.

The results here are consistent with common intuition. When the per-mile energy cost (e_j) of traveling on vehicle j increases, the consumer will travel less. In equation (4), we observe that the first term $\left(\frac{\frac{\partial^2 U}{\partial z^2}[-e_j x_j]}{SOC}\right)$ is the income effect (a negative effect) that represents the decrease in traveling as purchasing power decreases due to higher energy costs. The second term $\left(\frac{\frac{\partial U}{\partial z}}{SOC}\right)$ is the substitution effect (also a negative effect), causing the consumer to switch away from traveling to consuming other goods. The optimal miles traveled by the household (x_j) increases with household income as shown in Equation (5) because the term $\frac{\partial^2 U}{\partial z^2}[e_j]$ is negative due to diminishing marginal utility of the composite good (z). Equation (6) shows that the optimal miles traveled by the household decreases with fixed annual cost of vehicle j (F_j) because the term $-\frac{\partial^2 U}{\partial z^2}[e_j]$ is positive by the same reasoning. It is reasonable that households will want to travel more when they have higher income, but will want to travel less when the car they purchase is more expensive, leading to lower disposable income.

2.2 Aggregation and Dynamics

2.2.1 Aggregation of Demand

Thus far, our model has analyzed the decision-making process of a utility-maximizing household when faced with a discrete choice of which type of vehicle to adopt and a continuous choice of how many miles to travel. By extending the framework of our model, we are able to analyze aggregate consumer behavior to observe technology diffusion. We will assume that households have identical preferences but the source of heterogeneity stems from the differing levels of income. For each vehicle type j, we are able to derive the critical income level I_c^j where only households with incomes between I_c^j and I_c^{j+1} will choose to purchase vehicle type j. Suppose that the income distribution function of our population at time t is given by $g_t(I)$ and the cumulative income distribution (or share of households whose income does not exceed I) is given by $G_t(I)$, where $G_t(I) = \int_0^I g_t(I)dI$. We can define the desired stock of vehicle type j at time t as

$$S_j(t) = T\int_{I_c^j}^{I_c^{j+1}} g_t(I)dI = T[G_t(I_c^{j+1}) - G_t(I_c^j)] \tag{7}$$

where T is the total population size.

2.2.2 Dynamics of Demand

$S_j(t)$ represents the desired stock of vehicle j at time t, but the actual demand at any time is the desired stock minus the stock previously accumulated. Thus, the aggregate flow demand $Q_j(t)$ represents the increase in the desired stock over time. In other words, Equation (8) is the equation of motion of the stock dynamics where $Q_j(t)$ is the number of vehicles purchased at time t. It is assumed that in every period we start with the same initial distribution of vehicles and $Q_j(t)$ represents the adoption of new or used vehicles relative to this initial distribution. In addition, vehicles are purchased because the consumer is replacing an obsolete vehicle or is entering into the market for the first time. For simplicity, let us assume that $Q_j(t)$ is equal to or greater than zero. Future research may incorporate a more sophisticated extension to our model by updating the distribution of vehicles in each period and include an element of vehicle depreciation to more accurately forecast the adoption of vehicles.

$$Q_j(t) = \frac{\partial S(t)}{\partial t} = \dot{S(t)} \tag{8}$$

$$\begin{aligned} Q_j(t) \quad = \quad & S(t)\frac{\dot{T}}{T} + T\Bigg[\left(\frac{\partial G_t(I_c^{j+1})}{\partial t} - \frac{\partial G_t(I_c^t)}{\partial t}\right) \\ & + \dot{e}_j\left(\frac{\partial G_t(I_c^{j+1})}{\partial I_c^{j+1}}\frac{\partial I_c^{j+1}}{\partial e_j} - \frac{\partial G_t(I_c^j)}{\partial I_c^j}\frac{\partial I_c^j}{\partial e_j}\right) \\ & + \dot{F}_j\left(\frac{\partial G_t(I_c^{j+1})}{\partial I_c^{j+1}}\frac{\partial I_c^{j+1}}{\partial F_j} - \frac{\partial G_t(I_c^j)}{\partial I_c^j}\frac{\partial I_c^j}{\partial F_j}\right) \\ & - \dot{e}_{j-1}\left(\frac{\partial G_t(I_c^j)}{\partial I_c^j}\frac{\partial I_c^j}{\partial e_{j-1}}\right) - \dot{F}_{j-1}\left(\frac{\partial G_t(I_c^j)}{\partial I_c^j}\frac{\partial I_c^j}{\partial F_{j-1}}\right) \\ & + \dot{e}_{j+1}\left(\frac{\partial G_t(I_c^{j+1})}{\partial I_c^{j+1}}\frac{\partial I_c^{j+1}}{\partial e_{j+1}}\right) + \dot{F}_{j+1}\left(\frac{\partial G_t(I_c^{j+1})}{\partial I_c^{j+1}}\frac{\partial I_c^{j+1}}{\partial F_{j+1}}\right)\Bigg] \end{aligned} \tag{9}$$

There are several effects that determine the aggregate flow demand ($(Q_j(t))$) that we can observe from the above equation:

1. Population Effect $\left(S(t)\frac{\dot{T}}{T}\right)$
   The populations effect represents the increase of households whose incomes fall within the critical range of I_c^j and I_c^{j+1}. If there are more households within this range, it means that more households will purchase vehicle type j at time t.

2. Income Distribution Effect $\left(\frac{\partial G_t(I_c^{j+1})}{\partial t} - \frac{\partial G_t(I_c^t)}{\partial t}\right)$
   The income distribution effect represents the shift of households into (or out of) the critical range of income levels. This effect may be most prominent when dealing with a dynamically shifting economy such as India or China. Within a short period of time, we may observe a large number of households shifting to higher income levels due to high levels of economic growth in these

developing regions. In addition, increasing or decreasing income inequality levels that change the shape of the population income distribution are also captured here.

3. Variable Cost Effect
   The variable cost effect is one of the effects that affects the critical income levels. Since there is an upper-bound critical income (I_c^{j+1}) and a lower-bound critical income (I_c^j) for vehicle type j, any changes in its own variable cost (energy cost e_j) will potentially shift those critical income levels. Furthermore, changes in the variable costs of vehicle types $j-1$ and $j+1$ may also have an effect. We expect that an increase in own variable cost for vehicle type j will possibly increase I_c^j and/or lower I_c^{j+1}.

4. Fixed Cost Effect
   The fixed cost effect is similar to the variable cost effect. When vehicle type j's own fixed cost (F_j) or other fixed costs (F_{j-1} or F_{j+1}) changes, it will shift critical income levels within which households choose to purchase that vehicle.

In summary, the aggregate flow demand of vehicles ($Q_j(t)$) is determined by the population growth rate, the shift of income distribution within the population and the critical income levels (I_c^j and I_c^{j+1}). Factors such as own energy variable cost (e_j), own fixed cost (F_j) as well as the variable costs and fixed costs of similar options are determinants of the critical income levels.

2.3 Extension: Comfort

It is easily perceived that, to the household, miles traveled in a used compact vehicle (very possibly cramped and smelly) provides a substantially different level of utility than miles traveled in a new luxury vehicle. Lancaster (1966) [47] presented an innovative approach to the theory of consumer demand that proposes that consumers derive utility from the *characteristics* of goods instead of the goods themselves. From this perspective, vehicles do not provide utility directly, but the characteristics of the vehicle such as transportation, comfort or quality provide utility to the consumer. Lancaster's model reflects why different vehicles possessing vectors of similar characteristics are close substitutes for each other, and also enables us to analyze consumer reactions to the introduction of new vehicle types into the market. In addition, studies by Van Dender (2009) [84] and Greene et al. (2009) [36] show that "low willingness to pay for fuel economy by consumers translates into strategies on manufacturer' part that steer vehicle design towards more marketable attributes, like power and comfort", suggesting the existence of willingness to pay for the comfort or quality of a vehicle. Baltas and Saridakis (2009) [5] further show that "features related to comfort and luxury (e.g. leather interior, automatic air conditioning, alloy wheels) have also positive and significant effects" on vehicle pricing. Thus, it is not unreasonable to include comfort or quality of the vehicle as one of the extensions that explain the household vehicle choice decision. Practically, as with all modeling, we will attempt to use "the minimum number of characteristics that give sufficient explanatory power" in our model. We will look at which extensions or specifications of the model are most appropriate in the calibration stage in Chapter 3.

Following Lancaster, we can then extend our model formulation to include comfort of travel for each mile traveled, which we denote as q_j, as one of the key characteristics of vehicles in addition to transportation. The actual level of comfort for each type of vehicle can also be calibrated using industry survey data. With this extension of the model, household utility is now composed of three components: miles traveled, comfort while traveling and a composite good of everything else consumed. The utility maximization is now as follows

$$V_j \equiv \max_{x_j} U(x_j, q_j x_j, I - F_j - e_j x_j) \tag{10}$$

The first and second order conditions of the maximization problem and the comparative statics are as follows.

$$FOC: \quad \frac{\partial U}{\partial(x_j)} + \frac{\partial U}{\partial(q_j x_j)}[q_j] + \frac{\partial U}{\partial z}[-e_j] = 0 \tag{11}$$

$$SOC: \quad \frac{\partial^2 U}{\partial(x_j^2)} + \frac{\partial^2 U}{\partial(q_j x_j)\partial(x_j)}[q_j] + \frac{\partial^2 U}{\partial(z)\partial(x_j)}[-e_j] < 0 \tag{12}$$

$$\begin{aligned}
\frac{dx_j}{de_j} &= \frac{\frac{\partial^2 U}{\partial q_j x_j \partial z}[q_j x_j] - \frac{\partial^2 U}{\partial z^2}[e_j x_j] + \frac{\partial U}{\partial z}}{SOC} \\
&= \frac{-\frac{\partial^2 U}{\partial z^2}[e_j x_j] + \frac{\partial U}{\partial z}}{SOC} < 0 \qquad (13) \\
\frac{dx_j}{dI} &= \frac{-\frac{\partial^2 U}{\partial q_j x_j \partial z}[q_j] + \frac{\partial^2 U}{\partial z^2}[e_j]}{SOC} \\
&= \frac{\frac{\partial^2 U}{\partial z^2}[e_j]}{SOC} > 0 \qquad (14) \\
\frac{dx_j}{dF_j} &= \frac{\frac{\partial^2 U}{\partial q_j x_j \partial z}[q_j] - \frac{\partial^2 U}{\partial z^2}[e_j]}{SOC} \\
&= \frac{-\frac{\partial^2 U}{\partial z^2}[e_j]}{SOC} < 0 \qquad (15) \\
\frac{dx_j}{dq_j} &= \frac{-\frac{\partial^2 U}{\partial x_j \partial q_j} - \frac{\partial U}{\partial (q_j x_j)} - \frac{\partial^2 U}{\partial q_j x_j \partial q_j}[q_j]}{SOC} \gtrless 0 \qquad (16)
\end{aligned}$$

The results of the comparative statics here in the model extension are again consistent with common intuition. With this specification, the first order condition (Equation (11)) shows that the household will maximize utility when the marginal utility of travel, from both traveling $\left(\frac{\partial U}{\partial (x_j)}\right)$ and comfort when traveling $\left(\frac{\partial U}{\partial (q_j x_j)}[q_j]\right)$, is equal to the marginal cost of travel $\left(\frac{\partial U}{\partial (e_j)}[-e_j]\right)$. In other words, the household will increase the amount traveled until the marginal benefit of travel is equated to the marginal cost of travel, consistent with microeconomic theory. Again, we will assume that the marginal utility of comfort while traveling is constant across all income levels for simplicity $\left(\frac{\partial^2 U}{\partial q_j x_j \partial z} = 0\right)$. Equations (13), (14) and (15) show the same results as the baseline model analysis, the optimal number of miles traveled by the household (x_j) increases with income levels (I) and decreases with energy variable cost (e_j) and annual fixed cost (F_j). Equation (16) shows more interesting results with regards to comfort/quality. The first term of the equation $\left(\frac{-\frac{\partial^2 U}{\partial x_j \partial q_j}}{SOC}\right)$ represents the change in marginal utility of miles traveled with regards to a change in the comfort level of the vehicle and is assumed to be positive because as comfort increases, each mile traveled brings more utility for the household. The second term $\left(\frac{-\frac{\partial U}{\partial (q_j x_j)}}{SOC}\right)$ is also positive because as comfort from travel increases, utility also increases. Finally, the last term $\left(\frac{-\frac{\partial^2 U}{\partial q_j x_j \partial q_j}[q_j]}{SOC}\right)$ represents how the marginal utility of comfort from travel is affected by a change in the comfort level of the vehicle. This term is negative due to the diminishing marginal utility of comfort. When comfort level increases, households may, on one hand, want to increase the optimal amount of travel because it becomes relatively easier to obtain utility in this way. On the other hand, because of the diminishing marginal utility of comfort, households may choose to substitute other goods for travel instead. Thus, the sign of Equation (16) remains ambiguous, but when the simulations are conducted we may be better able to gain a sense of how households tend to react to higher comfort levels.

2.4 Extension: Household Structures

We further introduce a factor of household structures which accounts for differences in household composition as a source of consumer heterogeneity into the model to account for the differences in how different households view different types of vehicles. Although there may be a established comfort level for each type of car, different households place a different relative value on the comfort of any given car (i.e. households with children place higher comfort value on large vehicles because of the ease of transporting larger groups of people and equipment; households with elder members place higher comfort value on vehicles that are more easily accessible). Particularly, the relationship between household structures (or also called lifestyle factor) and energy consumption and sustainable development has been well documented by Weber and Perrels (2000) [85], Duchin (1996) [30], Schipper et al. (1989) [71], Schipper (1996) [70], Dalton et al. (2008) [22] and Brohmann (2010) [16]. If this relationship between household structures and household energy consumption is well establish, it is not far-fetched to also consider a relationship between household structures and vehicle choice and transportation energy demand. For simplicity, we consider only three types of household structures as a stylized exercise: households with children denoted by $h = 1$, households without children denoted by $h = 2$ and households aged above 65 denoted by $h = 3$. Now, the comfort parameter (q_{jh}) varies not only by vehicle, but also by type of household structure. We can write the indirect utility function as

$$V_j \equiv \max_{x_j} U(x_j, q_{jh}x_j, I - F_j - e_j x_j) \tag{17}$$

The first and second order conditions of the maximization problem with the household structures extension and the comparative statics are as follows.

$$FOC: \quad \frac{\partial U}{\partial (x_j)} + \frac{\partial U}{\partial (q_{jh} x_j)}[q_{jh}] + \frac{\partial U}{\partial z}[-e_j] = 0 \tag{18}$$

$$SOC: \quad \frac{\partial^2 U}{\partial (x_j^2)} + \frac{\partial^2 U}{\partial (q_{jh} x_j)\partial (x_j)}[q_{jh}] + \frac{\partial^2 U}{\partial (z)\partial (x_j)}[-e_j] < 0 \tag{19}$$

$$\begin{aligned}
\frac{dx_j}{de_j} &= \frac{\frac{\partial^2 U}{\partial q_{jh} x_j \partial z}[q_{jh} x_j] - \frac{\partial^2 U}{\partial z^2}[e_j x_j] + \frac{\partial U}{\partial z}}{SOC} \\
&= \frac{-\frac{\partial^2 U}{\partial z^2}[e_j x_j] + \frac{\partial U}{\partial z}}{SOC} < 0 && (20) \\
\frac{dx_j}{dI} &= \frac{-\frac{\partial^2 U}{\partial q_{jh} x_j \partial z}[q_{jh}] + \frac{\partial^2 U}{\partial z^2}[e_j]}{SOC} \\
&= \frac{\frac{\partial^2 U}{\partial z^2}[e_j]}{SOC} > 0 && (21) \\
\frac{dx_j}{dF_j} &= \frac{\frac{\partial^2 U}{\partial q_{jh} x_j \partial z}[q_{jh}] - \frac{\partial^2 U}{\partial z^2}[e_j]}{SOC} \\
&= \frac{-\frac{\partial^2 U}{\partial z^2}[e_j]}{SOC} < 0 && (22) \\
\frac{dx_j}{dq_{jh}} &= \frac{-\frac{\partial^2 U}{\partial x_j \partial (q_{jh})} - \frac{\partial U}{\partial (q_{jh} x_j)} - \frac{\partial^2 U}{\partial q_{jh} x_j \partial q_{jh}}[q_{jh}]}{SOC} \gtrless 0 && (23)
\end{aligned}$$

The comparative statics in this extension are almost identical to the results from the previous extension. The only difference appears in the comfort parameter (q_{jh}) where the comfort of each type of vehicle varies according to the household structure of the household utilizing the vehicle. However, the analytical results remain the same: the optimal number of miles traveled by the household (x_j) increases with income levels (I) and decreases with energy variable cost (e_j) and annual fixed cost (F_j) as shown in Equations (20) through (22). With this additional source of heterogeneity, we still observe in Equation (23) that the effects of comfort level changes (q_{jh}) on optimal number of miles traveled (x_j) is ambiguous by the same reasoning as the previous section. This household structures extension is included to illustrate one source of heterogeneity that can exist within the model. Chapter 6 discusses further sources of heterogeneity that may be incorporated in to the model.

2.5 Extension: Environmental Awareness

When households make a choice of which type of vehicle to purchase, they may consider the cost of buying, the cost of operating as well as the capacity and comfort of the vehicle. In addition, energy-efficient vehicles, especially ones labeled as hybrid vehicles, may provide an extra benefit of signalling environmental awareness. As environmental awareness increases, those households which purchase fuel-efficient vehicles will receive higher utility than those who purchase gas-guzzler vehicles. The Environmental Kuznets Curve (EKC) hypothesis, which proposes an inverted-U relationship between environmental quality and overall income levels of a nation, is premised upon the idea that as countries become more developed, they experience "increased environmental awareness, enforcement of environmental regulations, better technology and higher environmental expenditures" (Panayotou 1993 [63], Stern et al. 1996 [77]) that lead to the eventual decline of environmental degradation. In addition, there is evidence that some level of product segmentation is caused by the existence of consumer preferences or value for environmentally-friendly (or "green") goods (Conrad 2005 [21], Arora and Gangopadhyay 1995 [3], Lombardini-Riipinen 2003 [50], Moraga-Gonzalez and Padron-Fumero 2002 [59] and Andreoni 1990 [2]). The additional utility provided by the usage of environmentally-friendly or energy-efficient vehicles is accounted for through this extension of environmental awareness. Household utility is now composed of four components: miles traveled, comfort while traveling, environmental awareness (positively correlated with energy price) and a composite good. The indirect utility given vehicle type j is

$$V_j \equiv \max_{x_j} U(x_j, q_j x_j, \alpha_j, I - F_j - e_j x_j) \tag{24}$$

where α_j is the environmental awareness coefficient of vehicle j. The first and second order conditions of the maximization problem with the comfort extension and the comparative statics are as follows.

$$FOC: \quad \frac{\partial U}{\partial(x_j)} + \frac{\partial U}{\partial(q_j x_j)}[q_j] + \frac{\partial U}{\partial \alpha_j} + \frac{\partial U}{\partial z}[-e_j] = 0 \tag{25}$$

$$SOC: \quad \frac{\partial^2 U}{\partial(x_j^2)} + \frac{\partial^2 U}{\partial(q_j x_j)\partial(x_j)}[q_j] + \frac{\partial^2 U}{\partial \alpha_j \partial x_j} + \frac{\partial^2 U}{\partial(z)\partial(x_j)}[-e_j] < 0 \tag{26}$$

$$\frac{dx_j}{de_j} = \frac{\frac{\partial^2 U}{\partial q_j x_j \partial z}[q_j x_j] + \frac{\partial^2 U}{\partial \alpha_j \partial z}[x_j] - \frac{\partial^2 U}{\partial z^2}[e_j x_j] + \frac{\partial U}{\partial z}}{SOC}$$

$$= \frac{\frac{\partial^2 U}{\partial \alpha_j \partial z}[x_j] - \frac{\partial^2 U}{\partial z^2}[e_j x_j] + \frac{\partial U}{\partial z}}{SOC} < 0 \tag{27}$$

$$\frac{dx_j}{dI} = \frac{-\frac{\partial^2 U}{\partial q_j x_j \partial z}[q_j] - \frac{\partial^2 U}{\partial \alpha_j \partial z} + \frac{\partial^2 U}{\partial z^2}[e_j]}{SOC}$$

$$= \frac{-\frac{\partial^2 U}{\partial \alpha_j \partial z} + \frac{\partial^2 U}{\partial z^2}[e_j]}{SOC} > 0 \tag{28}$$

$$\frac{dx_j}{dF_j} = \frac{\frac{\partial^2 U}{\partial q_j x_j \partial z}[q_j] + \frac{\partial^2 U}{\partial \alpha_j \partial z} - \frac{\partial^2 U}{\partial z^2}[e_j]}{SOC}$$

$$= \frac{\frac{\partial^2 U}{\partial \alpha_j \partial z} - \frac{\partial^2 U}{\partial z^2}[e_j]}{SOC} < 0 \tag{29}$$

$$\frac{dx_j}{dq_j} = \frac{-\frac{\partial^2 U}{\partial x_j \partial (q_j)} - \frac{\partial U}{\partial (q_j x_j)} - \frac{\partial^2 U}{\partial q_j x_j \partial q_j}[q_j]}{SOC} \gtrless 0 \tag{30}$$

$$\frac{dx_j}{d\alpha_j} = \frac{-\frac{\partial^2 U}{\partial x_j \partial \alpha_j} - \frac{\partial^2 U}{\partial q_j x_j \partial \alpha_j} - \frac{\partial^2 U}{\partial \alpha_j^2}}{SOC}$$

$$= \frac{-\frac{\partial^2 U}{\partial \alpha_j^2}}{SOC} \leq 0 \tag{31}$$

Within this extension of the model, we again observe very similar comparative statics. Again, we will assume for simplicity that the marginal utility of comfort while traveling is constant across all income levels $\left(\frac{\partial^2 U}{\partial q_j x_j \partial z} = 0\right)$. One common term that appears throughout Equations (27) through (29) and is different than all previous model specifications is $\frac{\partial^2 U}{\partial \alpha_j \partial z}$. This term describes whether the marginal utility of environmental awareness is affected by income levels. In our simulation model, we will assume that the marginal utility of environmental awareness is constant across all income levels. However, it may also be plausible that this term is positive, indicating that as households become wealthier, they may gain more marginal utility from being environmentally-friendly. The analytical results here are not affected by whether $\frac{\partial^2 U}{\partial \alpha_j \partial z} = 0$ or $\frac{\partial^2 U}{\partial \alpha_j \partial z} > 0$, it results in the same comparative statics results. Equation (30) is identical to Equation (16) from the comfort extension, and its sign is ambiguous due to separate effects that may cause the optimal number of miles traveled (x_j) to increase or decrease when comfort level (q_j) increases. Equation

(31) shows that as environmental awareness increases (α_j) for vehicle type j, the optimal number of miles traveled (x_j) decreases or remains constant. The first term of this equation $\left(\frac{-\frac{\partial^2 U}{\partial x_j \partial \alpha_j}}{SOC}\right)$ can be assumed to be zero because the marginal utility of miles traveled is not affected by environmental awareness. The next term $\left(\frac{-\frac{\partial^2 U}{\partial q_j x_j \partial \alpha_j}}{SOC}\right)$ can also be assumed to be zero because we assume that the marginal utility of comfort is not affected by environmental awareness. It is plausible that environmental awareness may be a function of energy efficiency or energy costs, and will, in turn, affect the marginal utility of miles traveled (most likely causing a diminishing marginal utility of miles traveled as environmental awareness heightens). For ease of analysis, we will assume that these terms are constant, although the resulting sign would still be the same. In Equation (31), the optimal number of miles traveled will decrease if there exists diminishing marginal utility of environmental awareness $\left(-\frac{\partial^2 U}{\partial \alpha_j^2} < 0\right)$ and will remain constant if the marginal utility of environmental awareness is constant $\left(-\frac{\partial^2 U}{\partial \alpha_j^2} = 0\right)$ depending on the functional form utilized for the household utility function.

Chapter 3

The Simulation

To show that the specifications of our model closely simulates consumer adoption behavior, we run several simulations based on data in the U.S. to derive aggregate consumer adoption decisions in terms of the discrete choice of vehicle type and the continuous choice of miles to travel. The simulations examine the household adoption behavior of different types of vehicles as energy price increases over the past decade. Essentially, we will predict the dynamic pattern of the adoption of different types of vehicles and compare the simulated estimations with the actual sales data in the U.S. Given the energy prices and vehicle attributes of any particular year, the simulated numbers will show that within the group of people in the market to purchase a vehicle, what percentage would ultimately choose each type of vehicle.

After the simulation has been successfully calibrated, we are then able to apply the simulation model to various scenarios for predictive estimations. In a scenario previously mentioned, we can now use the simulation to show what the effects of fluctuating energy costs on the purchase of vehicles. If we were concerned that decreasing energy costs may trigger lower sales of more efficient vehicles and how that would affect the environment and future energy costs, the simulation will provide insight as to what types of consumer incentives or policy options may shift consumers towards better energy efficiency.

3.1 Simulation Functional Form

First, we begin by assuming that the sole source of heterogeneity in households arises from income and that households hold identical preferences. The pattern of income distribution within the population is one of the key determinants of aggregate adoption. Therefore, we will utilize the income distribution data from the Current

Population Survey to characterize the population. Following the proposed model, consider the case where the household has a CES utility function with three factors: miles traveled, comfort and disposable income. The following is the utility of a household which chooses to purchase vehicle type j under the baseline specification.

$$V_j = \max_{x_j} U_j(x_j, q_j x_j, z) = \max_{x_j}[b_1(x_j)^\rho + b_2(q_j x_j)^\rho + b_3(I - (e_j x_j + F_j))^\rho]^{\frac{1}{\rho}} \quad (32)$$

where $\rho = \frac{s-1}{s}$ and s is the elasticity of substitution.

Simulation	**Specification Used**
1	Baseline model with comfort and household structures extensions
2	Baseline model with all extensions and energy price as environmental awareness proxy
3	Baseline model with all extensions and survey data about consumer environmental awareness as proxy

We will present the results of three simulations with the above specifications. The first two simulations use the same model specification, but the final simulation uses a slightly modified utility function that accounts for the additional utility of purchasing high fuel efficiency vehicles such as a hybrid vehicle in times of high energy prices. The modified household utility which chooses vehicle type j is as follows:

$$V_j = \max_{x_j} U_j(x_j, q_j x_j, \alpha_j, z) = \max_{x_j}[b_1(x_j)^\rho + b_2(q_j x_j)^\rho + b_3(I - (e_j x_j + F_j))^\rho + b_4(\alpha_j)^\rho]^{\frac{1}{\rho}} \quad (33)$$

where the environmental awareness coefficient is defined as α_j. We use several variables as proxies for this environmental awareness coefficient defined in a fashion such that if the coefficient is increasing, households that purchase a more energy efficient vehicle would gain more utility than those who purchase a less efficient one. If environmental awareness remains constant from year to year (or changes at a low rate), the environmental awareness coefficient would be similar across vehicles. Rising energy cost may be positively correlated with awareness in the population. Therefore, we include the ratio of current year energy cost to previous year energy cost ($\alpha_j = \left(\frac{e_j(t)}{e_j(t-1)}\right)^{a_j}$) as one of the proxies of environmental awareness. Note that all specifications utilize the actual income distribution of the population from the Current Population Survey.

3.2 Calibration and Data

3.2.1 Vehicle Parameters

The simulations would be most complete if they included every single type, make and model of vehicle available in the market. However, since it is infeasible to do so, we divide all vehicles into six types for simplicity (and practicality): used compact vehicle, used large vehicle, new compact vehicle, new mid to full-size vehicle, new SUV vehicle and new hybrid vehicle. The comfort parameter associated with each type of vehicle is a stylized composite of comfort, vehicle interior passenger capacity, cargo capacity data from Espey and Nair (2005) [32] and manufacturer websites[1] since the dataset does not include all vehicle models and categories (it excludes SUVs completely).

The annualized fixed cost of owning a new vehicle is compiled from Edmunds.com's True Cost to Own®tool which includes costs of depreciation, financing, insurance, taxes and fees, fuel, maintenance and repairs excluding the costs from fuel since it is considered a variable cost.[2] For each vehicle, we take an average of this cost over the first five years of ownership. The calibrated cost parameters utilized in the simulation are composites of various representative/bestselling models within each vehicle type to represent each type as accurately as possible. In addition, parameters for used vehicles are more difficult to calibrate given the variety of models and age of vehicles in the used car market. Therefore, we will use two stylized representative used vehicle types: used compact vehicle and used large vehicle[3]. Fuel efficiency (MPG) is calculated using the same representative/bestselling models in each vehicle category based on Environmental Protection Agency tests[4]. The following table summarizes the calibration factors for our simulation:

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[1]Espey and Nair (2005) collected data from Consumer Reports and Ward's Automotive Report websites regarding vehicle crash test ratings, comfort, safety, reliability, etc. for approximately 130 vehicles. They kindly allowed us to use their dataset. In addition, it is augmented with vehicle interior passenger and cargo capacity data from manufacturer websites.

[2]Edmunds is a private company which has provided consumers with an independent source of new and used vehicle information, specifications and pricing guidelines through printed booklets since 1966, and it launched Edmunds.com online in 1996.

[3]The Bureau of Transportation Statistics reports that in 2005 the median age of vehicles in the U.S. is 8.9 years. Since this number includes all vehicles, it is skewed lower. We will assume a representative used vehicle that is 10 years old, 90% as comfortable, 50% as costly (fixed cost) and 90% as fuel efficient as new vehicles of the same size. Used large vehicles include both mid to full-size vehicles and SUVs

[4]Source: `http://www.fueleconomy.gov`

Vehicle Type	Examples	Comfort	Annual Fixed Cost	MPG
Used Compact		2.25	$2,350	29.7
Used Large		8.1	$3,350	14.4
New Compact	Honda Civic	2.5	$4,050	33
New Mid to Full	Ford Taurus	5.5	$5,600	24.5
New SUV	Ford Explorer	12.5	$6,700	16
New Hybrid	Toyota Prius	2.5	$6,000	40

Table 1: Calibration parameters (Source: Calibration and calculations)

3.2.2 Income Distribution Data

Income distribution in the United States is readily available from the annual Current Population Survey by the U.S. Census Bureau. Since there is no evidence of dramatic shifts in income distribution over the past decade in the U.S., we will take our income distribution data from the 2007 Annual Social and Economic Supplement of the Current Population Survey to represent the population. Table 2 shows a summary of the household income distribution.

One extension of our theoretical model is to account for heterogeneity in household structures and how different types of households perceive comfort in different types of vehicles. As a stylized exercise, in simulation specification 2, we use some anecdotal and casual observations to determine the comfort parameters as a function of the baseline comfort parameters previously established for each type of household.

Households that have no children are considered as the baseline household with baseline comfort parameters. Households which have children tend to place higher comfort value on larger vehicles with more cargo and passenger capacity, and also value reliability more (thus, lowering the comfort parameter for used vehicles). On the other hand, households with a household head aged 65 or above tend to place higher value on reliability and accessibility. It has been shown in economics and marketing literature that “young people find it easier to adapt to new technologies than older people” (Weinberg 2004). Thus, we will assume that senior households place a lower comfort value on new hybrid vehicles due to the fact that it is a relatively new technology. Table 2 summarizes the comfort parameters of heterogenous household structures.

Vehicle Type	**Baseline Comfort**	**w/ Children** $h = 1$	**w/out Children** $h = 2$	**Senior** $h = 3$
Used Compact	2.25	1.125	2.25	2.25
Used Large	8.1	24.3	8.1	12.15
New Compact	2.5	0.625	2.5	1.25
New Mid to Full	5.5	8.25	5.5	6.6
New SUV	12.5	37.5	12.5	18.75
New Hybrid	2.5	0.5	2.5	2

Table 2: Heterogeneous Comfort Parameters for Different Household Structures (Source: Calibrated calculations)

3.2.3 Vehicle Sales Data

In order to calibrate the simulation, we need data describing the market of vehicle sales. The sales in this market is composed of both new vehicles and used vehicles. According to the Bureau of Transportation Statistics, the total number of vehicles sold or leased fluctuates between approximately 55 million to 61 million from year 1996 to 2006. During this period, the market share of used vehicles has remained at around 70 percent. Although it would helpful to be able to distinguish the exact type of vehicle purchased in used car transactions, we are unfortunately unable to obtain such detailed data at this time.

Household Income	All Households (1000s)		w/ Children $h = 1$ (1000s)	w/out Children $h = 2$ (1000s)	Senior $h = 3$ (1000s)
\$0 - \$9999	8,689	7.49%	2,226	4,005	2,458
\$10000 - \$19999	13,726	11.83%	3,301	4,598	5,827
\$20000 - \$29999	13,521	11.66%	3,595	5,451	4,475
\$30000 - \$39999	12,698	10.95%	4,032	5,632	3,034
\$40000 - \$49999	10,951	9.44%	3,808	5,171	1,972
\$50000 - \$59999	9,530	8.21%	3,459	4,709	1,362
\$60000 - \$69999	7,889	6.80%	3,098	3,848	943
\$70000 - \$79999	6,904	5.95%	2,848	3,245	811
\$80000 - \$89999	5,441	4.69%	2,329	2,609	503
\$90000 - \$99999	4,510	3.89%	1,915	2,200	395
\$100000 - up	22,151	19.09%	9,625	10,578	1,948
Total	116,010		40,236	52,046	23,728
			34.68%	44.86%	20.45%

Table 3: 2007 U.S. Household Income Distribution (Source: U.S. Census Bureau, Current Population Survey, 2007 Annual Social and Economic Supplement)

	2002	**2003**	**2004**	**2005**	**2006**	**2007**
Used Vehicles	43025000	43572000	42545000	44138000	42566000	41418000
	71.91%	72.36%	71.61%	72.26%	72.06%	70.74%
New Vehicles	8534128	8551955	11378802	11365134	11362171	10795441
	28.09%	27.64%	28.39%	27.74%	27.94%	29.26%
Compact	1448315	1632689	1661442	1740400	1906692	1798321
	16.97%	19.09%	14.60%	15.31%	16.78%	16.66%
Mid to Full-size	2976678	2688513	2723655	2800204	2730855	2696485
	34.88%	31.44%	23.94%	24.64%	24.03%	24.98%
SUV	4086800	4204958	6910597	6618782	6472760	5961654
	47.89%	49.17%	60.73%	58.24%	56.97%	55.22%
Hybrid	22335	25795	83108	205748	251864	338981
	0.26%	0.30%	0.73%	1.81%	2.22%	3.14%
Total Sales	51559128	52123955	53923802	55503134	53928171	52213441

Table 4: Summary of all vehicle sales data in the U.S. (Source: National Automobile Dealer Association and Bureau of Transportation Statistics)

New vehicle sales data is more readily available. The National Automobile Dealers Association publishes annual aggregate data showing the market shares of each major automobile manufacturer in the U.S. This information is summarized in Table 3.

From this data, we are able to conclude that three major U.S manufacturers based in Detroit including Chrysler, Ford and General Motors along with two Japanese manufacturers including Toyota and Honda generate between 79 to 86 percent of all new vehicle sales in the country for the past 10 years. We then collected data from published manufacturer press releases that detail the sales numbers for each make and model and further categorized each vehicle into one of the four vehicle types (new compact vehicle, new mid to full-size vehicle, new SUV and new hybrid vehicle) for each of these five major producers as shown in Table 4. As national average gasoline price increased from $1.34 per gallon in 2002 to $1.85 in 2004 (a 38% increase)[5], the purchase of new compact and mid to full-size vehicles decreased while the purchase of new SUVs increased from 48.89% to 60.73% of all new vehicle sales. When the price of gasoline rose above a national average of $2.00, we observe a reversal of purchasing patterns. As the price of gasoline increased from $2.27 per gallon in 2005 to $2.81 in 2007, we see an increase in the purchase of new compact and hybrid vehicles whereas the purchase of new SUVs declined significantly. The price of gasoline increases to a dramatic $3.26 per gallon in 2008 and then drops back to $2.35 in 2009. These large fluctuations in energy prices may have significant effects on vehicle technology adoption. Future research may include an expansion of our model with additional data from years 2008, 2009 and beyond on income distribution, household demographics, vehicle sales and energy prices.

Although we observe an overall pattern of consumers switching towards purchasing more energy-efficient vehicles (smaller vehicles or hybrid vehicles) as energy price increases, we do not observe the same pattern within the three major U.S. manufacturers' portfolios. In each of these manufacturers' sales portfolio, we consistently observe that more than half of their sales depended on new SUVs and no apparent shift towards compact vehicles. We observe that the total market share of American-produced vehicles has declined steadily from 73.11% of all new vehicle sales in 1996 to 54.89% in 2006. We will later compare simulated aggregate consumer adoption estimations with the above presented data.

[5]Source: U.S. Energy Information Administration (`http://www.eia.doe.gov/emeu/steo/pub/fsheets/real_prices.xls`, retrieved on August 1, 2008 and August 6, 2010.)

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Chrysler	16.23%	15.23%	16.15%	15.62%	14.54%	13.28%	13.11%	12.79%	13.08%	13.60%	12.98%
Ford	25.46%	25.16%	24.84%	24.36%	23.91%	22.87%	21.27%	20.67%	19.39%	18.34%	17.26%
GM	31.42%	31.29%	29.41%	29.44%	28.31%	28.34%	28.63%	28.35%	27.61%	26.30%	24.65%
American	73.11%	71.68%	70.40%	69.42%	66.76%	64.49%	63.01%	61.81%	60.09%	58.24%	54.89%
Toyota	7.68%	8.13%	8.76%	8.73%	9.33%	10.17%	10.44%	11.22%	12.21%	13.34%	15.41%
Honda	5.59%	6.22%	6.50%	6.37%	6.68%	7.05%	7.42%	8.11%	8.27%	8.63%	9.15%
Nissan	4.97%	4.81%	3.99%	4.01%	4.34%	4.11%	4.40%	4.78%	5.07%	6.36%	6.18%
VW	1.08%	1.14%	1.72%	2.26%	2.51%	2.56%	2.52%	2.34%	1.98%	1.81%	1.97%
Other	7.57%	8.03%	8.64%	9.21%	10.38%	11.62%	12.21%	11.74%	12.38%	11.62%	12.41%
Foreign	26.89%	28.32%	29.60%	30.58%	33.24%	35.51%	36.99%	38.19%	39.91%	41.76%	45.11%

Table 5: U.S. New Vehicle Market Shares by Manufacturer. (Source: National Automobile Dealer Association)

	2002		2003		2004		2005		2006		2007	
Compact	1743850	18.17%	1904511	19.79%	1915203	15.22%	1946801	15.91%	2095496	17.40%	1974342	17.13%
Mid to Full	3499769	36.47%	3142606	32.65%	3081318	24.48%	3217014	26.29%	3229753	26.82%	2991284	25.95%
SUV	4331284	45.13%	4551803	47.29%	7507231	59.64%	6865080	56.11%	6464278	53.68%	6223853	53.99%
Hybrid	22335	0.23%	25795	0.27%	83108	0.66%	205748	1.68%	251864	2.09%	338981	2.94%
Total	9597238		9624715		12586860		12234643		12041391		11528460	

Table 6: U.S. New Vehicle Sales of the Top Five Manufacturers by Vehicle Type. (Source: Manufacturer press releases)

		2002		2003		2004	
Chrysler	**Compact**	264378	16.15%	227860	14.82%	229431	13.99%
	Mid to Full	396942	24.25%	329935	21.46%	367113	22.39%
	SUV	975402	59.59%	979719	63.72%	1043414	63.62%
	Total	1636722		1537514		1639958	
Ford	**Compact**	295535	13.57%	271822	13.13%	256724	12.31%
	Mid to Full	818626	37.60%	725915	35.06%	614387	29.47%
	SUV	1063110	48.83%	1072760	51.81%	1211021	58.08%
	Hybrid	0	0.00%	0	0.00%	2963	0.14%
	Total	2177271		2070497		2085095	
GM	**Compact**	535117	17.50%	685832	22.31%	646827	11.38%
	Mid to Full	1158750	37.89%	1033448	33.62%	1029179	18.11%
	SUV	1364542	44.62%	1354748	44.07%	4008276	70.52%
	Total	3058409		3074028		5684282	
Honda	**Compact**	343295	27.52%	342896	25.41%	335930	24.09%
	Mid to Full	492858	39.50%	475840	35.26%	481031	34.50%
	SUV	409231	32.80%	529718	39.25%	551109	39.53%
	Hybrid	2216	0.18%	1168	0.09%	26154	1.88%
	Total	1247600		1349622		1394224	
Toyota	**Compact**	305525	20.68%	376101	23.61%	446291	25.03%
	Mid to Full	632593	42.82%	577468	36.25%	589608	33.06%
	SUV	518999	35.13%	614858	38.60%	693411	38.88%
	Hybrid	20119	1.36%	24627	1.55%	53991	3.03%
	Total	1477236		1593054		1783301	

Table 7: U.S. New Vehicle Sales by Manufacturer and Vehicle Type. (Source: Manufacturer press releases)

		2005		2006		2007	
Chrysler	**Compact**	247072	14.01%	248113	14.85%	200664	12.23%
	Mid to Full	431809	24.48%	418693	25.06%	447115	27.26%
	SUV	1085058	61.51%	1003792	60.09%	992601	60.51%
	Total	1763939		1670598		1640380	
Ford	**Compact**	222281	12.61%	211353	12.84%	201129	13.59%
	Mid to Full	639091	36.26%	710251	43.15%	495928	33.50%
	SUV	885389	50.23%	701769	42.64%	758127	51.21%
	Hybrid	15880	0.90%	22549	1.37%	25108	1.70%
	Total	1762641		1645922		1480292	
GM	**Compact**	624124	11.72%	582683	11.59%	542961	11.68%
	Mid to Full	1027618	19.29%	1029818	20.49%	956178	20.57%
	SUV	3675611	69.00%	3413639	67.92%	3148889	67.75%
	Total	5327353		5026140		4648028	
Honda	**Compact**	338216	23.82%	368350	25.24%	388285	25.74%
	Mid to Full	456038	32.12%	437963	30.02%	457935	30.35%
	SUV	582057	41.00%	615215	42.16%	626532	41.53%
	Hybrid	43356	3.05%	37573	2.58%	35983	2.38%
	Total	1419667		1459101		1508735	
Toyota	**Compact**	515108	26.27%	684997	30.59%	641303	28.49%
	Mid to Full	662458	33.78%	633028	28.26%	634128	28.17%
	SUV	636965	32.48%	729863	32.59%	697704	30.99%
	Hybrid	146512	7.47%	191742	8.56%	277890	12.35%
	Total	1961043		2239630		2251025	

Table 8: U.S. New Vehicle Sales by Manufacturer and Vehicle Type. (Source: Manufacturer press releases)

3.3 Environmental Awareness

Environmental awareness is one portion of the household utility function that may affect how households choose different type of vehicles. Even during periods of stable energy prices and constant public policy regarding energy efficiency, the introduction of alternative fuel vehicles and the increasing popularity of these types of vehicles can be observed in historical vehicle sales data. To account for this effect, we will use several methods to proxy for environmental awareness of the population.

First, we examine the simulated results without the environmental awareness extension. Next, we hypothesize that environmental awareness is a factor of energy prices, when energy price increases, consumers become more aware of the environment and obtain higher utility from more energy-efficient vehicles. Lastly, we obtained survey data regarding the public awareness and understanding of environmental problems such as global warming to serve as proxies of consumer environmental awareness from Nisbet and Myers (2007) [62]. Two survey questions were chosen for the completeness of survey data through the recent years as summarized below:

1. "Next, thinking about the issue of global warming, sometimes called the 'greenhouse effect', how well do you feel you understand this issue-would you say very well, fairly well, not very well, or not at all?"

	2001	**2002**	**2003**	**2004**	**2005**	**2007**
Very well(%)	15	17	15	18	16	22
Fairly well (%)	54	52	53	50	54	54
Not very well (%)	24	25	27	26	24	19
Not at all (%)	6	6	5	6	6	4
N	1060	1006	1003	1005	1004	1009

Table 9: Source - Gallup annual environment poll

2. "I'm going to read you a list of environmental problems, as I read each one, please tell me if you personally worry about this problem a great deal, a fair amount, only a little, or not at all. First, how much do you personally worry about ... the 'greenhouse effect' or global warming?"

	2001	**2002**	**2003**	**2004**	**2006**	**2007**
Great deal (%)	33	29	28	28	36	41
Fair amount (%)	30	29	30	25	26	24
Only a little (%)	22	23	23	28	21	18
Not at all (%)	13	17	17	19	15	16
N	1060	1006	1003	1005	1000	1009

Table 10: Source - Gallup annual environment poll

From first glance at Figure 2, the simulated percentage of sales in each of the four specifications appear to closely follow the actual sales data in terms of magnitude as well as general trend. Upon a closer examination of the resulting graphs, it becomes apparent that the increasing popularity of hybrid vehicles can only be account for when we account for an environmental awareness factor in consumers' utility functions.

We further plotted the simulated versus observed percentage of vehicle sales data to better calibrate the simulation model in Figure 3. In addition to improvements in the prediction of hybrid vehicle sales, the specifications using energy prices and percentage of people who care a great deal about global warming as proxies yield higher R^2 values (0.9504 and 0.9595, respectively).

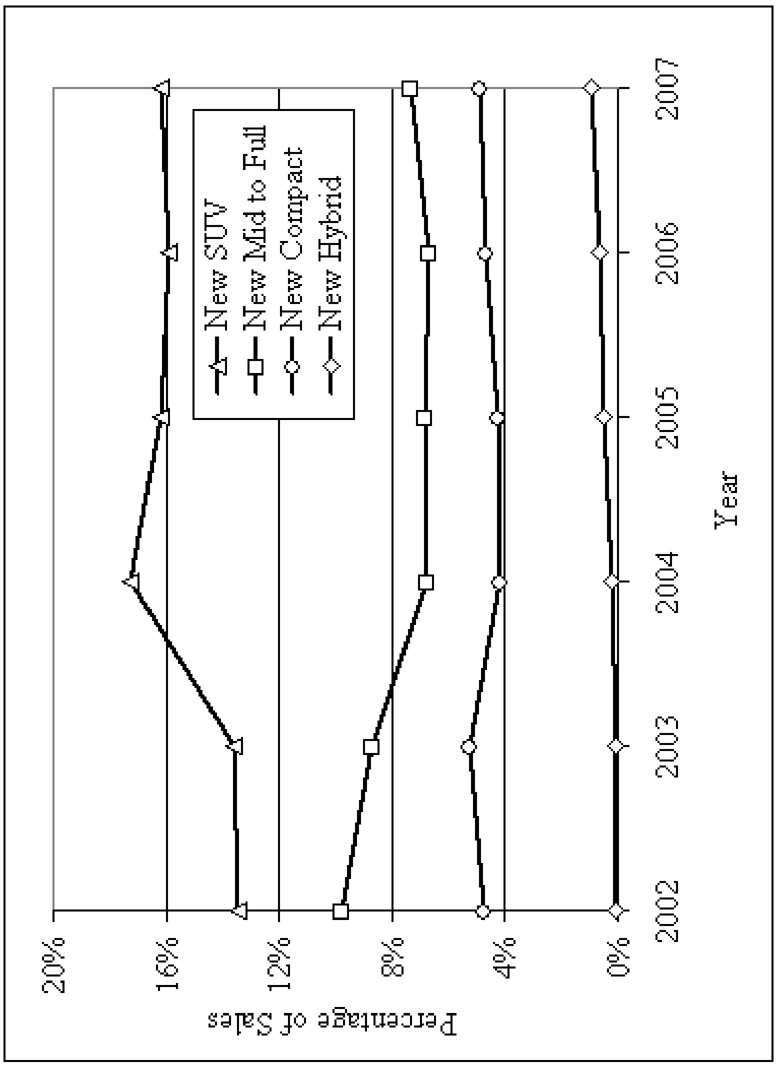
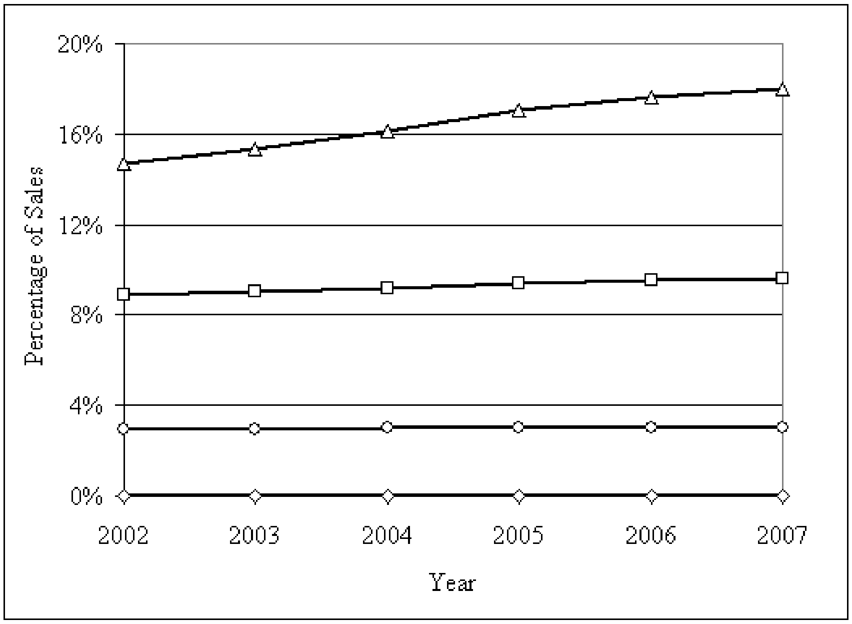
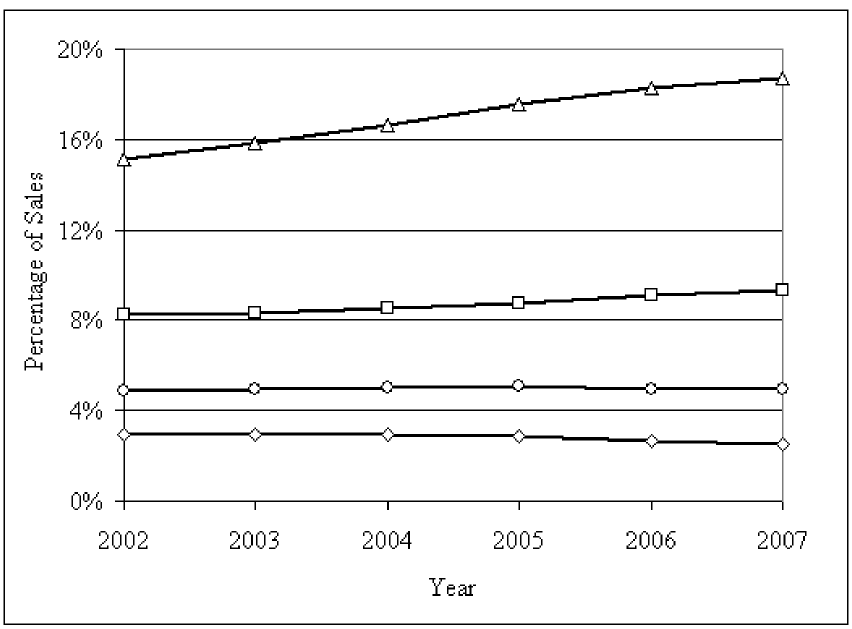


Figure 1: Observed percentage of sales

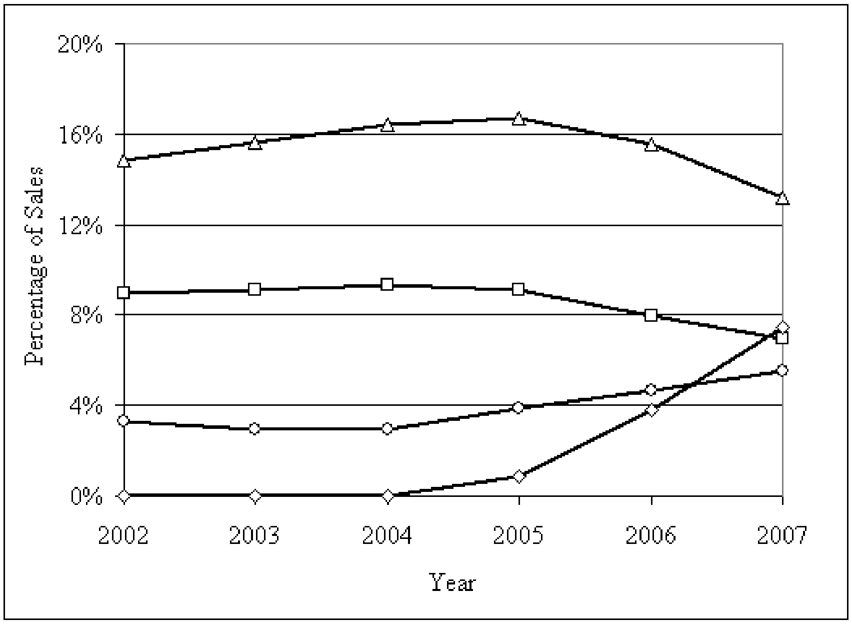


(a) No Proxy

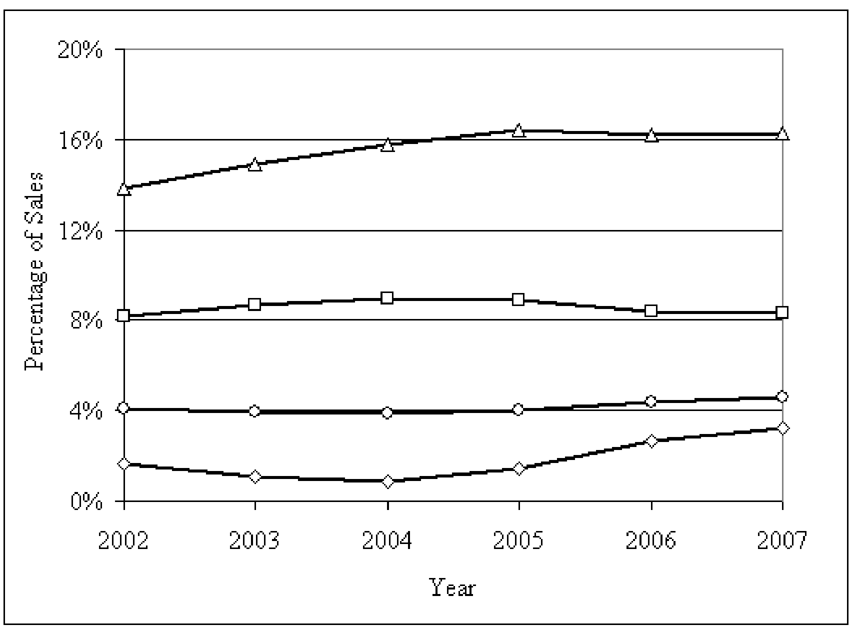


(b) Proxy: Energy prices

Figure 2: Results of calibrated simulations with all extensions using different proxies for environmental awareness

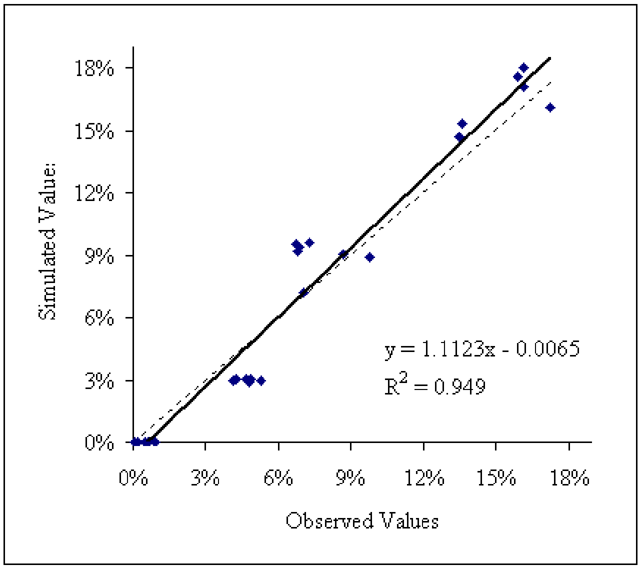


(c) Proxy: Percentage of people who understand global warming well or fairly well from Gallup annual Environment poll

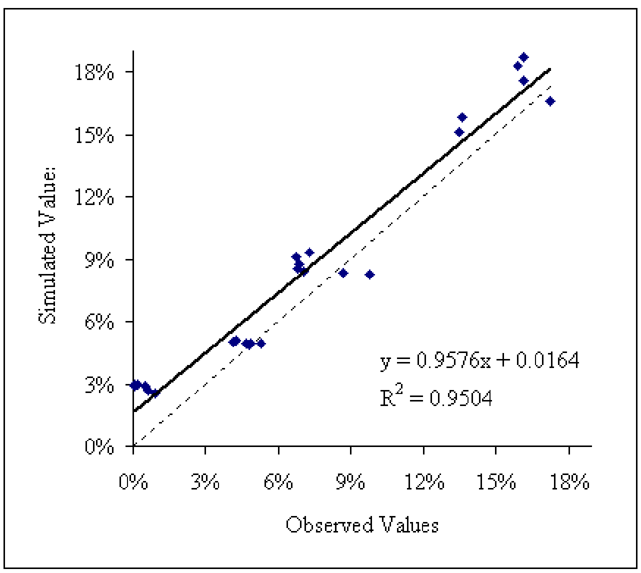


(d) Proxy: Percentage of people who worry about global warming a great deal from Gallup annual Environment poll

Figure 2: Results of calibrated simulations with all extensions using different proxies for environmental awareness

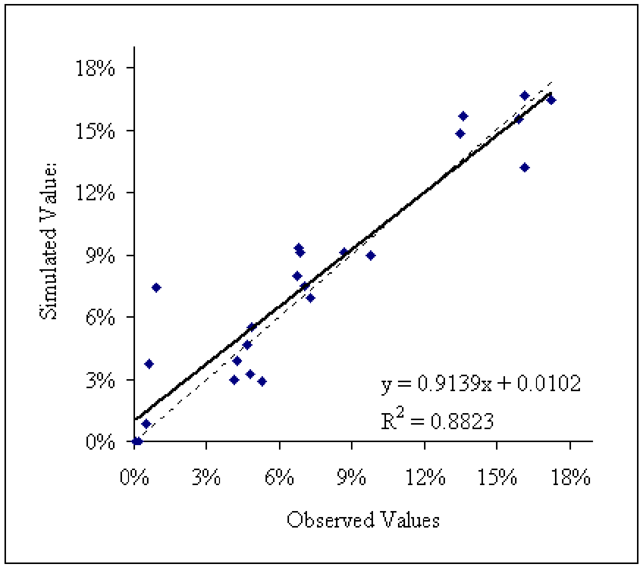


(a) No Proxy

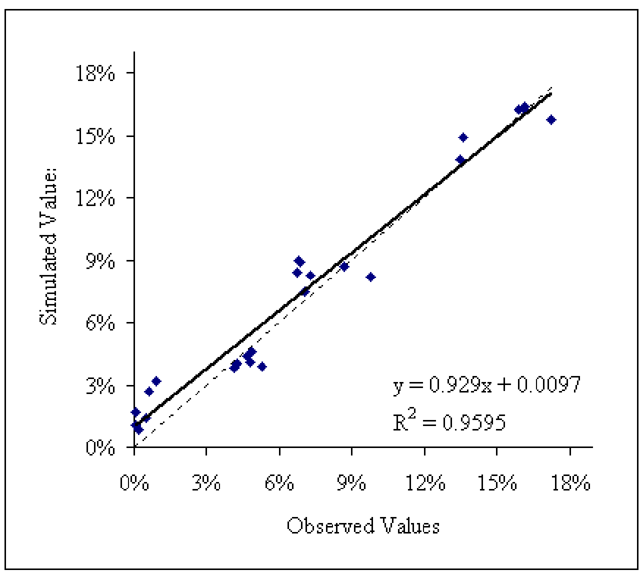


(b) Proxy: Energy prices

Figure 3: Simulated vs observed percentage of vehicle sales using different proxies for environmental awareness. The dotted line is the 1:1 line and the solid line is the linearly fitted line.



(c) Proxy: Percentage of people who understand global warming well or fairly well from Gallup annual Environment poll



(d) Proxy: Percentage of people who worry about global warming a great deal from Gallup annual Environment poll

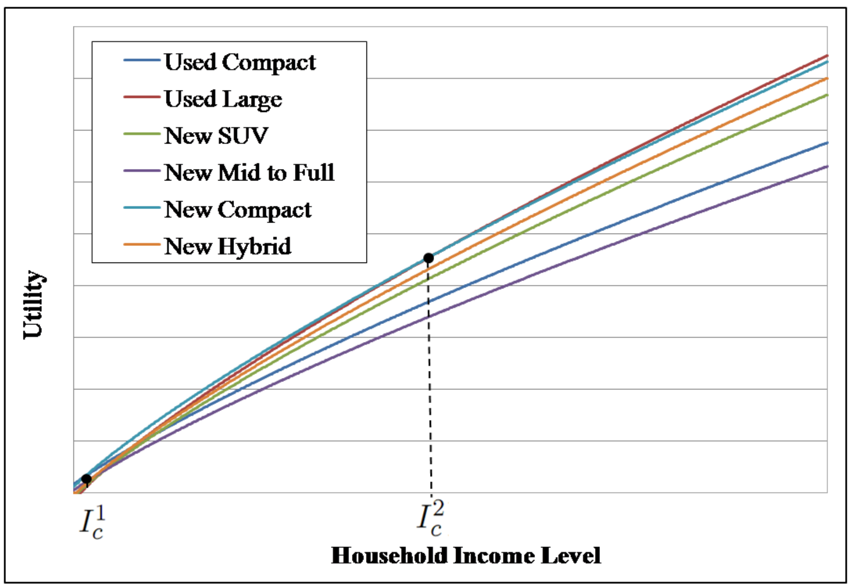
Figure 3: Simulated vs observed percentage of vehicle sales using different proxies for environmental awareness. The dotted line is the 1:1 line and the solid line is the linearly fitted line.

3.4 Calibration Results

The final simulation specification includes the extensions for comfort, environmental awareness as well as household structures to account for further household heterogeneity. For the years that we have sales data (2002-2007), we observe that the simulation closely follows the pattern of the observed actual percentage of sales in each specification. The calculated R^2 between the simulated data and the actual data ranges from 0.8823 to 0.9595 which indicates that the simulation explains approximately 88.23% to 95.95% of the variance in the actual data as shown in Figure 3. This test indicates that the simulation model is able to predict the percentage of sales reasonably well, especially when using the percentage of people who worry about global warming a great deal as the environmental awareness proxy. Within the first two specifications of the calibrated simulations (with no proxy and energy prices as proxy for environmental awareness) in Figures 2a, 2b, 3a and 3b, although the calculated R^2 value are high (0.949 and 0.9504), the simulations are only able to forecast the general trend of more purchases of new SUVs and new mid to full-size vehicles, but are unable to capture the dynamic fluctuations in Figure 1. This indicates to us that there must be some aspect of households' decisions that is not captured in these two specifications. One possible explanation is that consumer attitudes towards environmental awareness are fluctuating due to news or new published studies regarding climate change which we incorporate into the next two specifications. In the two specifications where environmental awareness survey data is used as proxies for environmental awareness in Figures 2c, 2d, 3c and 3d, the calibrated simulation is able to achieve a calculated R^2 of 0.9595 in the last specification and is able to capture the lower adoption percentages of larger vehicles in the later periods as well as the increasing rate of adoption of new hybrid vehicles. Therefore, we will choose the model specification shown in Figure 3d as the basis for simulating future scenarios.

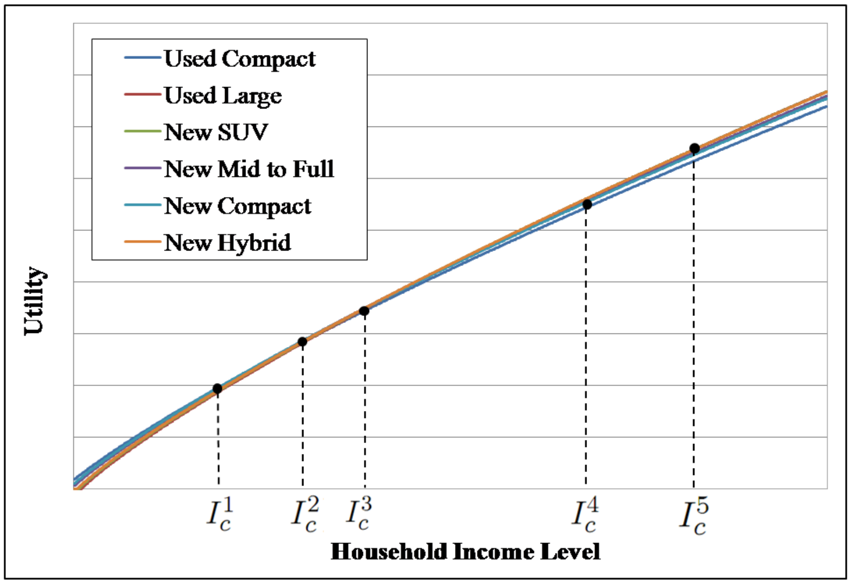
Using the chosen calibration specification, we plot the utility of households given their choice of vehicle type (j) and optimal choice of miles to travel at different income levels on Figure 4 for 2002. In Figure 4a, we observe the utility levels of households with children ($h = 1$). The three utility curves that represent the choice of used compact vehicles, used large vehicles and new SUVs form the utility frontier and represents the behavior of households with children within this scenario. For this particular type of household structure, all other types of vehicle are dominated by these three types. In other words, households with income levels lower than the critical income level (I_c^1) of approximately \$7,600 optimally chooses used compact vehicles. Households with income levels higher than I_c^1 but lower than I_c^2 of \$100,000 will choose used large vehicles. Those households with incomes greater than I_c^2 will purchase new SUVs.

For households without children ($h = 2$), we observe a wider range of optimal vehicle choices in Figure 4b. The utility frontier is formed by utility curves that represent the choice of used compact vehicles, used large vehicles, new compact vehicles, new mid to full-size vehicles, new hybrid vehicles and new SUVs, in this order. The critical incomes (I_c^1 through I_c^5) are \$44,000, \$65,000, \$79,000, \$142,000 and \$160,000, respectively. This outcome is quite consistent with the casual observation that the first adopters of new technologies are often those in higher income brackets. In senior households ($h = 3$), Figure 4c shows that the utility frontier is formed by the utility functions representing used compact vehicles, used large vehicles and new SUVs. The critical income at which these households switch from used compact vehicles to used large vehicles (I_c^1) is \$19,000, and the critical income at which they switch over to new SUVs (I_c^2) is \$93,000. In later periods (years 2003 through 2007) of the simulation calibration, as energy price, environmental awareness and other parameters are changing, the critical income levels shift accordingly, leading to different percentages of adoption.

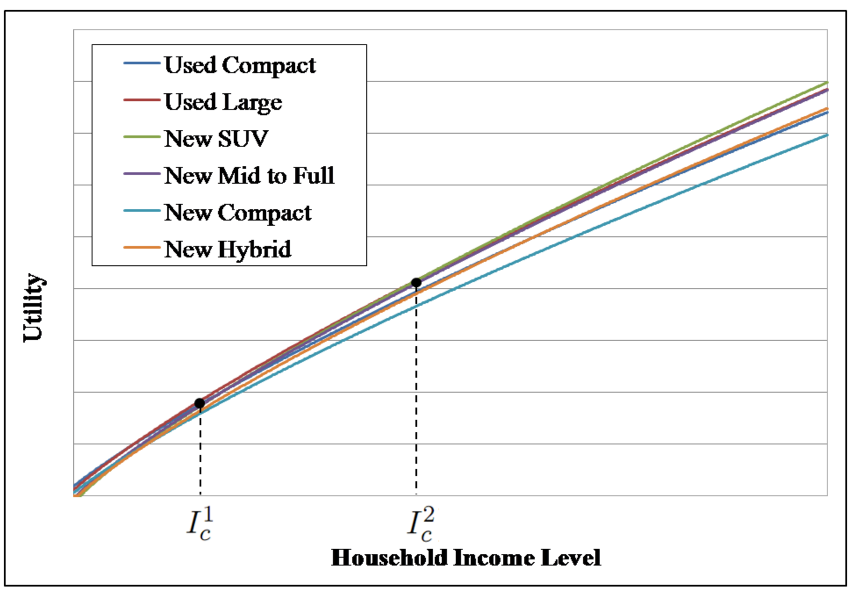


(a) Households with children (h=1)

Figure 4: Calibrated simulation utility maximization (2002)



(b) Households without children (h=2)



(c) Households with senior heads (h=3)

Figure 4: Calibrated simulation utility maximization (2002)

Chapter 4

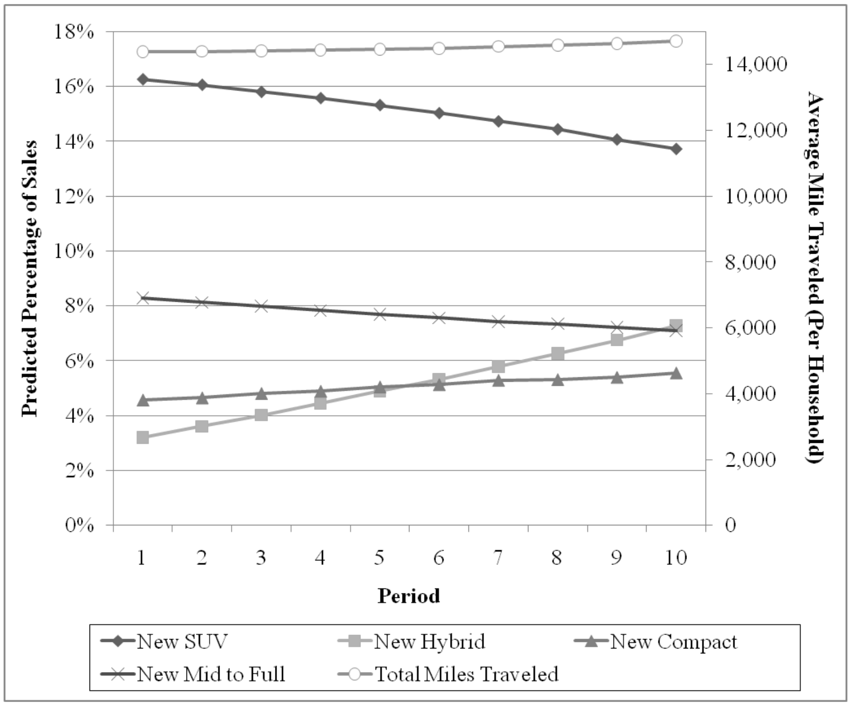
Simulated Future Scenarios - What if ...?

One of the main objectives of precisely calibrating the simulation model presented in this paper is to be able to glimpse into the future. How would fluctuating energy prices affect consumer adoption of new technologies? How would a changing demographic or income profile present a challenge to the diffusion of energy-efficient technology across the economy? Building on a theoretical foundation of consumer utility maximization and the threshold model of technology adoption/diffusion, this simulation model provides endless possibilities.

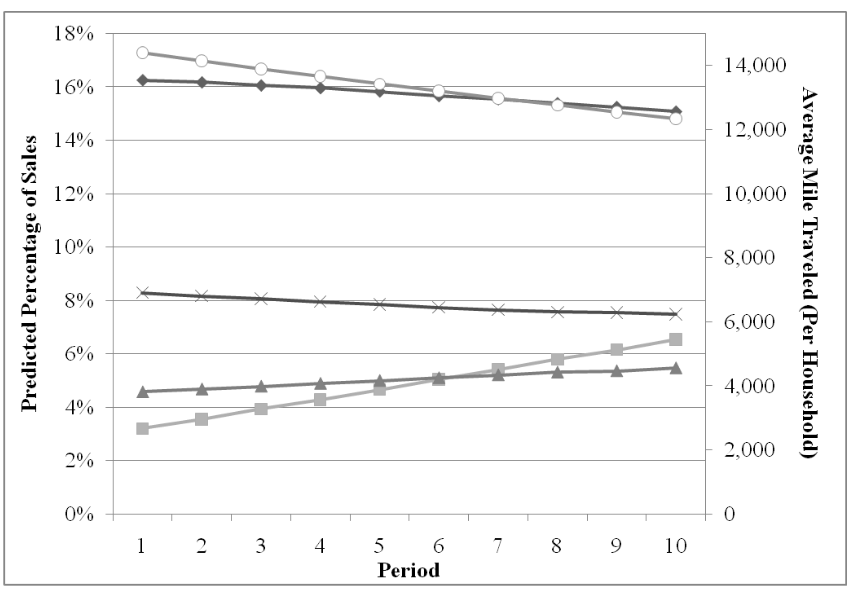
4.1 Energy Price Increases Annually

We start with the simple scenario of increasing energy prices. Assuming that all other prices remain constant, there are no changes in the composition of the population and no changes in transportation technologies, we perform simulations with energy prices increasing 1%, 3%, 5% and 10% annually. We further assume that environmental awareness (the percentage of people who worry about global warming a great deal) increases at a constant annual rate consistent with the previous years (approximately 1.7% per year).

In Figure 5, we observe some expected and unexpected results. As energy price increases, more consumers maximize utility by choosing to purchase hybrid vehicles and a decreasing percentage of the population purchases SUVs and mid to full-size vehicles. New SUV adoption starts at 16.26% in period for all specifications, and it ends up at 13.72%, 15.07%, 16.31% and 19.08% when energy price increases by 1%, 3%, 5% and 10% per period, respectively. When energy price increases by 1%

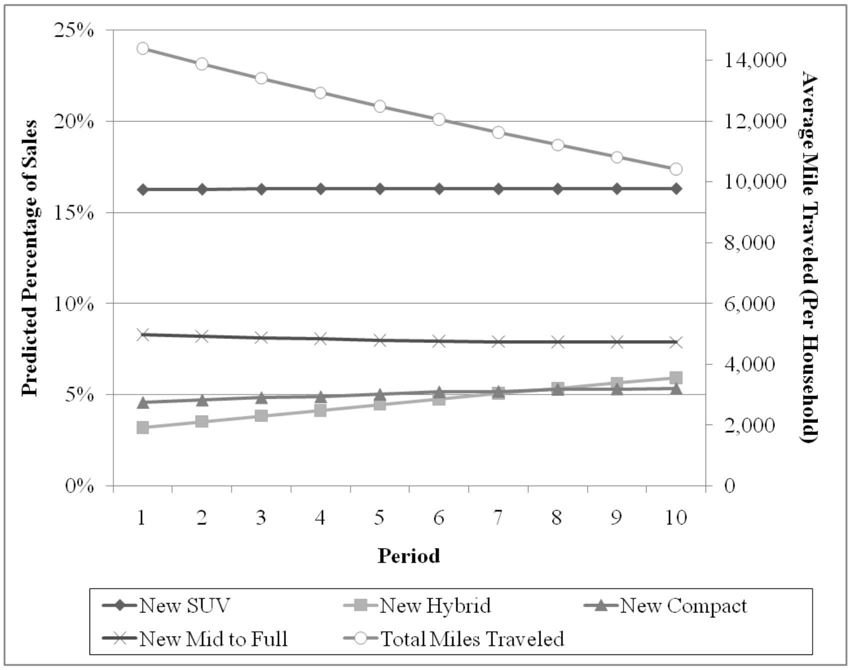


(a) 1% Annual Increase

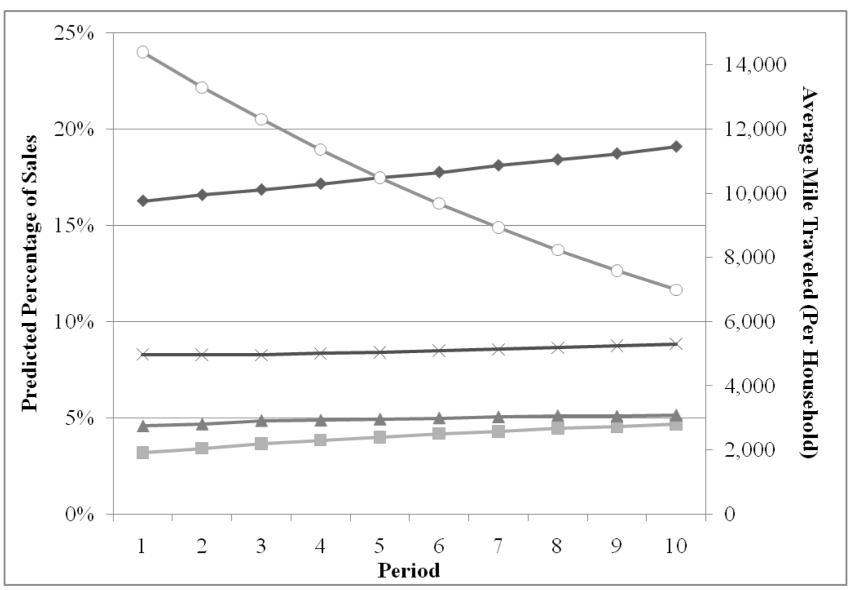


(b) 3% Annual Increase

Figure 5: Predicted percentage of sales with different annual rates of energy price increases.



(c) 5% Annual Increase



(d) 10% Annual Increase

Figure 5: Predicted percentage of sales with different annual rates of energy price increases.

per period along with increasing environmental awareness, the simulation model predicts that the percentage of all vehicle sales attributed to new SUVs decreases to 16.06%, 15.80% and 15.57% in the three periods following period 1, eventually decreasing to 13.72%. Similar household purchasing pattern is observed when energy price increases at 3% annually.An unexpected result occurs in the two cases where energy price increases 5% or more annually, we observe an increase in the purchase of SUVs and a low rate of adoption of hybrid vehicles. How could this be? Why do households purchase more fuel-consuming SUVs when the price goes up at the pump? This effect is due to the two part utility maximization behavior of households. When energy price increases by a small amount, such as 1% or 3%, households do not change their travel behavior dramatically (they still travel similar number of miles every year) which makes sense for them to adopt fuel-efficient vehicles. On the other hand, when energy price increases by larger amounts, such as 5% or 10% or more, households begin to compensate for the increasing variable cost of travel by significantly reducing their consumption of travel.

Alternatively, prominent studies in the field of urban economics from Alonso (1960) [1], Muth (1969) [61], Mills (1972) [58] and Brueckner (1987) [19] among others have examined evidence that households may prefer to relocate closer to Central Business Districts (CBD) where most economic activities occur as energy prices increase. Essentially, they illustrate a tradeoff between land rents and transportation costs, as one moves away from a CBD, land rents decrease but transportation costs increase. In this case, the net effect of energy price increases may actually lead to lower optimal number of miles if households relocate to reduce commute distance. On the other hand, it may also be true that households that move away from CBDs may reduce commute travel, but increase recreational travel and prefer large, comfortable vehicles such as the new SUV. This interaction between transportation cost and household location choices is an important consideration that we propose for future research in Chapter 6.

When energy price increases by 1% per period along with increasing environmental awareness, hybrid vehicle adoption starts at an observed 3.20% in the first period and increases to 3.61%, 4.02% and 4.44% in the next three periods, respectively. Hybrid vehicle adoption gradually reaches 7.27% of all purchases in the final period, growing at an average rate of 9.56%. One can observe similar patterns of increasing hybrid vehicle adoption when energy price increases at different rates as simulated, although the growth rate of adoption slows down to 8.28%, 7.09% and 4.27% when energy price increases at 3%, 5% and 10% annually, respectively. As energy price increases, we see a shift in the critical income level (I_c) at which households switch to buying a hybrid vehicle. The shift indicates that households with a lower income level begin to adopt the new technology, and that is one of the main factors contributing to the higher rate of adoption as energy price increases.

Surprisingly, we find that the adoption of hybrid vehicles is slower when energy price increases at a faster rate as seen more clearly in Figure 9. It is almost counter-intuitive that with higher per-mile costs, not more people switch to more energy efficient vehicles. However, the optimization mechanism is slightly more complicated in that consumers may choose to decrease the number of miles traveled when energy price increases. When the consumer travels less miles, the comfort/convenience generated from each mile provides greater marginal utility. The effect of decreasing optimal number of miles traveled dominates the effect of cheaper per-mile travel cost in hybrid vehicles when the energy price increases at a higher rate. Essentially, when energy price increases, households may maximize utility by shifting their behavioral pattern to travel less by reducing or combining unnecessary trips, carpooling, utilizing public transportation, or relocating to reduce commuting in the long run instead of opting for the more energy-efficient vehicle.

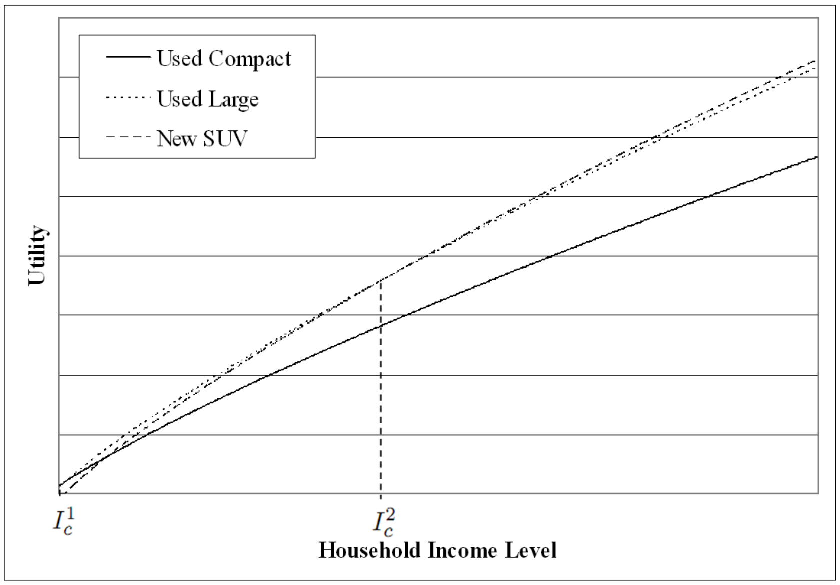
If we look at Figures 5a through 5d, we can see the pattern of miles traveled in each scenario. Households travel, on average, 14,394 miles per year according to the simulation model. When energy price increases by 1% per period, we observe that households increase the amount traveled each year, caused by the substitution towards the more energy-efficient new hybrid vehicle. In the subsequent specifications, we see an increasing trend of traveling less as energy price becomes higher, proportional to the energy price increases. The annual number of miles traveled per household drops to 12,347 miles in the last period when energy price increases by 3% per period, 10,424 miles when energy price increases by 5% and 6,990 miles when energy price increases by 10%. These decreases in household travel is equivalent to an annual rate of -1.69%, -3.52% and -7.71%, respectively. When households reduce the amount traveled each year, the marginal utility of comfort/convenience/quality becomes a much more significant factor in the vehicle adoption decision. In the last specification, households are traveling almost 50% less in period 10 than in period 1, making it more important to purchase a vehicle that would be comfortable and practical for those few miles traveled.

One might jump to the conclusion that the simulation indicates a price elasticity of demand for gasoline (or miles traveled) to be -0.56 when energy price increases by

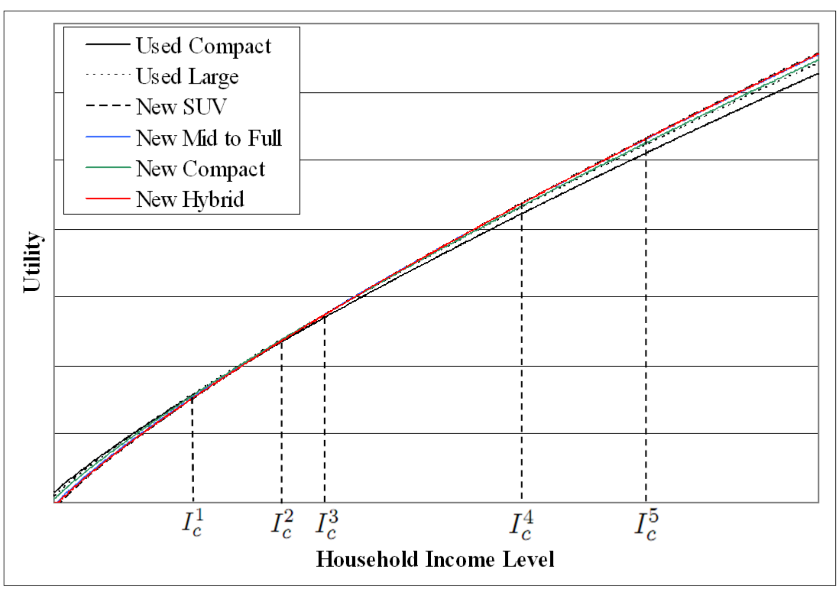
3% per period, or -0.70 when it increases by 5% per period, or -0.77 when it increases by 10% per period. Those familiar with the literature may note that this number is fluctuating and not entirely consistent with than those found in meta-analyses such as Espey (1996) [31] and Goodwin et al. (2004) [34] which range from -0.1 to -0.64 depending on if one is looking at short-run versus long-run or volume of fuel versus volume of traffic. However, it is important to remember that the case study presented here not only includes energy price increases, but also changes in the attitude towards environmental awareness. Furthermore, household travel is a utility maximizing choice dependent upon the type of vehicle adopted. This is precisely the reason that we are utilizing the simulation model instead of merely examining marginal effects. However, it is important to note that these changes in optimal miles traveled only applies to those households purchasing a vehicle and not to the vast majority of households who choose to keep their original vehicles.

Figure 6 shows the household utility maximization of the three types of household structures in the baseline period 1. In households with children (h=1), we observe that low-income households with incomes below the critical income level (I_c^1) of \$7,200 choose to purchase used compact vehicles. Mid-income households between critical income levels of \$7,200 (I_c^1) and \$90,000 (I_c^2) go with used large vehicles. Those in the upper-income households (income greater than \$90,000) choose to adopt new SUVs. Households without children (h=2) adopt a wider range of vehicles, choosing used compact vehicles, used large vehicles, new compact vehicles, new mid to full-size vehicles, new hybrid vehicles and new SUVs depending on their income levels. Figure 6b shows that the critical income levels for this type of household are \$40,200 (I_c^1), \$58,200 (I_c^2), \$71,850 (I_c^3), \$120,650 (I_c^4) and \$155,800 (I_c^5). Senior households (h=3) choose used compact vehicles if their income level falls below \$17,600 (I_c^1) shown in Figure 6c. Senior households with incomes between \$17,600 (I_c^1) and \$84,150 (I_c^2) choose used large vehicles while those with incomes above \$84,150 purchase new SUVs.

Figures 7 and 8 show the shifts in the critical incomes in the last period (period 10) between the two specifications of 1% per period energy price increase and 10% per period energy price increase. In households with children (h=1), the critical income level at which households switch from purchasing used compact vehicles to used large vehicles (I_c^1) remains almost constant in Figures 7a and 8a. They also do not differ much from period 1. When energy price increases by 10% per period, Figure 8a shows that the critical income at which households switch from used large vehicles to new SUVs (I_c^2) decreases to \$80,050 from \$90,000 in period 1. This movement of the critical income level is a reflection of the dramatic increase in energy price (variable cost of travel). We can observe a similar trend for senior households (h=3) where the critical income level between used large vehicles and new SUVs (I_c^2) decreases from \$84,150 to \$75,000 (Figures 7c and 7c). Comparing Figure 7b with Figure 6b, one can see a large shift in the critical income level (I_c^5) where households switch from new hybrids to new SUVs, increasing from \$155,800 to \$186,800. This indicates that at these rates of energy price increase, more households of this type find it more attractive to purchase new hybrid vehicles since the energy price increase does not decrease the amount traveled by a large amount. When energy price increases by 10% per period, this critical income level (I_c^5) decreases slightly to \$152,700 in the last period as displayed in Figure 8b. This indicates that at faster rates of energy price increase, households adjust their behavior to travel less, resulting in more adoption of new SUVs which provide better comfort/quality per mile traveled.

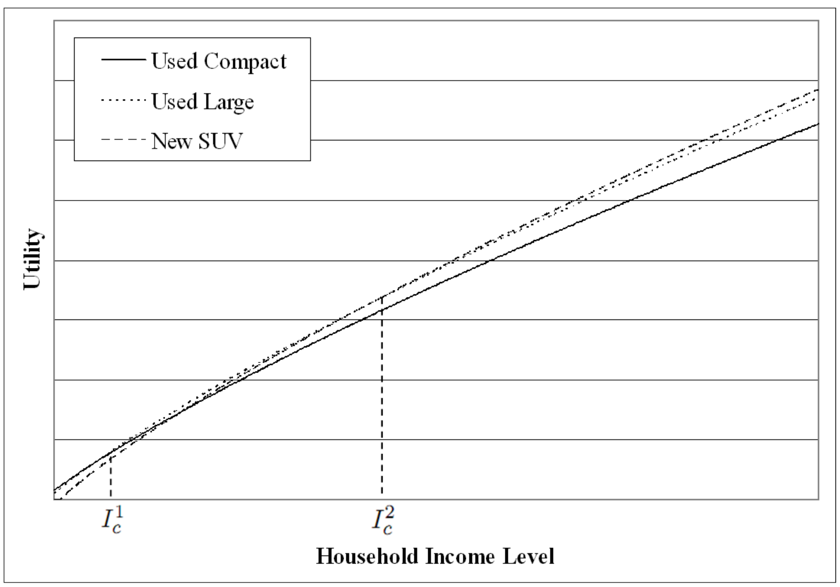


(a) Households with children (h=1)



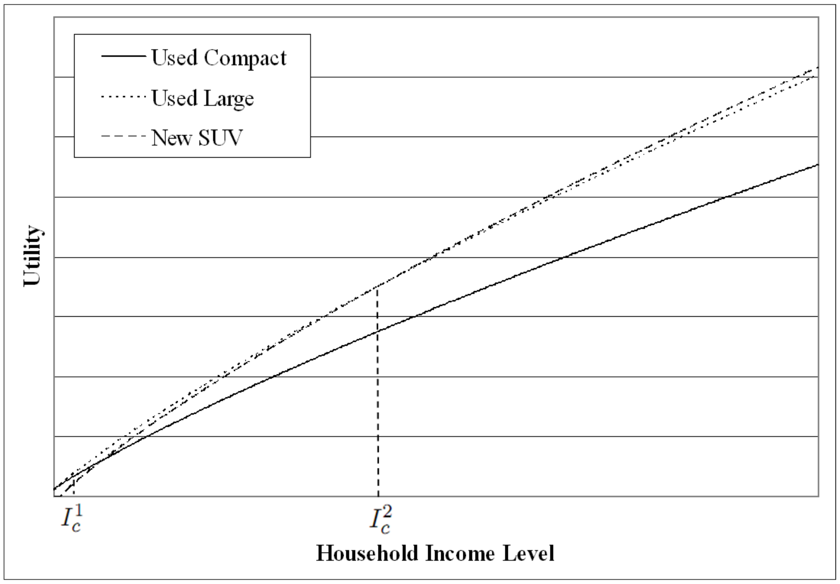
(b) Households without children (h=2)

Figure 6: Household utility maximization - Period 1.

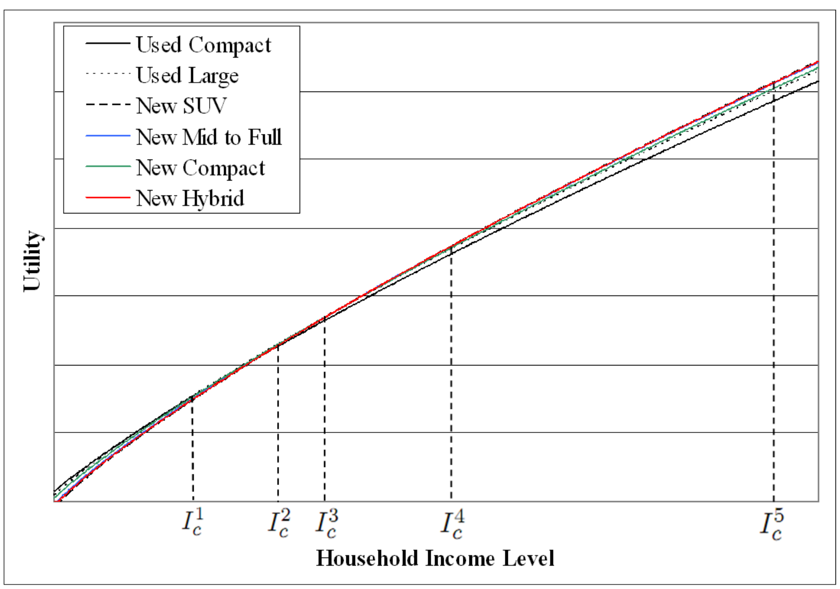


(c) Households with senior heads (h=3)

Figure 6: Household utility maximization - Period 1.

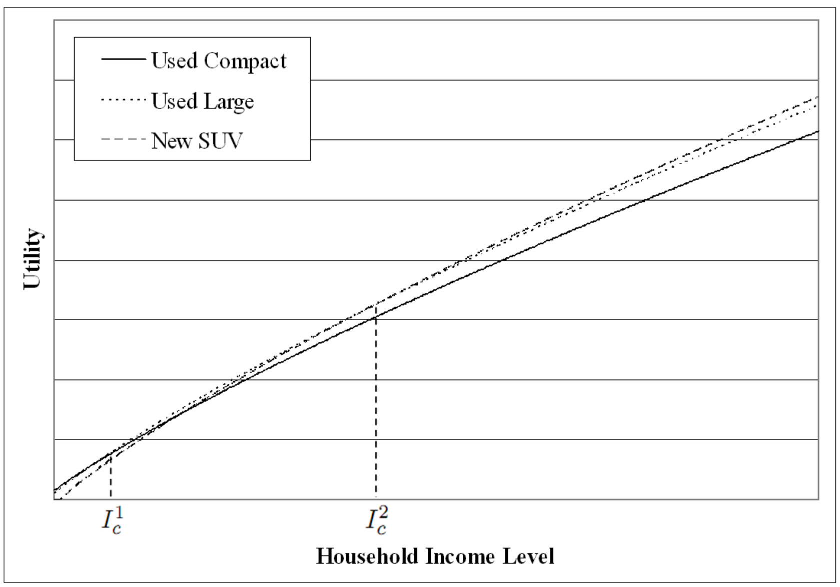


(a) Households with children (h=1)



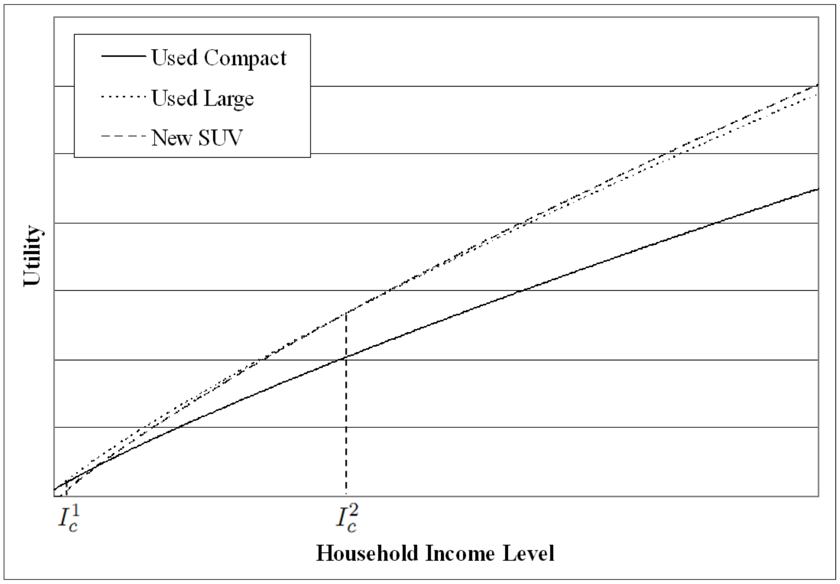
(b) Households without children (h=2)

Figure 7: Household utility maximization with 1% annual energy price increase - Period 10.

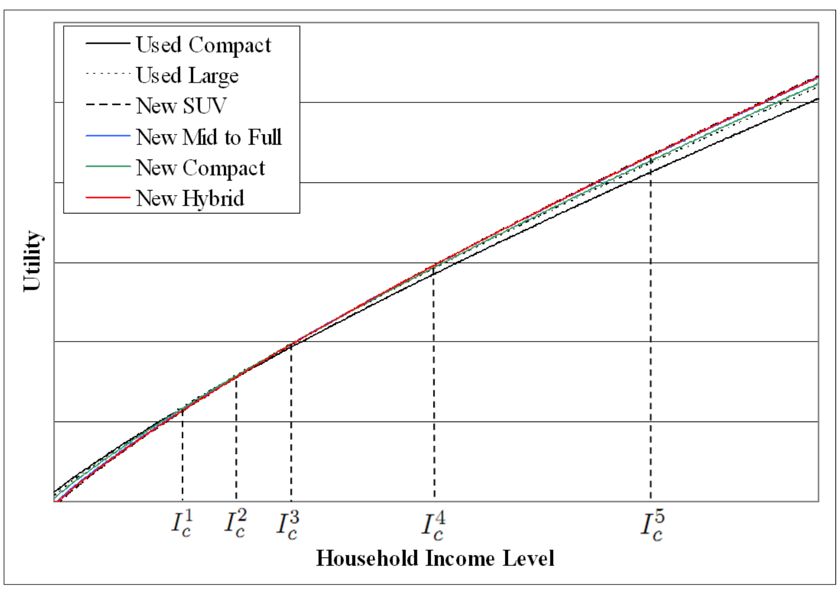


(c) Households with senior heads (h=3)

Figure 7: Household utility maximization with 1% annual energy price increase - Period 10.

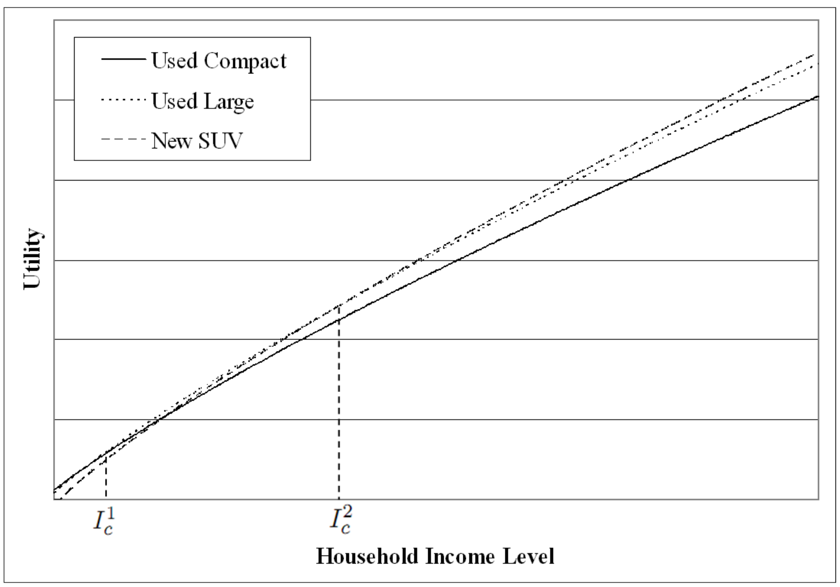


(a) Households with children (h=1)



(b) Households without children (h=2)

Figure 8: Household utility maximization with 10% annual energy price increase - Period 10.



(c) Households with senior heads (h=3)

Figure 8: Household utility maximization with 10% annual energy price increase - Period 10.

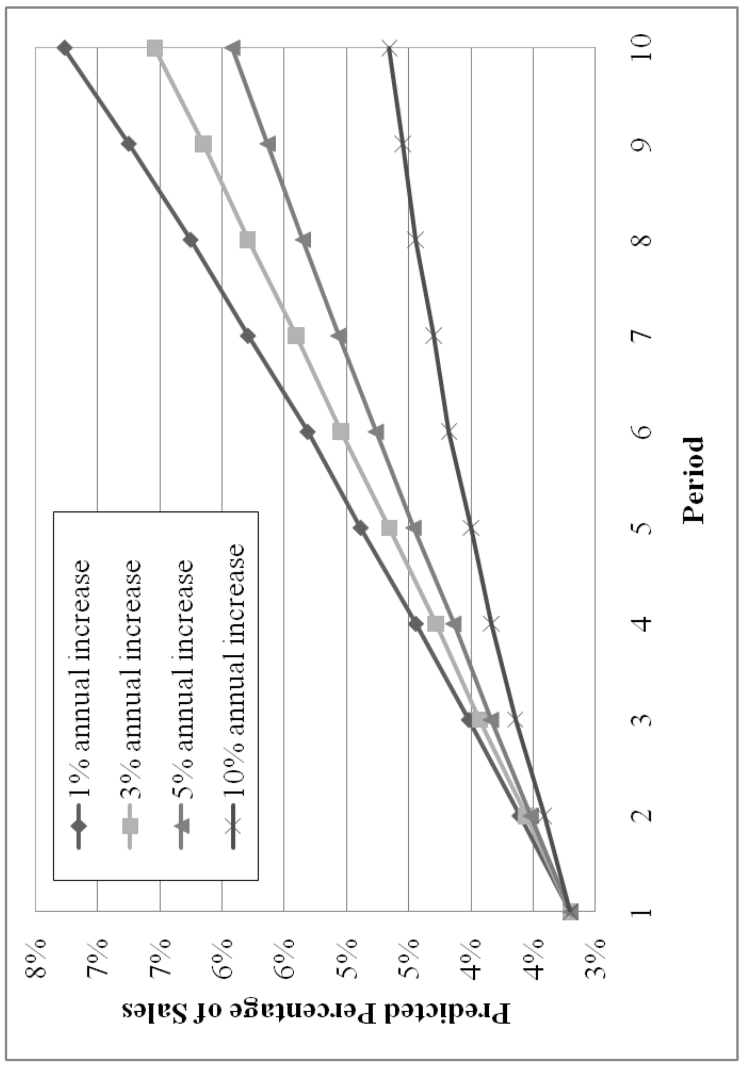


Figure 9: Predicted percentage of hybrid vehicle sales with different annual rates of energy price increases.

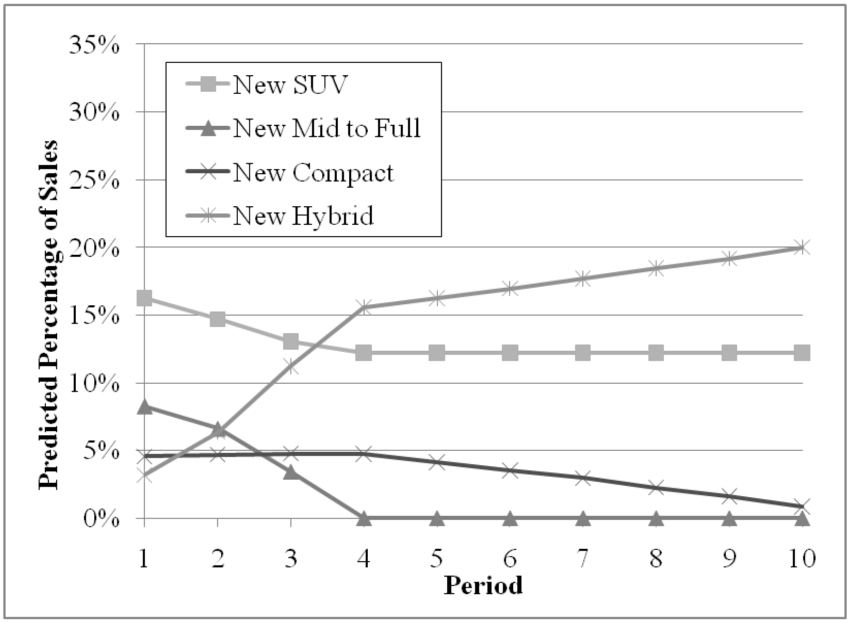
4.2 Hybrid Vehicle Price Decreases due to Learning-by-Doing

One of the key factors in the consumer choice model is the fixed price of vehicles. Conventional vehicles with gasoline combustion engines have been mass produced for decades, and they are produced using what is usually classified as a mature technology. On the other hand, hybrid vehicles and alternative fuel vehicles are considered relatively new technologies that have only been on the market since the beginning of the century. These new technologies may have significant production cost reductions (and, subsequently, price reductions) due to the learning-by-doing process, economies of scale or learning by technological progress. Of course, in reality, both the process of learning-by-doing and subsidies for hybrid or alternative fuel vehicles (see next section for a more detailed discussion of government policies) exist concurrently. For example, when the Toyota Prius first came onto the market, households purchasing the vehicle received rebates. These rebates increased the initial percentage of adoption by reducing the effective price (fixed price), allowing learning-by-doing to occur in the meanwhile. As the rebates are phased out, the learning-by-doing process may lead to lower costs of production and perhaps lower prices for consumers, resulting in more pronounced adoption in the long run even after the rebates run out.

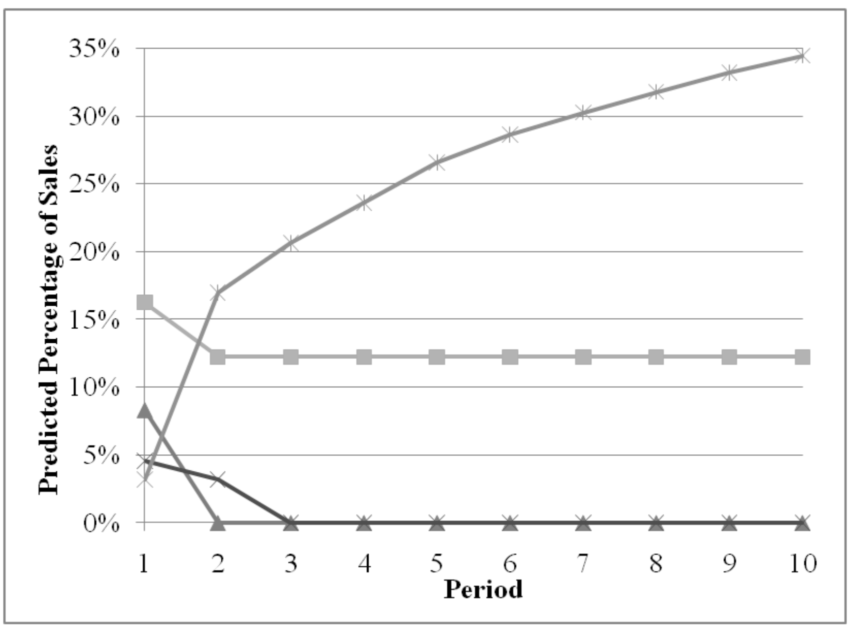
Learning-by-doing was first presented by Arrow (1962) [4] in his explanation of endogenous growth theory. This process represents a reduction in production costs as the production crew, machinery production line becomes more productive as they become more experienced. Hybrid vehicles also enjoy increasing economies of scale as their production levels have more than doubled according to the historical sales data presented in Chapter 3. In addition, government subsidies to develop clean vehicle technologies and to reduce reliance on gasoline also contribute to learning by technological progress. Although literature in this area has calculated learning rates between 5% and 20% (the percentage reduction in cost when production doubles)for various technologies (McDonald and Schrattenholzer 2001 [57], Leiby and Rubin 2003 [48]), the actual price to consumers may not directly reflect the reduction in production costs.

Given that the hybrid vehicle employs relatively new technology while other conventional vehicles employ more mature technology, we propose a scenario where the fixed cost of hybrid vehicles is decreasing for households (i.e. the price of hybrid vehicles decreases due to learning-by-doing). This simulation further assumes that other vehicle prices and attributes remain constant. The results are displayed in Figure 10. We observe significant effects of hybrid vehicle price decreases on its adoption, with adoption speed proportional to the speed of the price decrease. With a constant energy price shown in Figures 10a and 10b, the adoption of hybrid vehicles grows at an average rate of 26.63% and a dramatic 56.19% per period when the fixed cost of purchasing falls by 1% and 5% annually, respectively. In addition, as depicted in Figures 10c and 10d, we observe that the increasing energy price contributes to the adoption of hybrid vehicles as well. When energy price increases by 3% per period, the percentage of households that choose to purchase hybrid vehicles now grows at an average rate of 27.01% and 56.51% when the fixed cost of new hybrid vehicle falls by 1% and 5% annually, respectively. The main force pushing households to adopt alternatively technology here appears to be the falling fixed cost (i.e. price of the vehicle), where the increasing variable cost (i.e. energy cost) is a lesser contributing factor. This is clearly illustrated in Figure 11 where the predicted percentage of sales for new hybrid vehicles are summarized for each of the four simulated scenarios. In addition, we observe that in each scenario, the percentage of households purchasing larger vehicles such as new SUVs and new mid to full-size vehicles decrease. However, it is of interest to note that in all cases, the percentage of households purchasing new SUVs holds constant around 12% to 13%. This can be seen as the convenience and comfort of larger vehicles cannot be substituted by other types of vehicles even if it becomes increasingly expensive to operate (higher energy price) and its relative price becomes higher (lower new hybrid price through learning-by-doing).

As the new hybrid vehicle price decreases due to learning-by-doing, it attracts buyers from not only from the new large vehicle sector, but also attracts buyers who would have purchased used vehicles previously. In all scenarios, we start out with approximately 67.68% of households in the used car sector. When energy price is constant through all periods, in the last period households choosing to purchase used vehicles drops to 66.88% with 1% annual decrease in new hybrid price and 53.30% with 5% annual decrease in new hybrid price. When energy price increases by 3% per period, the percentage drop to 65.45% and 52.15% in the last period with 1% and 5% annual decrease in new hybrid vehicle price, respectively. Affordability clearly drives the adoption of new vehicle technology adoption as illustrated here.

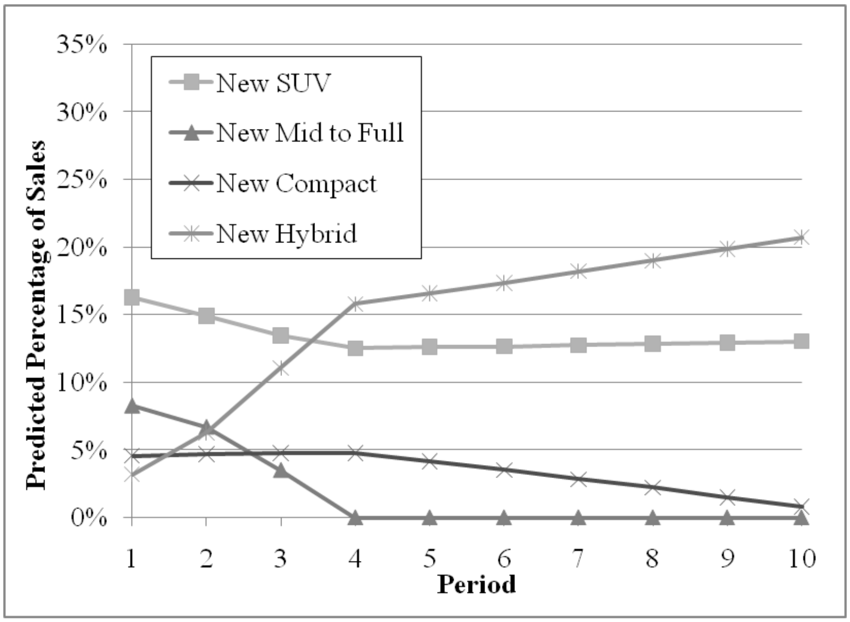


(a) 1% annual decrease with no energy price change

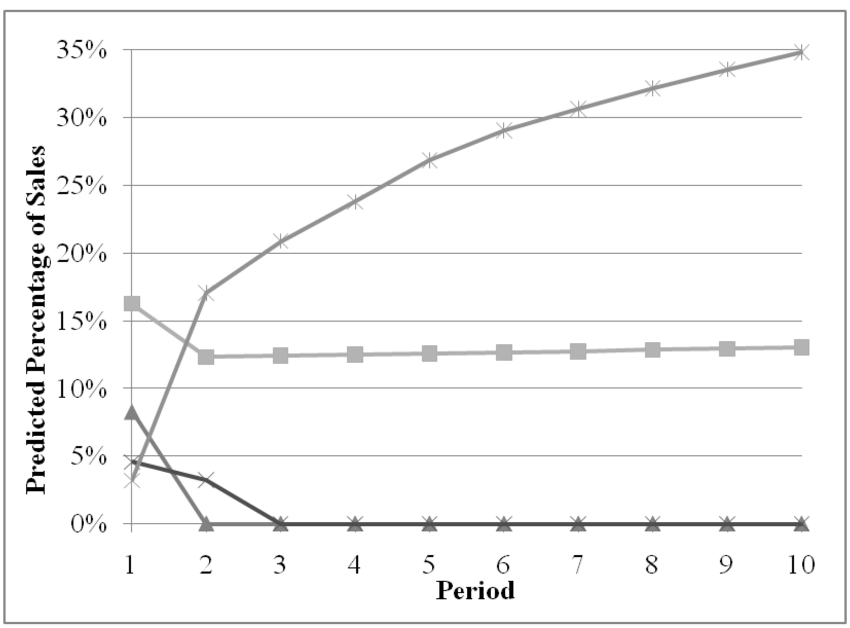


(b) 5% annual decrease with no energy price change

Figure 10: Predicted percentage of sales with different annual rates of hybrid vehicle price decreases and energy price increases.



(c) 1% annual decrease with 3% energy price increase



(d) 5% annual decrease with 3% energy price increase

Figure 10: Predicted percentage of sales with different annual rates of hybrid vehicle price decreases and energy price increases.

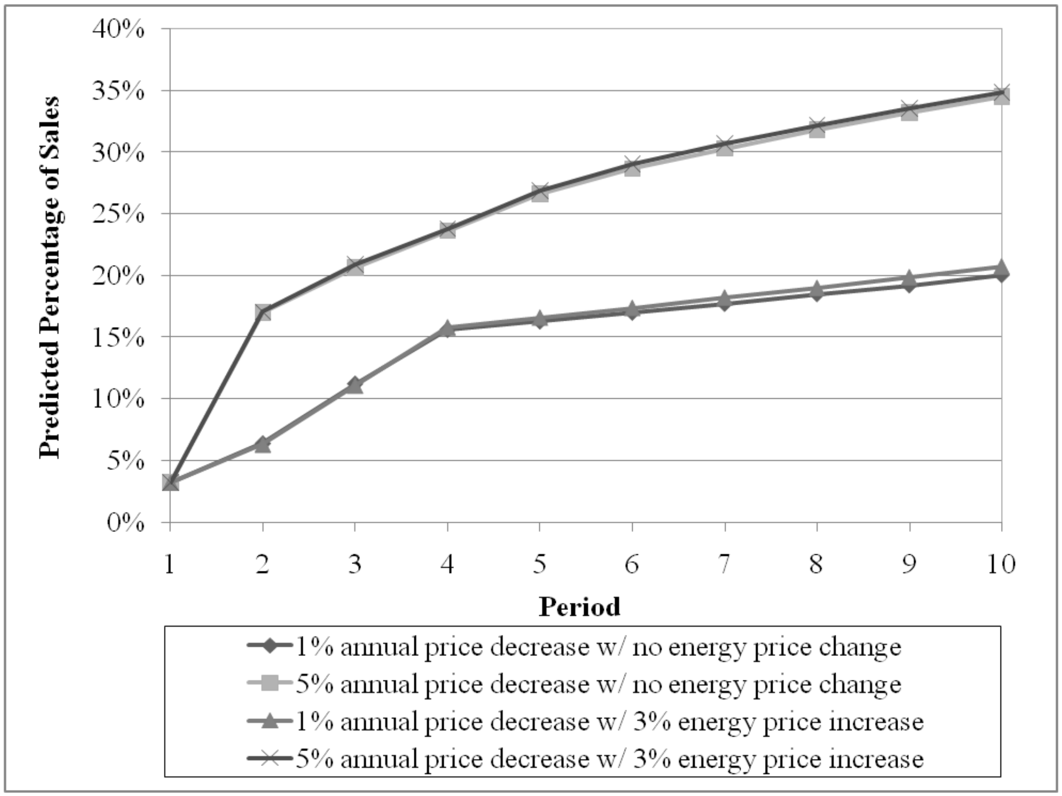


Figure 11: Predicted percentage of hybrid vehicle sales with different annual rates of hybrid vehicle price decreases and energy price increases.

4.3 Government Policy Changes

Government policies often play a large role in shaping the adoption of new technologies through taxes or subsidies. As mentioned previously, the diffusion of new technology follows the S-shaped curve where early adoption is followed by the takeoff period. Public policies may potentially serve to speed up the process in which the technology enters the takeoff period which exhibits a high adoption rate. We will examine the impact of changes in current gasoline taxes as well as subsidies in the form of tax credits or deductions on hybrid vehicle adoption.

4.3.1 Tax Incentives for Hybrid Vehicles

Adoption of new technologies is often facilitated or encouraged through labeling programs, tax incentives, promotional pricing or rebate programs by the government on both federal and state levels. For example, the Energy Star program jointly administered by the U.S. Environmental Protection Agency and the U.S. Department of Energy provides certification and labeling of energy efficient consumer and business products. Such Energy Star programs, since its inception in 1992, have encouraged the adoption of energy efficient products in categories such as household appliances, heating and cooling equipment, lighting, water heaters, etc. (including up to 40,000 individual products by 2,400 manufacturers as of 2008) through rebates at the federal and state levels. Similarly, the U.S. Department of Energy has implemented federal tax deductions or credits to encourage the adoption of alternative fuel vehicles such as hybrid vehicles.

Prior to 2006, the government offered up to $2,000 in tax deductions if households purchased one of the models listed in Table 11 in tax years 2003 through 2005. The actual savings to households depends on the tax bracket of the household, ranging from $200 (federal tax bracket of 10%) to $700 (federal tax bracket of 35%) if the household purchased an eligible hybrid vehicle before the end of 2005.

Pursuant to the Energy Policy Act of 2005, federal tax credits were introduced to encompass a larger number of hybrid vehicle models with credits ranging from $250 to $3,400 depending on the level of energy efficiency. However, the credit is subject to phase out for manufacturers who have sold more than 60,000 hybrid vehicles (i.e. Toyota and Honda hybrid vehicles are no longer eligible in 2009). The following simulation shows the effects of a tax credit ranging from $500 to $10,000

Make	**Model**	**Eligible Model Years**
Ford	Escape Hybrid	2005-2006
Honda	Accord Hybrid	2005
Honda	Civic Hybrid	2003-2005
Honda	Insight	2000-2005
Lexus	RX 400h	2006
Mercury	Mariner Hybrid	2006
Toyota	Highlander Hybrid	2006
Toyota	Prius	2001-2005

Table 11: Vehicles eligible for tax deductions prior to 2006

on the purchase of different types of vehicles (annualized in the same fashion as vehicle fixed costs over a five year period as \$100 to \$2,000).

Figure 12 shows that even small amounts of tax credits changes the perceived fixed cost of purchasing hybrid vehicles, shifting the critical income level at which households switch to hybrid vehicles down. As the tax credit increases, we observe increasing adoption of hybrid vehicles in lieu of compact vehicles and mid to full-size vehicles because the tax credits makes hybrids cheap enough to afford. When the hybrid tax credit is equal to \$3,000 (annualized as \$600), new hybrid vehicles and new SUVs completely dominate the market as the other vehicle types no longer possess a fixed cost, comfort and variable cost combination that is attractive to any households. Notice that a significant percentage of households still purchase new SUVs because new hybrid vehicles cannot act as an appropriate substitute for the size and comfort of the larger SUV. The results are consistent with the fixed cost effect derived in previous chapters: when fixed cost decreases, the critical income levels within which households choose to purchase hybrids shifts, resulting in higher adoption (or aggregate flow demand). The simulation presents proof that hybrid tax credits can be extremely effective in encouraging the adoption of alternative fuel vehicles.

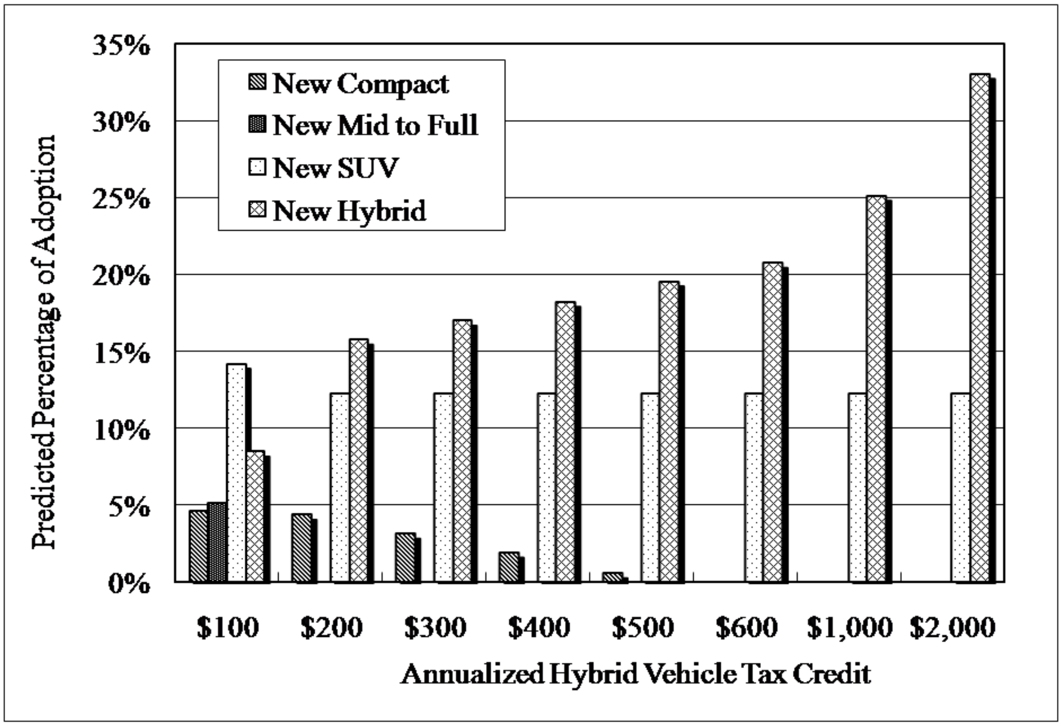


Figure 12: Predicted percentage of hybrid vehicle sales with tax credits

4.3.2 Gasoline Tax

According to the American Petroleum Institute, the mean gasoline tax is $0.456 per gallon in the first quarter of 2009, of which $0.184 represents the federal tax and $0.272 represents the mean state tax. How would adjusting the gasoline tax impact the adoption of new vehicle technology? Numerous studies have looked at the impact of gasoline taxes on gasoline consumption (Bento et al. 2009 [9], Hausman and Newey 1995 [39] and West 2004 [86]). For example, Bento et al. (2009) [9] finds that every $0.01 per gallon increase in the gas tax decreases the equilibrium consumption of gas by 0.2%. However, we would like to look at how vehicle adoption and diffusion is influenced by changes in gas tax policy. It is important to note that the impact on consumer behavior is dependent upon whether we observe a temporary or permanent adjustment of the tax. If the tax change is a permanent adjustment, we should be able to observe a variable cost effect on the purchase of vehicles along with a positive/negative effect (with a decrease/increase of the gas tax) on the optimal number of miles traveled by the household. In this simulation,

Gas Tax Policy	Tax per gallon	New SUV	New Hybrid	New Compact	New Mid to Full
Normal Tax	$0.456	16.26%	3.20%	4.57%	8.29%
Total Tax Holiday	$0.000	15.25%	3.55%	4.50%	7.98%
State Tax Holiday	$0.186	15.68%	3.39%	4.58%	8.07%
Federal Tax Holiday	$0.272	15.90%	3.32%	4.55%	8.14%
Double Normal Tax	$0.912	17.11%	2.91%	4.59%	8.52%
Double State Tax	$0.726	16.81%	3.02%	4.59%	8.41%
Double Federal Tax	$0.640	16.64%	3.06%	4.57%	8.40%

Table 12: Predicted percentage of all vehicle sales with various tax policy scenarios

we assume all adjustments are permanent in nature.

In Table 12, we observe the unexpected result of more adoption of hybrid vehicles as a result of tax holidays and less adoption as a result of doubling taxes. This may appear to be counterintuitive, but it is important to keep in mind the simultaneous choices of the optimal type of vehicle to purchase and optimal miles to travel made by each household. The permanent tax holiday means lower variable cost of travel which leads to an increase in the number of miles traveled. When the household travels more miles, the marginal utility of comfort/convenience diminishes. As the optimal number of miles traveled increases, the combination of the effect of diminishing marginal utility of comfort and the increased importance of fuel efficiency lead to greater adoption of hybrid vehicles.

Another effect not included in the simulation is the effect of signalling through the gasoline tax. If it is the case that when the government increases the tax (leading to lower hybrid adoption shown by the simulation), it is signalling a greater concern for the environment, then it would be reasonable to see increasing environmental awareness with a gas tax increase. Combining the tax increase with environmental awareness increase could possibly lead to greater adoption of hybrid vehicles depending on how much environmental awareness increases.

4.4 Income Distribution Shifts

Economic growth in a country tends to increase the real income levels of the population which shifts the income distribution. In this section, we attempt to dissect the effects of an overall income increase in the economy on the adoption of vehicle technologies. In the U.S., Piketty and Saez (2003) [64] use IRS tax statistics to examine real household income growth. They show that from 1993 to 2008[1] households experienced a 1.3% annual gain in average real household income (including realized capital gains but before individual taxes). It makes sense to take a look at how these changes to an economy might affect the adoption and diffusion of vehicle technology. For simplicity, we assume that these income increases are uniform across the distribution (we consider changes in income distribution shape in the next section). Again, we assume all other population characteristics (including distribution of income), demographics and vehicle attributes remain constant to specifically isolate the effects of the income distribution increase.

As different regions may experience different rates of real household income increases, we conduct six separate simulations that show different rates of income distribution shift including 1% increase per period, 5%, 10%, 15%, 20% and 25% per period. Figure 13 shows the percentage of all vehicle sales as predicted by the simulation model. The results show the Income Distribution Effect $\left(\frac{\partial G_t(I_c^{j+1})}{\partial t} - \frac{\partial G_t(I_c^t)}{\partial t}\right)$ derived from the theoretical model that represents the shift of households into (or out of) the critical range of income levels for each type of vehicle. As the economy becomes wealthier, more households shift into the critical range of income levels for the more expensive vehicles such as the new SUV or new hybrid vehicle. In the first period, 16.26% of households choose to purchase new SUVs, 3.20% new hybrid vehicles, 4.57% new compact vehicles and 8.29% new mid to full-size vehicles. In the first two scenarios where income distribution increases by 1% and 5% per period shown in Figures 13a and 13b, we observe slight decreases in new hybrid vehicle purchases to 3.06% and 2.67% in the final period, respectively. We also observe corresponding small increases in new SUVs to 17.68%, new compact vehicles to 4.73% and new mid to full-size vehicles to 8.66% when income distribution shifts by 1% per period. When income distribution shifts by 5% per period, we start seeing significant growth in the purchase of new SUVs, increasing to 17.98%, 19.72%, 21.46% and 23.19% in the periods following the first, equating to an average 9.29% annual

[1] The data series are updated online regularly. The latest update from July 2010 reflects IRS tax data through 2008 and was accessed at `http://elsa.berkeley.edu/~saez/`.

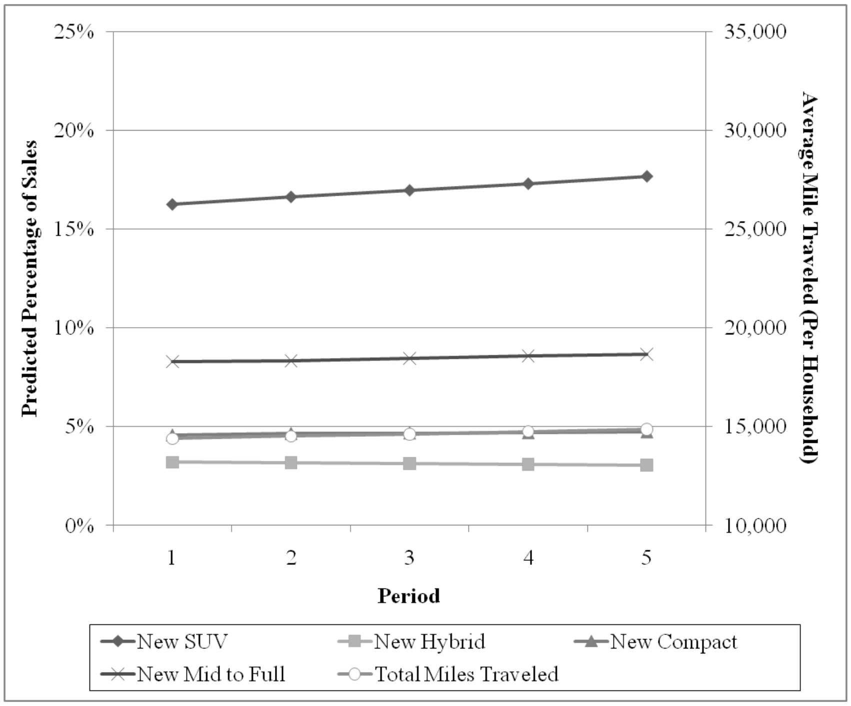
growth in the adoption of new SUVs.

The results in the next four specifications (income distribution shifts by 10% to 25% per period) show more dramatic changes in the adoption patterns of vehicles. At lower levels of income increases in the economy such as 1%, 5% increase and earlier periods of 10%, 15%, 20% and 25% increase, we see a common pattern of lower new hybrid vehicle adoption seen in Figure 14 compared to the first period. It appears that new hybrid vehicle adoption only starts to pick up when the overall income distribution has shifted by a total of approximately 30%. This effect continues to be consistent with the Income Distribution Effect and can be explained by the movement of a larger percentage of the population into the critical income range for purchasing new hybrid vehicles. The main determinant of how many households move into this range is essentially the shape of the income distribution curve. The new hybrid vehicle purchase percentage reaches 4.20%, 5.15%, 5.49% and 5.62% in the final period in each of the four specifications.

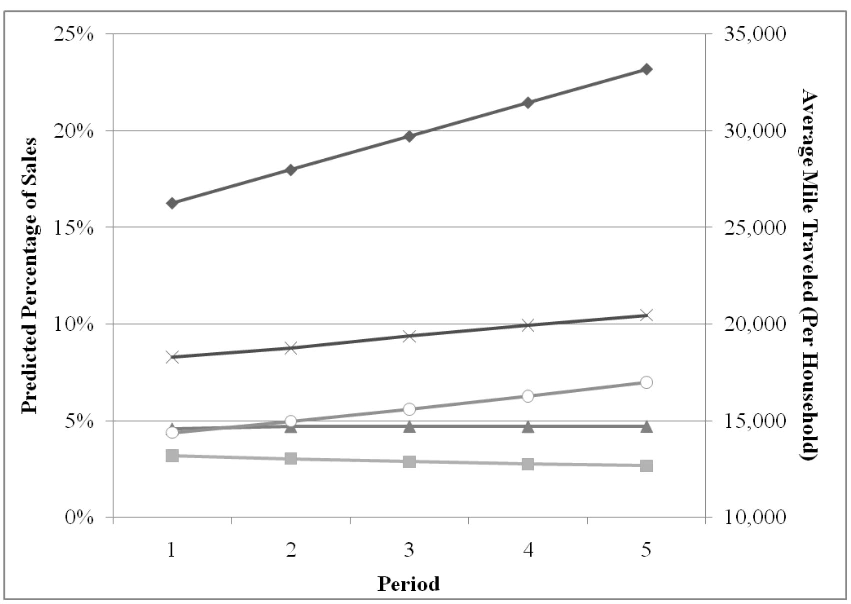
The growth rate of new SUV adoption increases in these four scenarios with larger rates of income distribution shift (10% to 25% per period). The resulting predicted percentages are much more dramatic compared with those for new hybrid vehicles. When income distribution shifts by 10% per period, the average annual growth rate of new SUV adoption is 16.07% (Figure 13c), resulting in 29.46% of all purchases in the final period. In the scenario where income distribution grows by 15% per period, the average annual growth rate of new SUV purchases becomes 22.35%, resulting in 36.30% in the final period (Figure 13d). When income grows by 20%, the average annual growth rate is even higher at 28.15%, and the percentage of new SUV sales is 43.60% in period 5 (Figure 13e). This rate increases to 33.29% if income distribution shifts by 25% per period shown in Figure 13f, indicating a significant increase in the number of households that shift into the critical income range for new SUVs. In the last period of this specification, 50.84% of all vehicle purchases are new SUVs.

There are two effects in play that cause the high percentage of new SUV purchases. One effect is the Income Distribution Effect which means households are becoming wealthier and more of them are within the critical income range to purchase more expensive vehicles. The second effect involves the household utility maximizing choice of miles to travel. In Figures 13a through 13f, we observe that an average household household travels about 14,394 miles per year in the first baseline period. As households become wealthier, they appear to want to travel more, indicating that travel is indeed a normal good. In the six specifications of 1% to 25% per period increases in the income distribution, we observe an increase to 14,874, 16,992, 20,485, 24,281, 28,298 and 32,782 miles in the last period, respectively. Although the increasing number of miles traveled mean that households would want to minimize their variable cost of travel by switching to a more fuel-efficient car, this effect is dominated by the Income Distribution Effect.

Although economies such as the U.S. or European nations have not experienced such large income distribution shifts in the recent years, developing economies such as China or India or economies that benefit from the discovery of significant natural resources are prime candidates for large income distribution shifts. If such income distribution shifts are coupled with large populations, then the effects of vehicle adoption and utilization are posed to be significant in terms of fuel consumption, local environmental issues (i.e. congestion or air quality) and global environmental problems (i.e. global warming). In addition, rapid periods of economic growth may be coupled with growing economic inequality which alters the shape of the income distribution. We will explore this possibility in section 4.5.

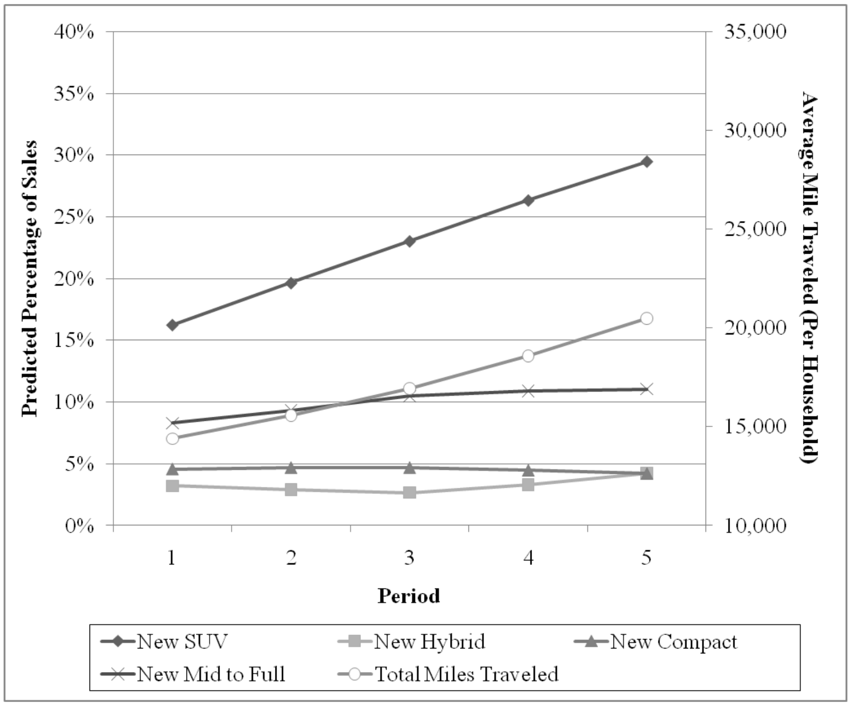


(a) 1% annual increase

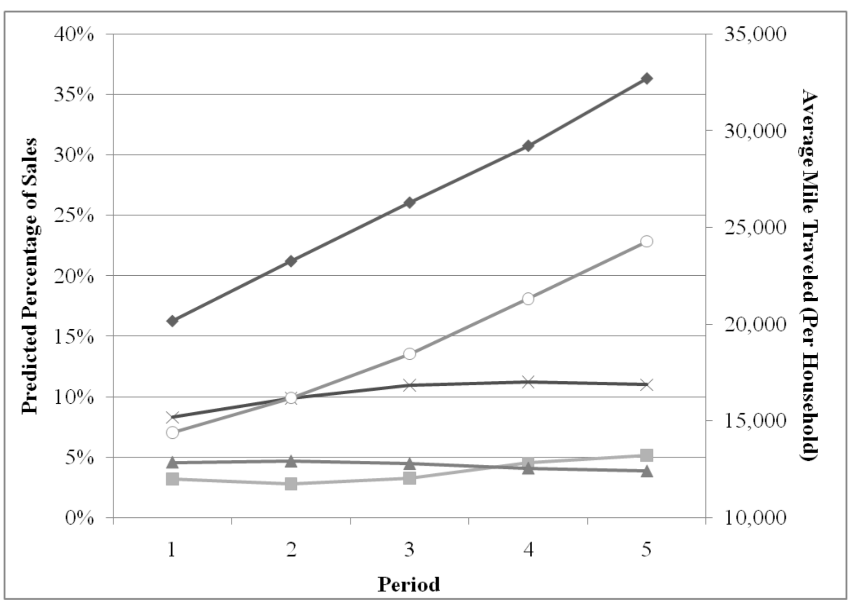


(b) 5% annual increase

Figure 13: Predicted percentage of all vehicle sales with various annual rates of income increase.

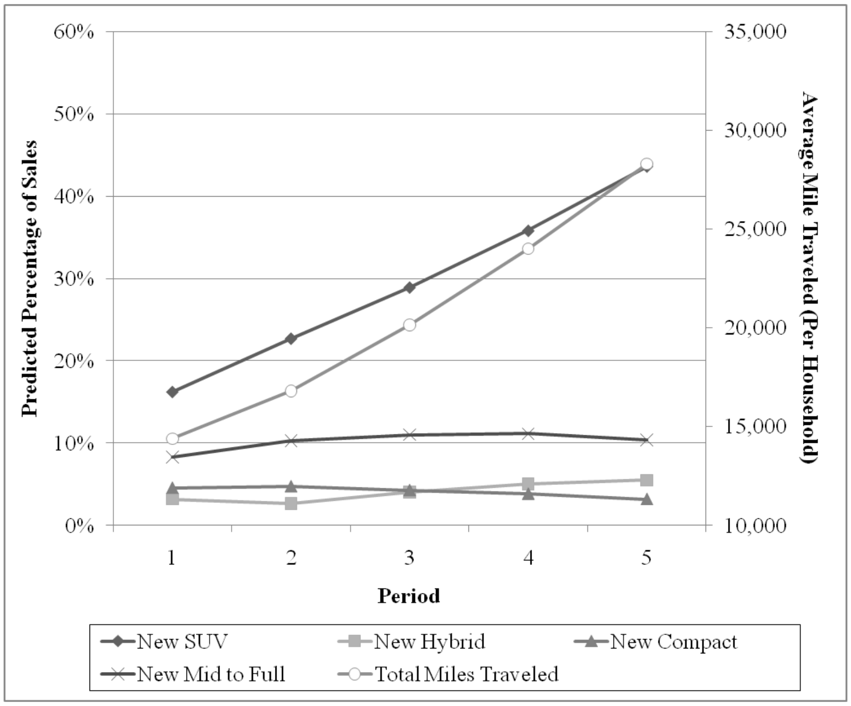


(c) 10% annual increase

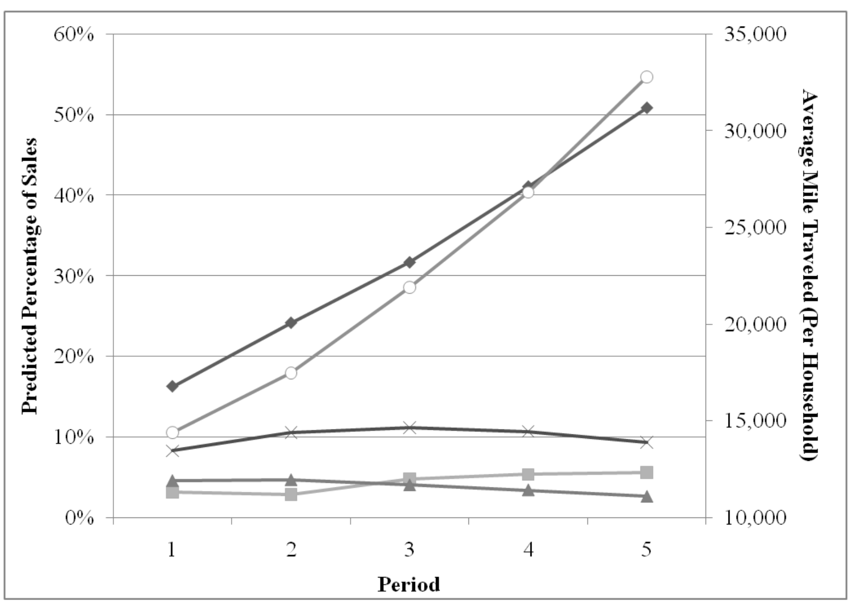


(d) 15% annual increase

Figure 13: Predicted percentage of all vehicle sales with various annual rates of income increase.



(e) 20% annual increase



(f) 25% annual increase

Figure 13: Predicted percentage of all vehicle sales with various annual rates of income increase.

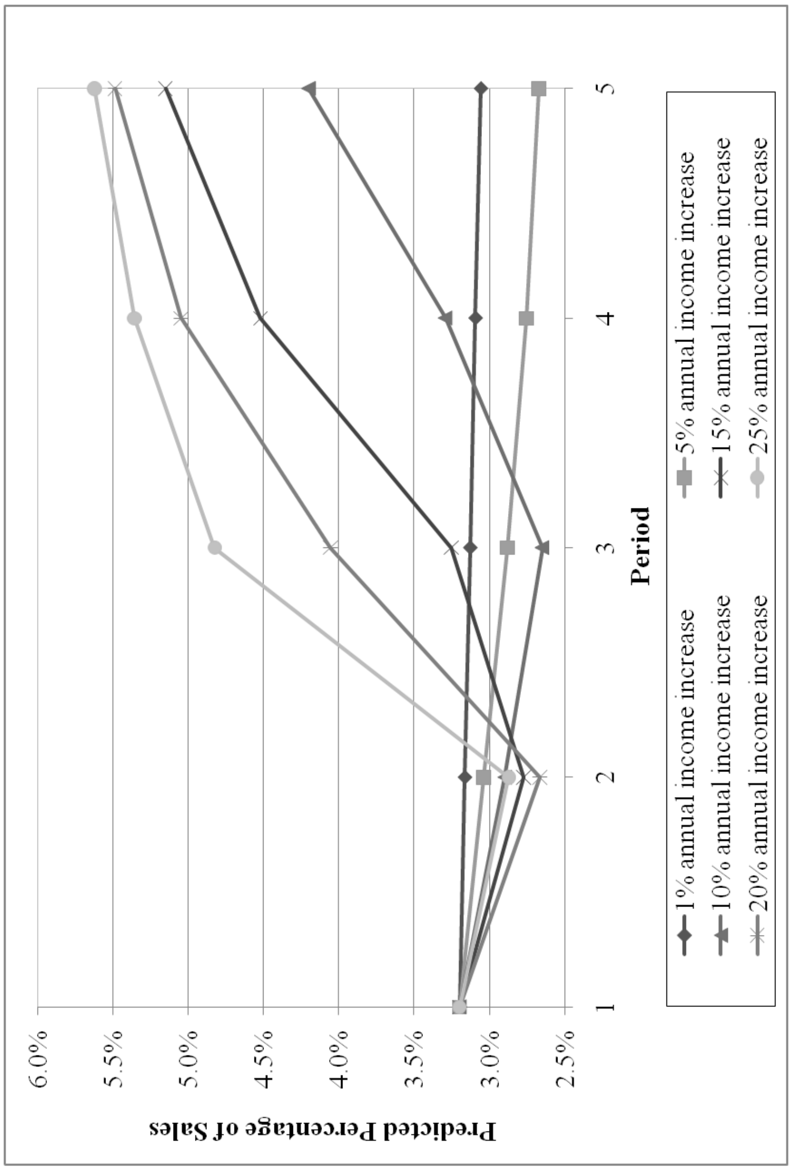


Figure 14: Predicted percentage of hybrid vehicle sales various annual rates of income increase.

4.4.1 Income Distribution Shifts with Increasing Environmental Awareness

In regions with prominent economic growth, it is reasonable to postulate a positive correlation between income levels and environmental awareness, especially in developing economies such as China or India where income levels are growing rapidly. As a portion of the population comes out of poverty or as households become wealthier, they are able to place more concern on environmental quality or other quality-of-life issues instead of worrying about survival and fulfilling basic human needs. This increasing environmental awareness is related to the Environmental Kuznets Curve (EKC) hypothesis discussed in many studies including Dinda (2004) [29], Dasgupta et al. (2002) [24], Panayotou (1993) [63] and Stern et al. (1996) [77] and may be present in both developed and developing economies. If we are looking at an economy where environmental awareness starts at a low level, we may see even higher rates of growth in that parameter. This will be explored later in Chapter 5. In this simulation, we will assume that the environmental awareness coefficient increases at a constant annual rate consistent with the previous years in the U.S (approximately 1.7% per year) as discussed in Section 3.3. This extended scenario uses the same income distribution shifts as the previous section along with an annual environmental awareness increase of 1.7% to take a look at how vehicle adoption patterns may differ when the population becomes more aware of the potential environmental damages associated with certain transportation alternatives or fuel consumption.

As expected, increasing levels of environmental awareness paired with growing income levels results in an increasing rate of hybrid vehicle adoption. The results in Figure 15 stress the critical role of environmental awareness in the diffusion of new vehicle technologies in this model. Comparing Figure 16 with Figure 14 where there are no increases in environmental awareness, we observe larger resulting adoption of new hybrid vehicles due to increasing levels of environmental awareness. In the simulations, the predicted percentage of new hybrid vehicle purchases increases from 3.20% in the first period to 4.34%, 4.80%, 5.55%, 7.17%, 7.73% and 7.80%, respectively in the fifth period of each specification in Figure 15. The preliminary drops in hybrid vehicle adoption is an effect caused by the shape of the income distribution curve. In general, because the new hybrid vehicle is one of the more expensive vehicle options, the wealthier the population becomes, the higher the adoption. This effect if further augmented by the increasing environmental awareness. In addition, in the first two specifications we can also observe an increase in the percentage of households who choose to purchase new compact vehicles, another type of fuel-efficient transportation. When the income distribution increases by 1% annually, new compact vehicles adoption increases from 4.57% to 5.03% at the end of the simulation period. However, as income distribution reaches an increase of 10% or more per period, the adoption of new compact vehicles start to decrease. These results mainly reflect the Income Distribution Effect illustrated in the theoretical model.

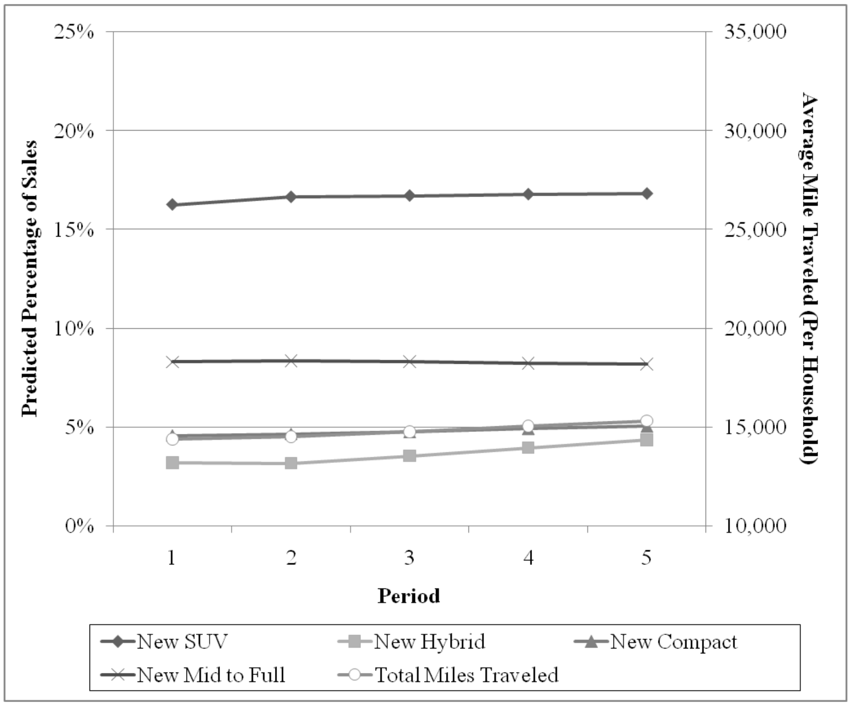
Although the increasing adoption of new hybrid vehicles and new compact vehicles is encouraging for environmentalists, we must also note the optimal number of miles traveled by each household. Two effects cause the higher number of miles traveled. One is the increasing income distribution mean that households have more disposable income which they can spend on traveling. The other effect is the result of the adoption of more energy-efficient alternatives due to higher environmental awareness. When households purchase energy-efficient vehicles, the variable cost of travel drops significantly, resulting in higher optimal number of miles traveled.

In the specification where income shifts by 1% per period, we observe an increase in average household travel from 14,394 miles to 15,314 miles in the final period. With higher income shifts, the trend continues at greater magnitudes and average annual household travel increases to 17,452, 20,885, 24,900, 28,988 and 33,452 miles in period 5 when income distribution increases by 5%, 10%, 15%, 20% and 25% per period, respectively. The result is that when more households are adopting fuel efficient vehicles, the average number of miles traveled increases compared to the earlier specification without increases in environmental awareness. This result presents some evidence of the rebound effect that was proposed by Khazzoom (1980) [46] in the context of household appliances. He proposed that when appliances or cars face higher energy efficiency standards or mandates, the gains from the higher efficiency may be offset by the increased usage by consumers. There is evidence of the rebound effect in the context of vehicle efficiency standards, with many estimations regarding the existence and magnitude of the effect (Greene 1992 [35], Greene et al 1999 [37], Small and Dender 2007 [75] and Sorrell et al. 2009 [76]), but that is beyond the purview of this discussion.

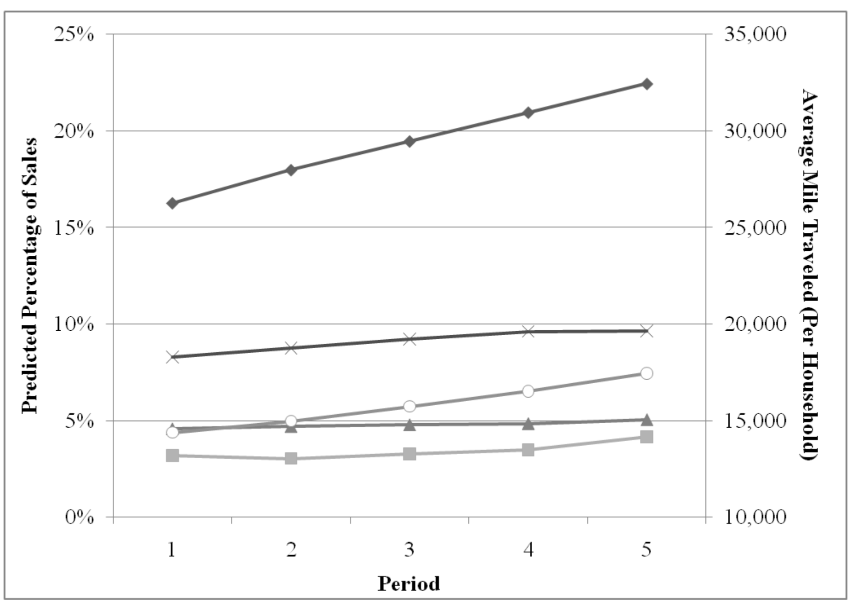
Although it is straight-forward that as consumers become more concerned about the environment, they substitute towards fuel-efficient or low-emissions vehicles such as the new hybrid vehicle, the results still show that new SUV purchases increasing to 16.81%, 22.45%, 28.85%, 35.25%, 42.31% and 49.54% in the last period of each specification. This is equivalent to an average annual growth rate of 0.84% and

8.41% when the income distribution shifts by 1% and 5% annually. The average annual increase in new SUV purchases is 15.47% with an income distribution shift of 10% per period, 21.47% with a shift of 15% per period and 27.23% with a shift of 20% per period. The average annual growth rate increases to a dramatic 32.46% if the income distribution shifts by 25% annually. The effects of the income distribution shift leads to large increases in new SUV adoption due to households moving into the critical income range for this type of vehicle, and the effect is proportional with the size of the shift. The pattern of large vehicle adoption is slightly slower compared to the previous simulation specifications (see Figure 13) where environment awareness remains constant, although not by much (total percentage of new SUV purchases ends at 49.54% with environmental awareness increases and 25% income distribution shift compared with 50.85% without environmental awareness increase).

Therefore, the effects of large income distribution shifts are still dominant compared to the environmental awareness factor. Focusing on areas such as India where income distribution shifts may indeed be occurring, such rapid patterns of adopting large, comfortable, fuel-consuming vehicles may be a major cause of concern. The results show that we simply cannot rely on environmental awareness or environmental education to curb the adoption of large vehicles and to promote the adoption of alternative fuel vehicles. Even in the last specification when income distribution shifts by 25% per period, the percentage of new hybrid vehicle adoption is less than 1/6 of new SUV adoption and is less than one out of ten of all vehicles purchased in that period. In Section 5.1, we will construct a complete scenario facing developing nations with shifting income distributions to further examine the policy implications and solutions.

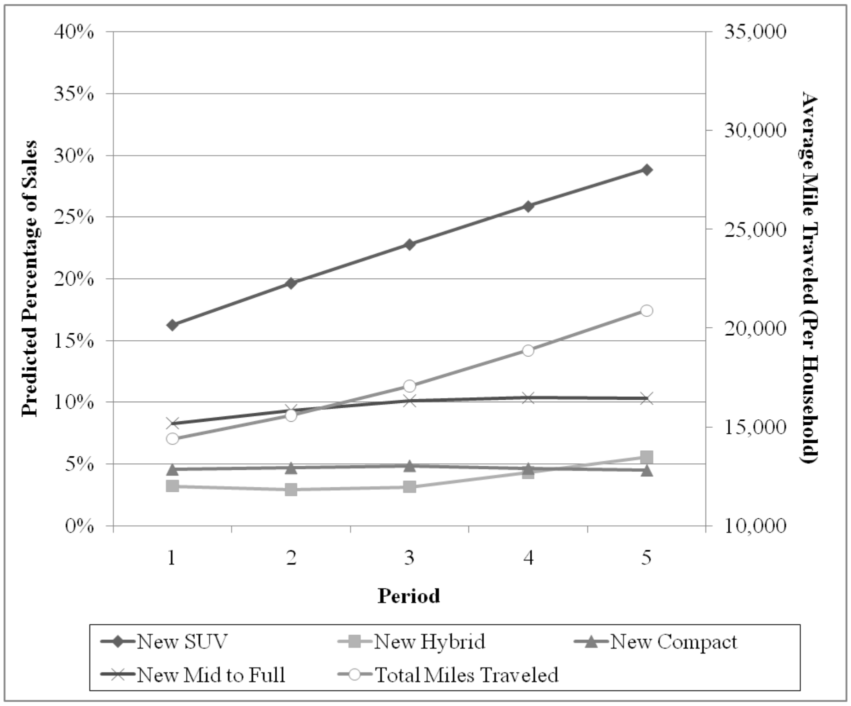


(a) 1% annual increase

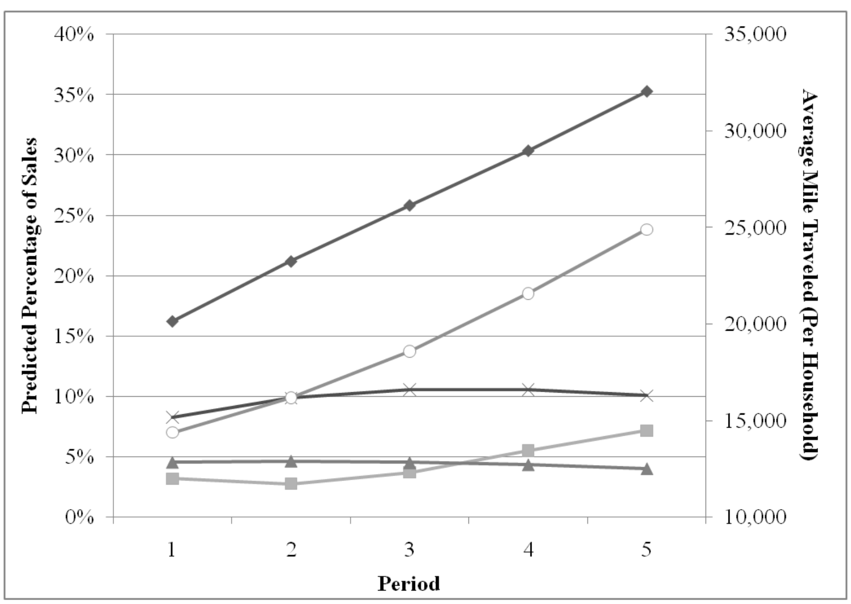


(b) 5% annual increase

Figure 15: Predicted percentage of all vehicle sales with various annual rates of income increase paired with increasing environmental awareness.

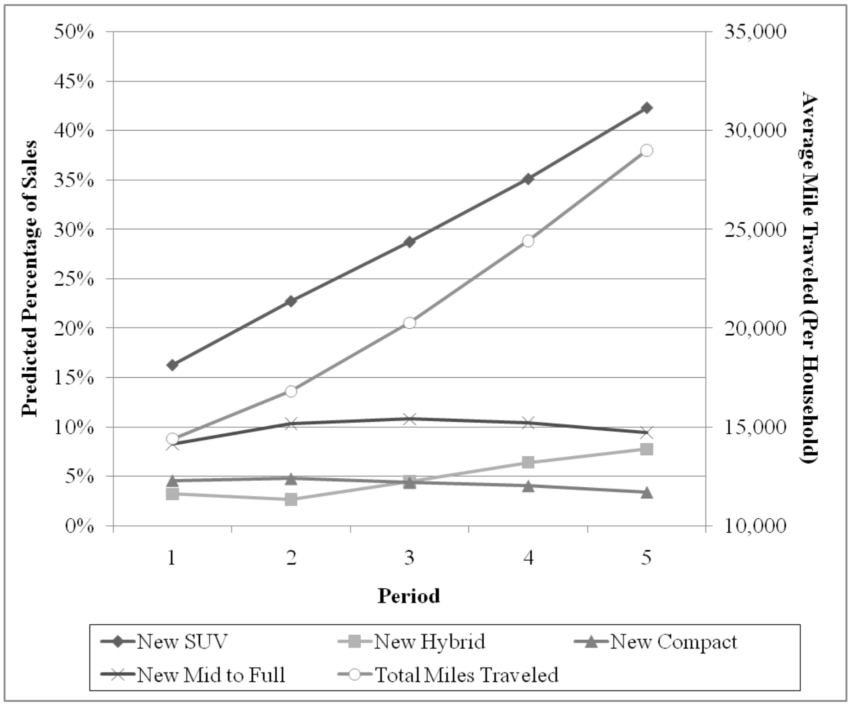


(c) 10% annual increase

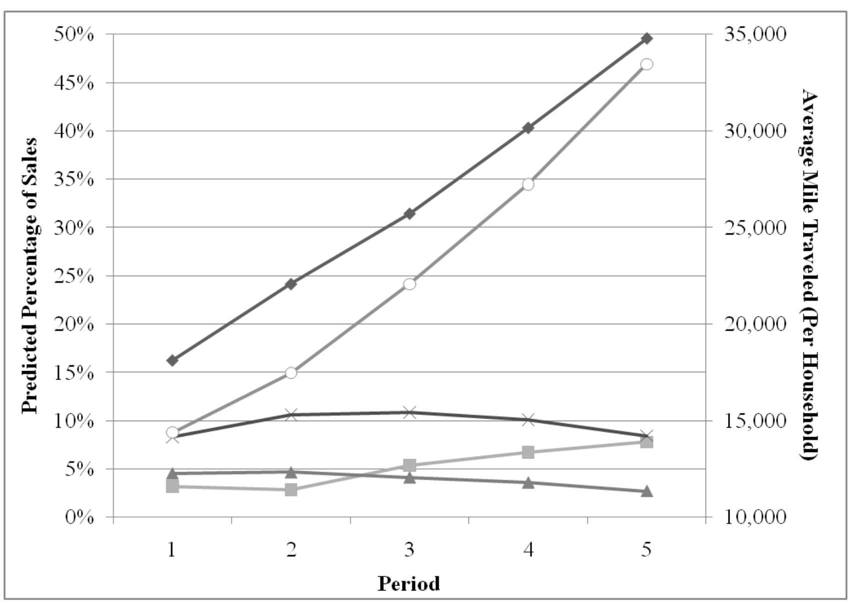


(d) 15% annual increase

Figure 15: Predicted percentage of all vehicle sales with various annual rates of income increase paired with increasing environmental awareness.



(e) 20% annual increase



(f) 25% annual increase

Figure 15: Predicted percentage of all vehicle sales with various annual rates of income increase paired with increasing environmental awareness.

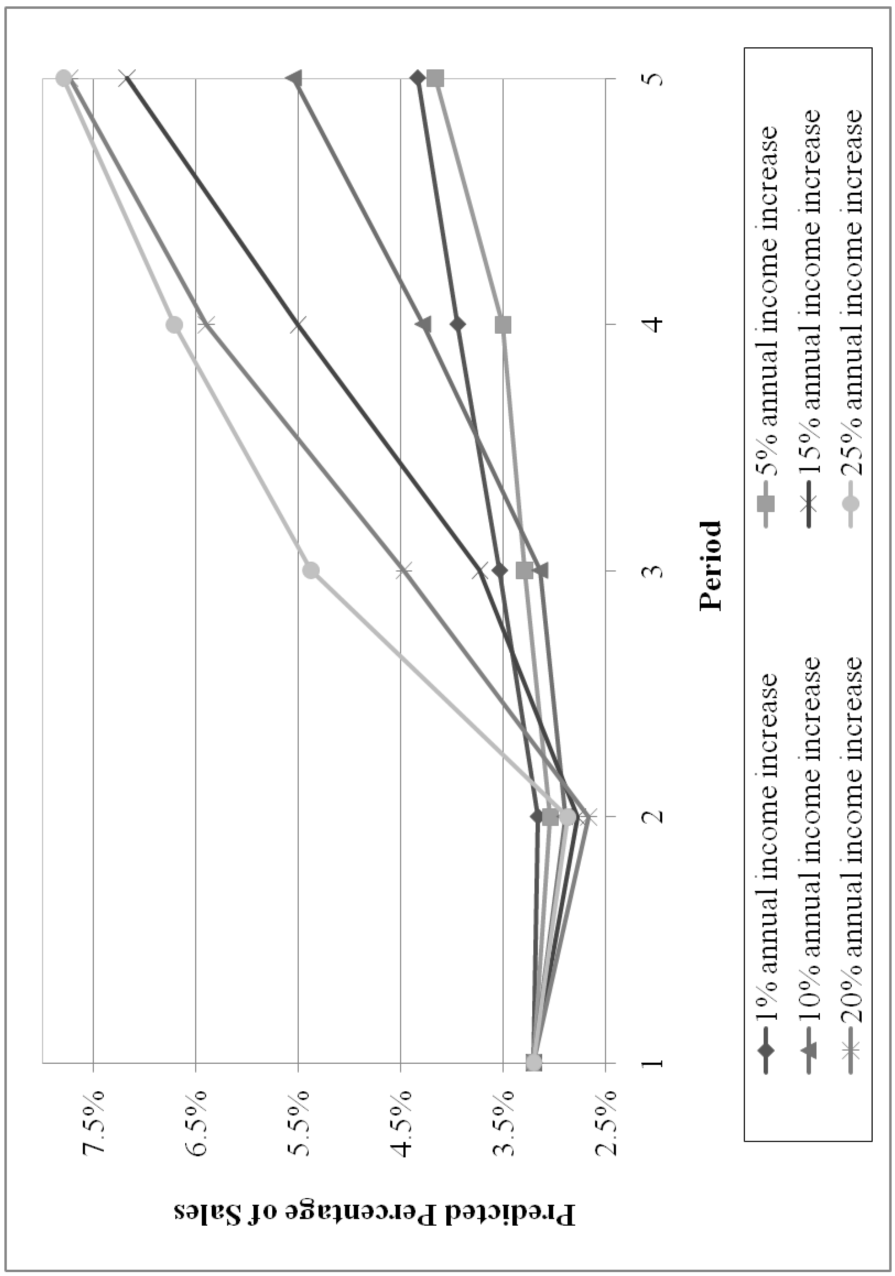


Figure 16: Predicted percentage of hybrid vehicle sales various annual rates of income increase paired with increasing environmental awareness.

4.5 Shape of Income Distribution Changes

Changes in the shape of the income distribution is often observed as the dynamics of the economy are shifting. In the U.S., as the economy grows, many measures of inequality indicate an increasing gap between the poor and the wealthy. In other words, the rich are becoming richer. Piketty and Saez (2003) [64] show that the top 1 percent wage share in the U.S. to be increasing since the 1970s, corroborating findings by Katz and Murphy (1992) [44]. To simulate such a scenario, we propose a hypothetical new income distribution as illustrated in Figure 17 that consists of a similar mean level of income, but more concentration of the population in the two extremes of the distribution. We assume that the distribution of different types of households within each income level remains constant for simplicity and are similar to those in the calibrated U.S. simulation (approximately 35% households with children, 45% households without children and 20% senior households, see Table 3). We assume energy prices, environmental awareness, demographics and vehicle attributes and prices remain constant to specifically examine how changes in the shape of the income distribution may affect vehicle adoption.

The results in Table 13 show that the increased percentage of wealthy households in the population causes a significant increase in the purchase of new SUVs, but only a small increase in the purchase of hybrid vehicles. As the shape of the income distribution changes, the critical income regions for each type of vehicle do not shift. The only change is the number of households that fall into each critical region. Those in the lower extreme of the income distribution will keep purchasing used vehicles instead of new, and we see an increase in used compact vehicle purchases as well. Thus, the exact shape of the income distribution is the key contributor to these results.

	New SUV	**New Hybrid**	**New Compact**	**New Mid to Full**
Original Distribution	16.26%	3.20%	4.57%	8.29%
New Distribution	20.88%	3.55%	3.30%	9.76%

Table 13: Predicted percentage of all vehicle sales with a different shape of income distribution.

The simulation model provides a novel tool for the analysis of complex dynamics on technology adoption. We can also forecast the resulting effects of the social trend towards less children or even no children in the household by utilizing the distribution of different types of household structures. In addition, the simulation is well-equipped to forecast the effects of an ageing society, prevalent in many developed regions such as Europe or Japan or booming young societies such as those in Asia as demonstrated in the next chapter or increasing/decreasing income inequality. Chapter 5 will examine more complex scenarios combining the capabilities of the simulation model illustrated in this chapter.

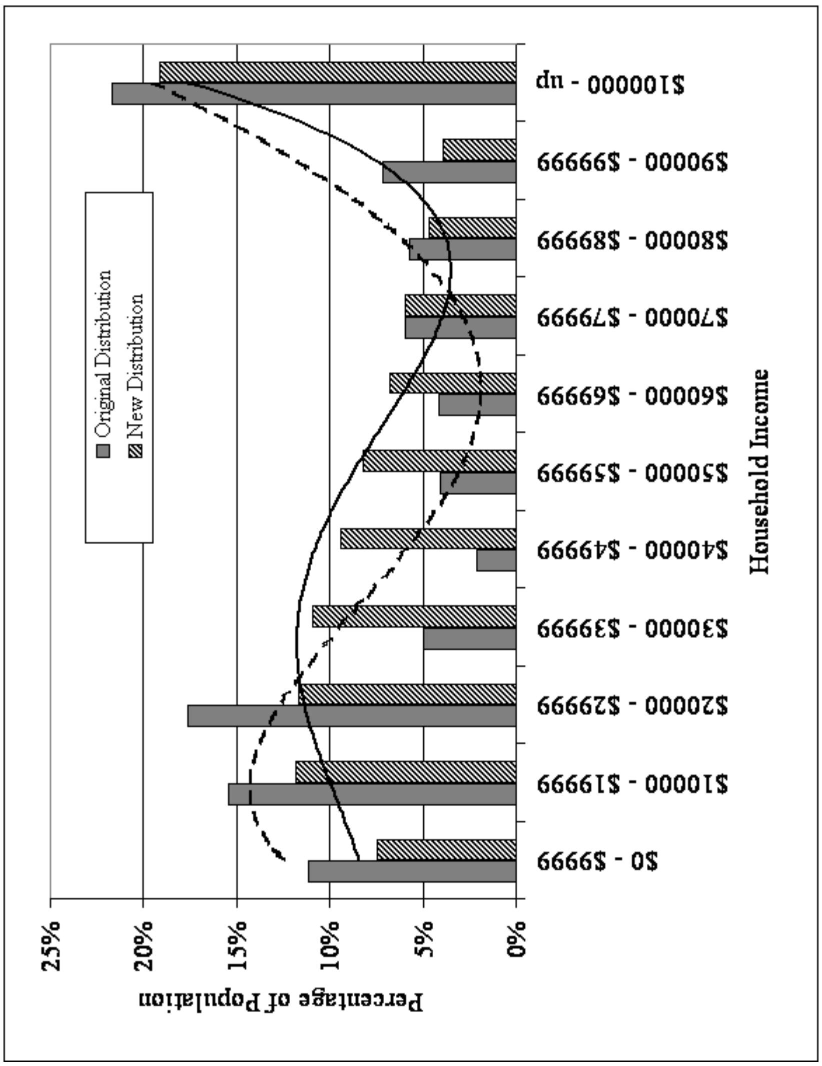


Figure 17: Original observed income distribution in the U.S. and hypothetical income distribution. The solid line is the fitted shape of the original distribution and the dotted line is the fitted shape of the new income distribution.

Chapter 5

Simulation Case Studies

Chapter 4 illustrates the capabilities of the simulation model on forecasting future adoption of new technologies given individual parameter changes in the scenarios such as energy price changes or demographic changes. This chapter will demonstrate the ability of the simulation model to accommodate complete and complex case study scenarios. Given historical data to appropriately calibrate the simulation model for any specific country or region, we can utilize the same simulation platform to predict technology adoption and diffusion in various scenarios. The case studies can incorporate changing price of energy, changing price of technologies, different sets of transportation options or policies, shifting demographics and household structures, changing income distribution, changing attitudes towards the environment or global warming, introduction of different types of public transportation or a combination of all of the above.

For example, we could utilize the simulation model for a province or region in China where government agencies may be concerned with traffic or environmental problems. After calibrating the simulation model with data, we can then use forecasts on future dynamics of the population, including household structure changes, ageing and income changes, along with several policy alternatives that may be under consideration (i.e. providing incentives to purchase less polluting vehicles or offering new public transportation options or launching a campaign to promote environmental awareness) to identify the effects on vehicle technology adoption. This section explores three case study scenarios. Case Study I examines the dynamics of emerging economies such as China or India. Case Study II looks at ageing developed economies such as Europe or Japan. Finally, Case Study III takes the entire simulation model a step further by adding public transportation as an alternative.

5.1 Case Study I: Emerging Economies (China/India)

5.1.1 Main Scenario

In emerging economies such as China or India, as the economy experiences high growth, the population demographics may experience dramatic changes as well. In addition to greater demand for energy as the population becomes wealthier, we hypothesize that the demand for higher-priced vehicles such as the SUV or hybrid vehicle will increase. Rising income inequality appears to be another characteristic of these booming economies. In particular, the Gini coefficient in China has increased from 0.22 in 1987 to 0.34 in 2001 in urban areas and from 0.32 to 0.37 in rural areas (Benjamin et al. 2008 [8]). The increasing trend of inequality is even more evident when we consider all areas of China together: the combined Gini coefficient rises from 0.37 in 1991 to 0.44 in 2000. This presents evidence that the income distribution shape and structure may indeed be changing, which is what this scenario will be exploring.

This case study simulation utilizes historical data from the China Statistical Yearbook on the income distribution of rural household income. Figure 18 shows the shift of the income distribution. Although the data does not include the income distribution for the entire country for both rural and urban areas (the income data from the Chinese Statistical Yearbook is tabulated differently for rural and urban areas, presenting difficulty to aggregate both areas together[1]), it already displays a significant shift in the period from 1995 to 2008. Because we know that inequality appears to be higher when we consider the entire nation (Gini coefficient of 0.44 in 2000 compared to 0.37 in rural areas and 0.34 in urban areas in 2001), we can only expect that the shape of the overall income distribution to display even more significant movements. So we will proceed with using the rural income distribution shift to demonstrate the effects on vehicle adoption in the region, keeping in mind that the actual effects may be even more significant than what is demonstrated through the simulation if the overall income distribution shapes are applied.

For this case study, we assume a 5% per period increase in energy price. We will follow the income distribution trend presented in Figure 18 to simulate vehicle choice for five periods, assuming that the composition of household structure is similar to the U.S. simulations (approximately 35% households with children, 45% households

[1] Wu and Perloff (2005) [87] construct an excellent aggregate income distribution for years 1985 to 2001. However, it does not include the income distribution for the periods we are considering.

without children and 20% senior households, see Table 3) and is constant through the five periods. We further assume that in such economies that the increase in environmental awareness is negligible and that the hybrid vehicle price does not enjoy a learning-by-doing decrease (hybrid vehicle price remains constant) because they are less prevalent (due to low sales volume, less availability or less research and development).

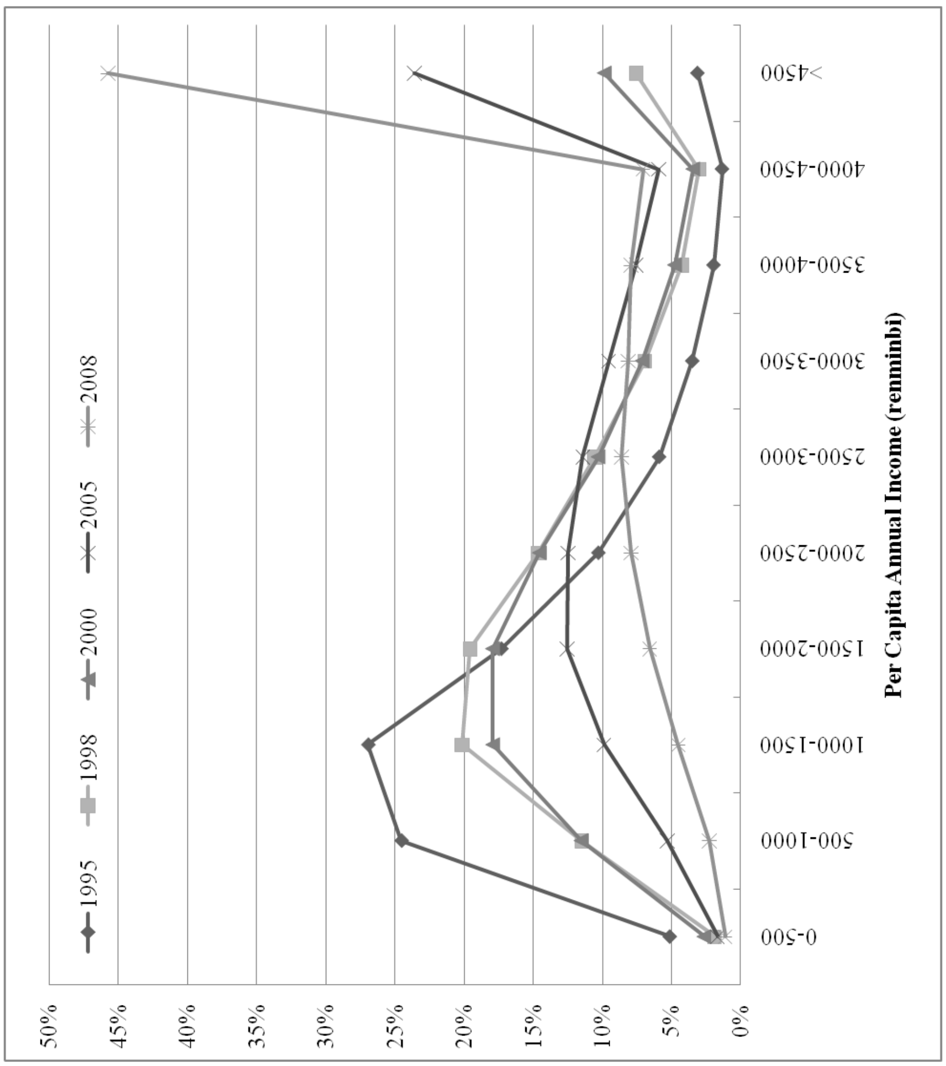


Figure 18: Selected rural household per capita annual income distribution in China. (Source: China Statistical Yearbook)

5.1.2 Main Scenario - Results and Discussion

In this emerging economies case study, we observe a trend towards bigger, better (more comfortable) and newer vehicles shown in Figure 19. The theory suggests that when energy price increases, we observe the Variable Cost Effect which shifts critical income levels such that more households fall into the range for adopting energy-efficient vehicles. Although the energy price rises by 5% in each period in this scenario, its effects here are dominated by the effects of the shifting income distribution, making new SUVs and new mid to full-size vehicles more affordable and more attractive to a higher percentage of the vehicle-purchasing households. It appears that a large percentage of car-purchasing households prefer to purchase new vehicles instead of used ones as their income level increases, and this is one of the main driving forces behind the increases in the adoption of all categories of new vehicles. Approximately 93% of households purchased used vehicles in the first period and gradually decreases to 41% in the last period as households become wealthier. Hybrid vehicle adoption starts at close to zero (0.45%) in the first period and increases to 1.05%, 1.33%, 3.09% and 5.80% in the next four periods, respectively. At the same time, the percentage of households that purchase new SUVs starts at 2.44% in the first period and increases to 6.03%, 7.95%, 18.98% and 36.33% in the next four periods, respectively.

In response to higher energy prices each period, theory tells us that the average household would be choosing to maximize utility by driving less, possibly by combining trips, carpooling or walking. However, the effects of the shifting income distribution are much larger than the effects caused by the energy price increases in the overall scenario, and we instead observe an increase in the miles traveled by the average household. We observe an increase from an average of 7,199 miles traveled per year in the first period to 17,270 miles in the last period, increasing by an average 25.00% per period in response to a 5% per period increase in energy prices and large increases in the income distribution. Households are driving more in larger, more comfortable vehicles because they can afford to do so and the effects are quite dramatic.

Figures 20 through 22 display the household utility maximization curves of the three different types of household structures for periods 1 and 5. For households with children (h=1), we observe quite similar utility frontiers in periods 1 (Figure 20a) and 5 (Figure 20b) with low-income households purchasing used compact vehicles, mid-income households purchasing used large vehicles and high-income households purchasing new SUVs. The critical income at which this type of households switch from used compact vehicles to used large vehicles (I_c^1) is about \$7,200 in the first period and \$7,000 in the last period. The critical income at which these households switch from used large vehicles to new SUVs (I_c^2) is approximately \$90,000 in the first period and \$87,700 in the last period. This means that the critical income ranges in which households choose to purchase used compact vehicles and used large vehicles are smaller in the last period while the critical income range for new SUVs is larger. The percentage of households with children who adopt each type of vehicle depends on how many households have incomes levels falling within those ranges in any given period.

For households without children (h=2), we also see small shifts in the utility frontiers from period 1 (Figure 21a) to period 5 (Figure 21b). The utility frontiers for household type 2 are formed by utility curves that represent the choice of used compact vehicles, used large vehicles, new compact vehicles, new mid to full-size vehicles, new hybrid vehicles and new SUVs, in this order. In the first period, Figure 21a shows that the critical incomes (I_c^1 through I_c^5) are at \$40,200, \$58,150, \$71,850, \$120,650 and \$155,800, respectively. In the last period, Figure 21b shows that the critical incomes (I_c^1 through I_c^5) have changed to \$39,050, \$56,800, \$70,100, \$118,700 and \$149,700, respectively. These trends indicate that as energy price becomes higher and travel becomes relatively more expensive (compared to comfort and other goods), there is a certain amount of substitution towards spending money on more comfortable vehicles. The decreasing number of miles traveled as gas price increases also contributes to the increasing marginal utility of comfort, fueling part of the substitution towards larger vehicles.

We observe in Figure 22 that households with senior heads (h=3) are predicted to purchase only used compact vehicles, used large vehicles and new SUVs according to the simulation. The critical income level at which they switch from the adoption of used compact vehicles to used large vehicles (I_c^1) starts at \$17,600 in period 1 and ends up at \$17,200 in period 5. The critical income level at which they switch from purchasing used large vehicles to new SUVs (I_c^2) decreases from \$84,150 in period 1 to \$81,800 in period 5. These shifts in critical incomes are small for each type of household structure and cannot account for the dramatic results predicted in Figure 19. Again, the trend shows larger critical income ranges for new SUVs. Although energy price increases (or variable cost of travel increases) of this magnitude (5% per period) may result in changes in vehicle adoption, the changes in critical income ranges only contributes partially to the results. The income distribution shifts as dramatic as those in developing economies (i.e. China or India) are the main contributors to the pattern of vehicle technology adoption shown in this case study.

The high increase in the adoption of larger, less fuel-efficient and more polluting vehicles not only signifies higher fuel consumption and increased levels of greenhouse gas emissions in the present, but may signify much broader impacts in terms of climate change, fuel prices and fuel-shortage problems in the long run, especially considering China and India's combined population of 2.5 billion (approximately 37% of world population). This case study does not purport to accurately demonstrate the exact vehicle adoption and diffusion patterns in countries such as China or India, since the simulation model has not been rigorously calibrated with data from these regions. Rather, it illustrates a possibly alarming trend in vehicle technology adoption and diffusion which could be further studied in future research. An extension of this case study involving public transportation is conducted in Case Study III Scenario 5.

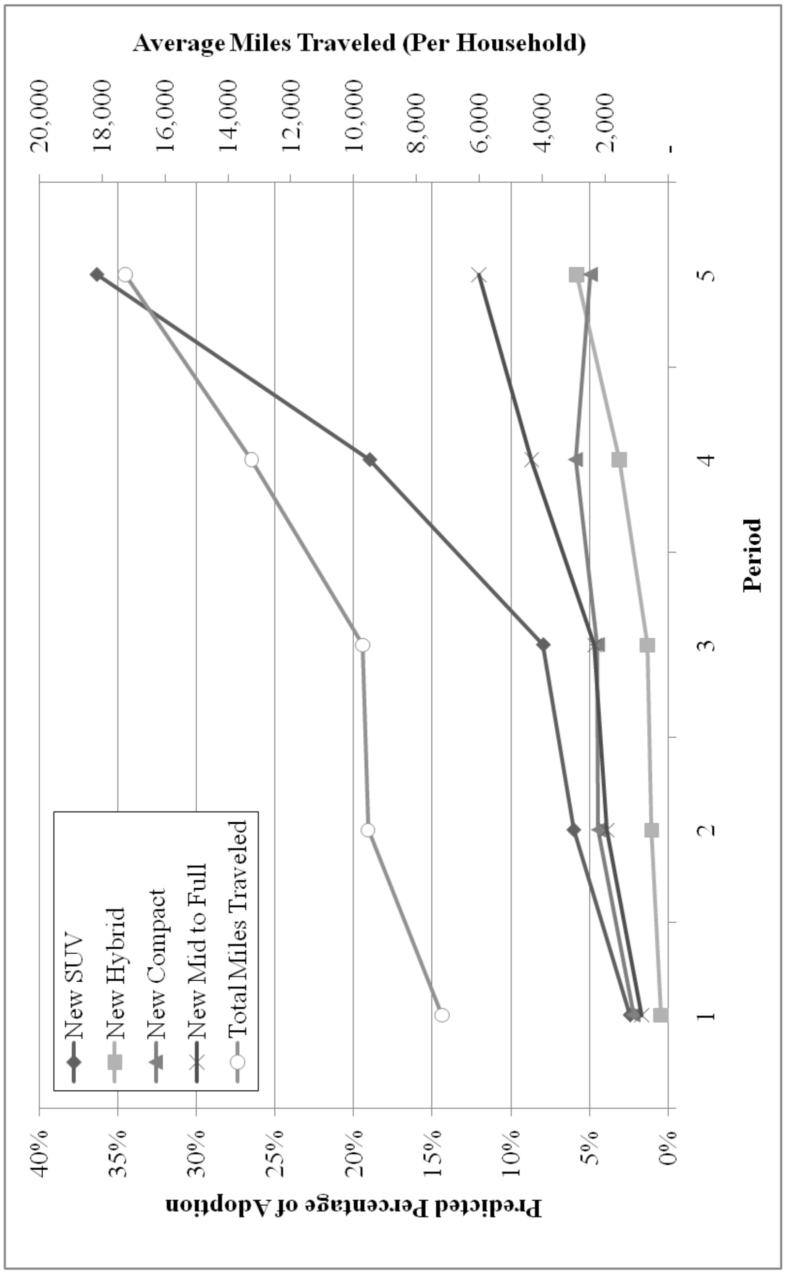
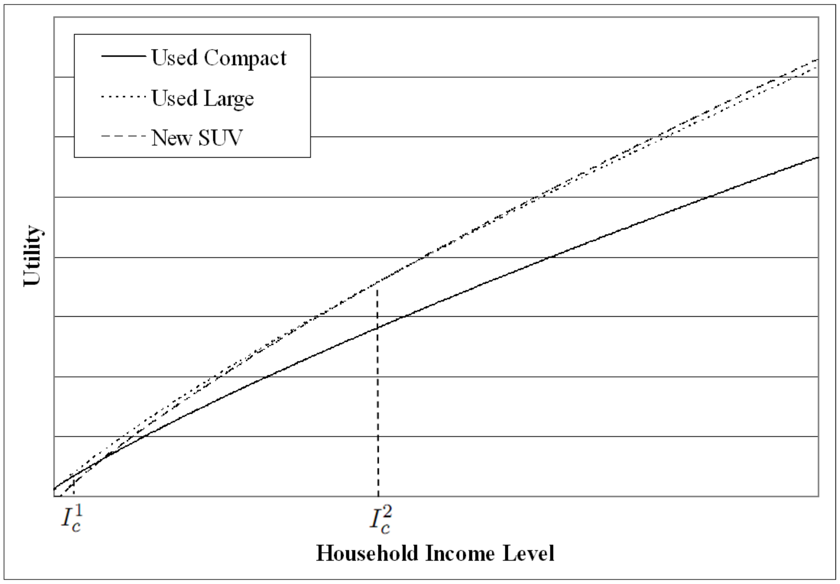
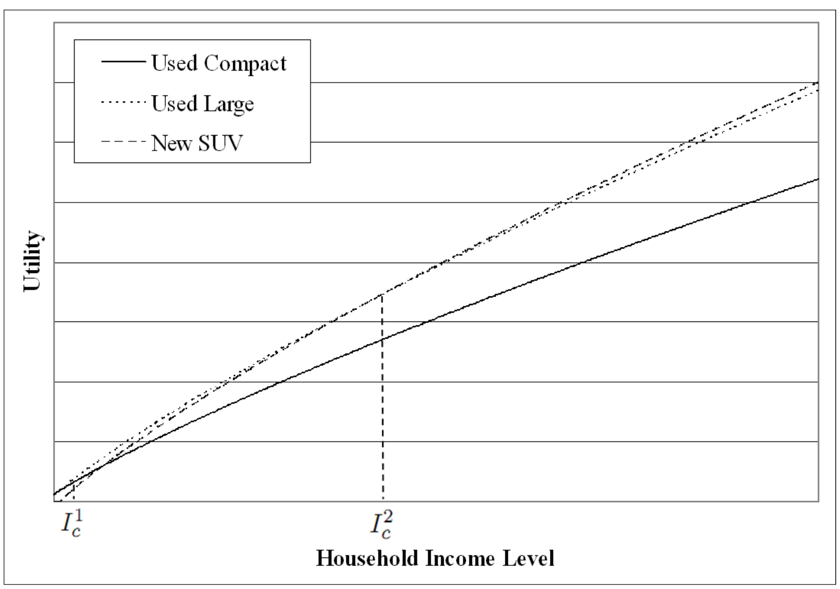


Figure 19: Case Study I: Predicted percentage of all vehicle sales.

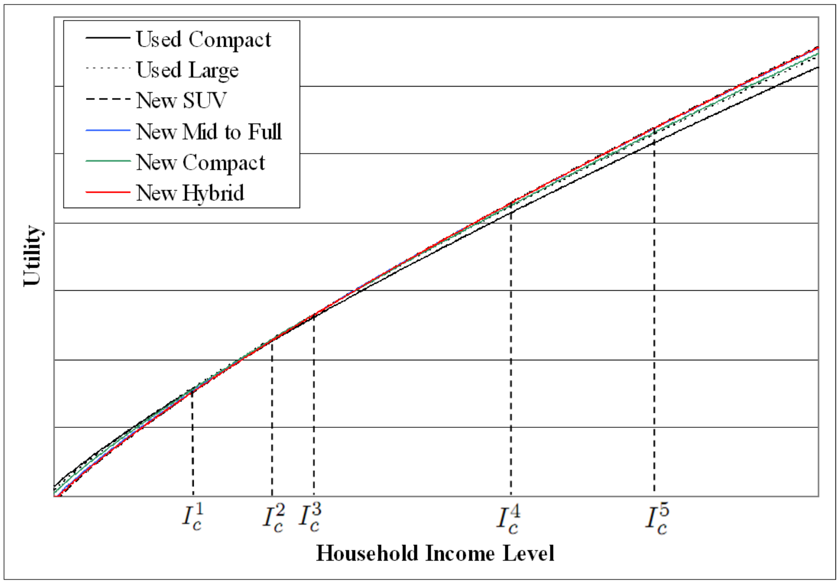


(a) Period 1

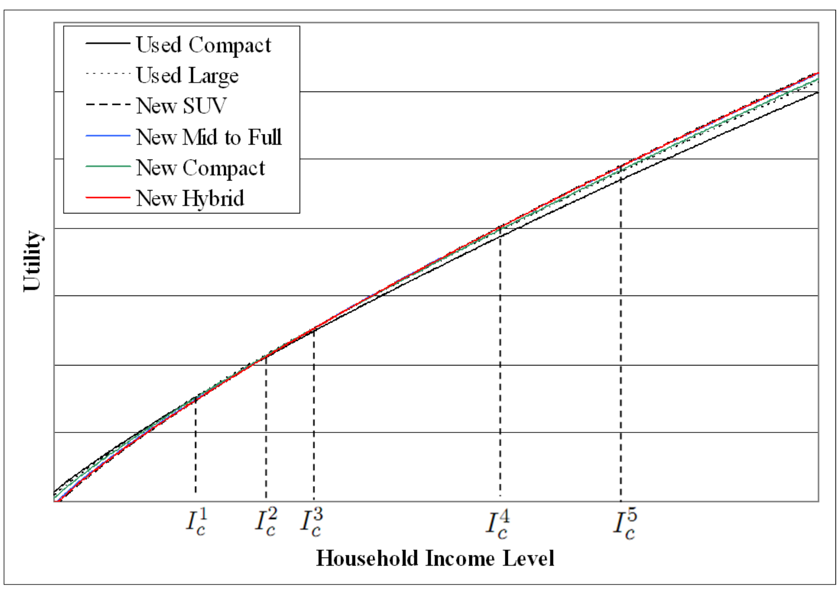


(b) Period 5

Figure 20: Case Study I - Scenario 1: Household utility maximization of households with children (h=1).

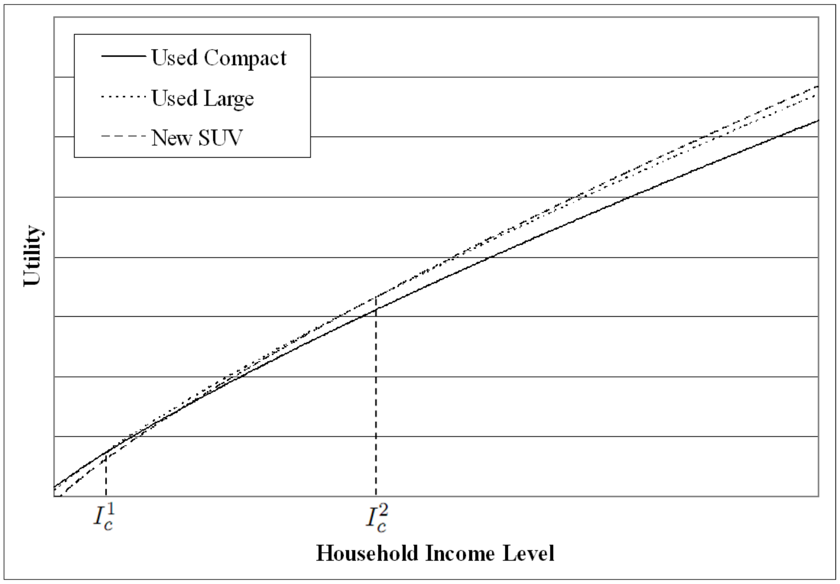


(a) Period 1

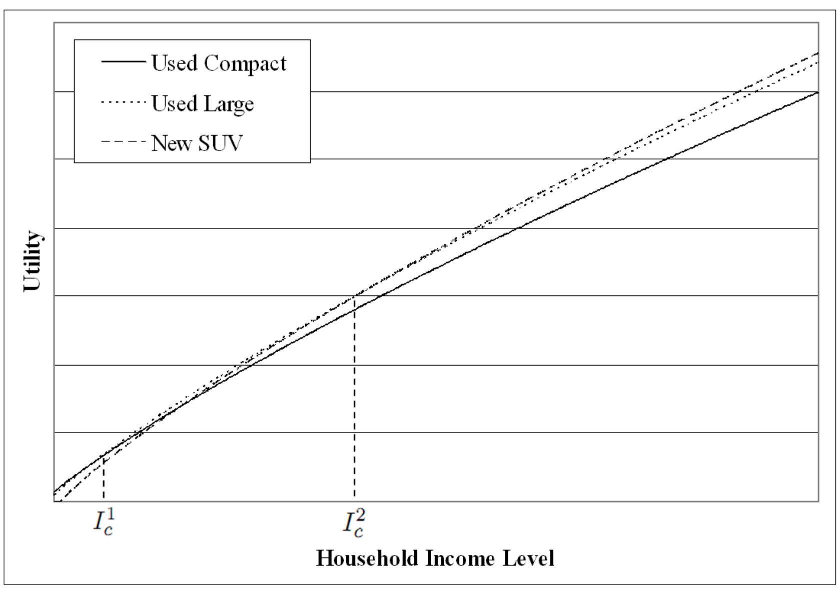


(b) Period 5

Figure 21: Case Study I - Scenario 1: Household utility maximization of households without children (h=2).



(a) Period 1



(b) Period 5

Figure 22: Case Study I - Scenario 1: Household utility maximization of households with seniors (h=3).

5.1.3 Extended Scenarios

Both China and India are developing nations that have experienced tremendous economic growth in the past fifty years and are continuing to grow. High, unprecedented rates of economic growth (large, dramatic shifts in the income distribution and the shape of income distribution) coupled with high population growth rates on top of large populations in these regions make it especially difficult to predict the pattern of vehicle adoption. According to the World Development Indicators published by the World Bank, the average annual real GDP growth rate in China from 1960 to 2008 is a staggering 9.91% and annual population growth is 1.44%. The average annual real GDP growth rate in India is 5.05% in the same period with an annual population growth of 2.03%. With these growth rates, it may well be that the historical patterns observed in the developed world will not provide enough guidance for China or India. We will use the simulation model and extend the scenario based on recent observations of the region to generate predictions regarding the pattern of household vehicle adoption, and to decipher the underlying decision mechanism.

Year	**Length of Highways** (km)	**Length of Expressways** (km)
1990	1,028,348	
2000	1,402,698	
2003	1,898,000	29,700
2004	1,870,700	24,300
2005	3,345,200	41,000
2006	3,456,999	45,300
2007	3,583,715	53,900

Table 14: China road infrastructure (Source: 2008 China Statistical Yearbook)

One of the key characteristics of the economic development in China is the rapid construction of transportation infrastructure such highways and expressways in the recent years, shown in Table 14. At the end of 2007, China had more than tripled the length of highways from 1990. Expressways (or what we can interstate freeways in the U.S.) increased to 53,900 km at the end of 2007, with the National Expressway Network Plan announced in 2005 to expand the network to 85,000 km by 2020[2].

[2]For reference, the Federal Highway Administration states that the U.S. Interstate Highways System consists of 46,876 miles or 75,439 km in length.

With more transportation infrastructure being constructed, it may be the case that it will dramatically reduce the discomfort of road travel when households drive on paved, wider, faster roadways. This means that the comfort for all types of vehicles will increase.

The opposite effect is that households may perceive the increased infrastructure as an incentive to buy more cars and drive more. This will cause comfort to decrease overall due to the increased congestion or pollution while traveling. The data from the 2008 China Statistical Yearbook in Table 15 shows that from 2003 to 2007, the number of private vehicles increased dramatically from 12.192 million vehicles to 28.762 million vehicles, equivalent to an average annual increase of 35.90%. Not only are the number of vehicles increasing, the growing economy and the construction of transportation infrastructure were also coupled with large increases in vehicle miles on the roads, as evidenced by the increase of total passenger-km on highways (100 million passenger-km) from 7,695.6 to 11,506.8 in 2007, almost a 50% increase in passengers on highways in less than 5 years. This indicates possible congestion occurring even with the rapid construction of new roadways in China.

To account for the possible increases and decreases in the overall comfort level, Extended Scenarios 1 (a), (b) and (c) will simulate overall comfort level increases of 10% per period, 50% per period and 100% per period. We will continue to use the same income distribution shifts as the Main Scenario of this case study, constant environmental awareness and energy price increases of 5% per period. In Extended Scenarios 2 (a) and (b), we explore the possibility of decreases in overall comfort levels that comes with congestion or pollution with 10% decrease in comfort per period in Extended Scenario 2 (a) and 50% decrease per period in Extended Scenario 2 (b).

Year	**Total Passenger-Km on Highways** (100 million passenger-km)	**Private Vehicles**
2003	7,695.6	12,192,300
2004	8,748.4	14,816,600
2005	9,292.1	18,480,700
2006	10,130.8	23,333,200
2007	11,506.8	28,762,200

Table 15: China passenger travel and private vehicles. (Source: 2008 China Statistical Yearbook)

Finally, we want to explore the possibility of equally dramatic increases in environmental awareness in China as the economy grows. If one were to believe the existence of the Environmental Kuznets Curve (EKC), which shows an inverted-U relationship between environmental quality and overall income levels of a nation, then one could hypothesize that as developing economies become wealthier, the population would experience higher levels of environmental awareness. Dinda (2004) [29] surveys the current literature on the theory and empirical evidence regarding the EKC and provides an excellent explanation of the EKC:

> In the first stage of industrialization, pollution grows rapidly because high priority is given to increase material output, and people are more interested in jobs and income than clean air and water (Dasgupta et al., 2002 [24]). The rapid growth inevitably results in greater use of natural resources and emission of pollutants, which in turn put more pressure on environment. People are too poor to pay for abatement, and/or disregard environmental consequences of growth. In later stage of industrialization, as income rises, people value the environment more, regulatory institutions become more effective and pollution level declines.

The existence of the EKC, for which pollutants or in which regions it may apply are beyond the discussion in our paper. We merely consider it as a possibility and extend this case study scenario to assume that the EKC exists in the case of vehicle-produced pollutants, and households possess higher levels of environmental awareness as the economy grows. To show the effects in our extended case study scenario, we will assume large increases in environmental awareness of 10% per period in Extended Scenario 3 (a), 50% per period in Extended Scenario 3 (b) and 100% per period in Extended Scenario 3 (c). Income distribution and energy price changes will follow the same specification as the Main Scenario, and comfort levels remain constant.

Finally, we look at what could happen to vehicle adoption when both comfort levels and environmental awareness are increasing dramatically. Extended Scenario 4 includes a 100% increase per period in overall comfort levels and a 100% increase in environmental awareness.

5.1.4 Extended Scenarios - Results and Discussion

Results from Extended Scenarios 1 (a) through (c) are shown in Figure 23 with overall comfort levels increasing at 10% per period, 50% per period and 100% per period due to the increasing transportation infrastructure construction in developing economies such as China. Focusing first on Extended Scenario 1 (a) in Figure 23a, we observe that new SUV adoption starts at 2.44% in the first period and increases to 4.49%, 5.78%, 13.57% and 25.74% in the subsequent periods. This increase in the adoption of bigger and better vehicle types is consistent with the results from the Main Scenario of this case study, although the increase appears to be slower, increasing by an average of 84.33% per period. New hybrid vehicle adoption, on the other hand, sees large increases as transportation infrastructure is being constructed. It starts at a low level of 0.45% of all households choosing to purchase new hybrids and eventually increases to 3.67%, 6.60%, 14.47% and 25.28% in the next four periods, increasing at an astonishing average rate of 248.06% per period. New compact vehicles also experience high growth, growing from a predicted percentage of sales at 2.21% to 9.45%, 12.31%, 14.09% and 11.08%. The fluctuation in the adoption of new compact vehicles is attributed to the Income Distribution Effect of changing number of households within the critical income range of this type of vehicle as the income distribution shape is shifting dramatically.

In addition, we observe that the average total number of miles traveled by households increases from 7,199 miles in the first period to 10,796, 11,530, 16,242 and 21,736 miles in the following periods. Comparing the average number of miles traveled to the results from the Main Scenario, we see a larger increase in the Extended Scenario 1 (a). Those who choose to purchase hybrid vehicles or compact vehicles experience a lower variable cost of travel, even with the 5% annual increase in energy prices, and they will choose to travel more miles compared to if they choose to purchase larger vehicles such as the new SUV. In addition, when comfort/quality levels increase, a household with a given income level which chooses to adopt a certain type of vehicle will drive fewer miles in their utility maximization. Another effect involves the increasing income distribution. If a household experiences income increases and still optimizes by choosing the same vehicle type, then it will drive more in this vehicle. If the household optimizes as its income increases by switching to a different type of vehicle, then it might drive more or less depending on the fuel-efficiency of the vehicle chosen, following from the theoretical derivations. All of these effects combined show that the effect from income distribution shift and the effect from larger portion of the population switching to more fuel-efficient vehicles (both driving households to travel more miles) dominates all other effects in this case study.

Normally, one may think that with more highways being built and better roads to travel on, perhaps households will choose to purchase more large cars to enable them to travel comfortably. These results show quite the opposite effect, with increasing adoption of smaller, more fuel-efficient vehicles such as the new compact vehicle and the new hybrid vehicle. If we looked more specifically at the behavior of different household structures, it may give us a bit more insight into the results. In households with children (h=1), the critical income level at which households switch from used compact vehicles to used large vehicles starts at $7,250 in the first period and increases to $7,650 in the last period. This shift indicates that as overall comfort levels are increasing, households with children find it more bearable to drive a used compact vehicle, resulting in a larger critical income range. The households that fall into the critical income range between $7,250 to $90,000 choose to purchase the used large vehicle in the baseline period. The upper limit of this range increases to $90,800 in the last period of the simulation, and is because households are also finding more bearable to drive a used large vehicle for larger ranges of income when overall comfort is increasing. Households with income levels above $90,000 in the first period and above $90,800 in the final period will choose to drive the new SUV. Senior households (h=3) show a similar pattern of adoption, with the critical income range for used compact vehicles and used large vehicles increasing, and the range for new SUVs decreasing, in contrast to the Main Scenario where the range for used compacts and used large vehicles are decreasing and the range for new SUVs is increasing.

Households without children (h=2) choose used compact vehicles, used large vehicles, new compact vehicles, new mid to full-size vehicles, new hybrid vehicles and new SUVs depending on their income levels. In the first period, the critical income levels for this type of household are $40,200, $58,200, $71,850, $120,650 and $155,800. As we move to period 2 where overall comfort level increases by 10% as more roads are being built, new SUVs are dominated by new hybrid vehicles, and households of type 2 will only choose used compact vehicles below an income level of $43,350, used large vehicles between $43,350 and $49,200, new compact vehicles between $49,200 and $75,550, new mid to full-size vehicles between $75,550 and $88,050 and new hybrid vehicles above $88,050. In the subsequent 3 periods, we observe that both used large vehicles and new mid to full-size vehicles no longer possess a combination of characteristics that is attractive for buyers of this type.

Households will choose between used compact vehicles, new compact vehicles and new hybrid vehicles in these 3 periods. These results indicate that when comfort levels increase above a certain threshold, vehicles such as the new hybrid vehicle or new compact vehicle may become "comfortable enough" for households and also possess the qualities of low variable cost of travel and low fixed cost of purchase, making them much more attractive as a package.

Extended Scenarios 1 (b) and (c) results are displayed in Figures 23b and 23c. We can see that the patterns of adoption are very similar to Extended Scenario 1 (a) which we discussed in detail. With comfort level increases of 50% and 100% per period, the effects are heightened and the resulting substitution towards new hybrid vehicles instead of new SUVs is much larger in magnitude. In Extended Scenario 1 (b), new hybrid vehicle adoption increases from 0.45% to 5.31%, 6.89%, 15.19% and 26.24% in the last periods. In Extended Scenario 1 (c), as the national transportation infrastructure becomes completed at an even faster speed, we see new hybrid vehicle predicted percentage of sales jump to 5.42%, 7.13%, 15.78% and 32.66% in the periods following the first. New SUV adoption only increases to 14.37% in the final period of Extended Scenario 1 (b) and 8.12% in the final period of Extended Scenario 1 (c). In addition, if we compared the resulting optimal number of miles traveled per household on average, we see decreases in miles traveled as comfort levels increase. This is because comfort is substituted to a certain degree for miles traveled, and the average miles traveled by each household in the final period is still higher than the Main Scenario (18,825 miles in Scenario 1 (c) period 5 compared with 17,270 miles in the final period of the Main Scenario) without increases in comfort. However, this should not be taken as a sign that as national infrastructure is being built that we would observe less overall driving by households and become disillusioned that construction will solve or ameliorate the problems of congestion and pollution. The percentages predicted only represent those households who intend to purchase a vehicle for transportation at a given point in time. The simulation forecasts the aggregate flow demand and not the aggregate stock of vehicles. As more households are in the position to be able to purchase a vehicle (the Population Effect), the actual number of vehicles purchased may increase as well, adding to the overall stock of private vehicles on the road.

In Extended Scenarios 2 (a) and (b), we explore the possibility of increasing congestion and pollution on the roads which leads to a negative growth of the overall comfort factor. The scenario that we are trying to emulate here is that even as more roads are being built and improved, the increasing stock of vehicles causes severe congestion (and also pollution from idling cars traveling at low speeds) which means that every trip now takes longer, becomes more frustrating and less desirable as a result. Figure 24a shows the results of Extended Scenario 2 (a) where overall comfort decreases by 10% per period, and the results are quite dramatic. New SUV adoption starts at the same 2.44% in the first period and quickly rises to 7.40%, 10.51%, 27.17% and 53.69% in the final periods, increasing by an average of 125% per period. Not only does new SUV adoption increase extremely rapidly, the percentage of adoption of all other vehicle types quickly drop to 0%. Both new hybrid vehicle and new compact vehicle adoption drops to 0% in the second period whereas new mid to full-size drops to 4.35%, 3.79%, 3.61% and 0% in the final four periods. Of course, part of the increase in new SUV purchases can directly be attributed to the shift in income distribution, but it does not explain the whole picture. When overall comfort levels decrease and travel becomes highly problematic due to congestion, gridlocks and pollution, households who can afford to purchase a larger, more comfortable vehicle will choose to do so in order to maximize their comfort (and utility) while being stuck in traffic. Therefore, we see large increases in the adoption of new SUVs in this scenario. Although households are opting for new SUVs with higher levels of comfort, they are choosing to do so at the cost of traveling less, due to the high variable cost of travel associated with the new SUV. We observe that the average household travels 7,209 miles in the first period, 8,702 miles, 8,691 miles, 11,566 miles and 14,962 miles in the next periods. Results from Scenario 2 (b) in Figure 24b show the same pattern but accelerated, with new SUV adoption rising to 67.45% in the final period. The percentage of households choosing to purchase new hybrid vehicles, new compact vehicles and new mid to full-size vehicles drops to 0% in period 2 of this specification.

Extended Scenarios 3 (a), (b) and (c) simulate the situation where environmental awareness grows along with economic development at a rate of 10% per period, 50% per period and 100% per period, respectively. Figure 25a shows the results of Extended Scenario 3 (a). The 10% increase in environmental awareness is approximately six times the rate of the environmental awareness proxy used in our U.S. calibrated simulations of 1.7%. This large disparity in the growth rate of environmental concern is not unreasonable, especially in developing countries where it starts at a very low level. The trend of new SUV adoption is increasing as before, starting at 2.44% in the first period and increasing to 5.43%, 6.14%, 14.32% and 26.98% in the following periods. This is equivalent to a growth rate of 89% per period. As households start to care about environmental issues more, they will choose to maximize their utility by switching to vehicles with better fuel-efficiency, leading to the slower growth of new SUV adoption. The result also illustrates that although the adoption of new SUVs is growing at a slower rate, it is still increasing, an effect of the increasing income distribution and changing shape of income distribution. Both new hybrid vehicle and new compact vehicle sales benefit from increasing environmental awareness due to their relatively better energy efficiency. New hybrid vehicles start at 0.45% of all vehicle purchases and increases to 1.92%, 3.80%, 9.85% and 20.11% in the next four periods. New compact vehicles also display a similar trend, increasing from 2.21% in predicted sales to 5.07%, 5.79%, 8.01% and 7.09%.

It is also important to note that the functional form for household utility includes environmental awareness only as a function of the vehicle type (and its fuel-efficiency), and it is not affected by number of miles traveled. Thus, the simulation model shows that a household at a given income level who chooses the same vehicle type will maximize utility by choosing to travel the same number of miles (if their income level remains constant) even if environmental awareness increases every period. In other words, the environmental awareness parameter does not influence the amount of travel conducted by each household. In Extended Scenario 3 (a), we see that the average household travels 7,209 miles in period 1. This number increases to 9,902 miles in period 2, 10,669 miles in period 3, 15,493 miles in period 4 and 21,459 miles in period 5. Comparing the amount of travel to the Main Scenario, we observe an increase in the number of miles traveled as environmental awareness increases. The increased travel can be attributed to the increased percentage of households who choose fuel efficient vehicles such as the new hybrid or new compact. When they choose such a vehicle, their variable cost of travel decreases and they will maximize utility by traveling more. In addition, the effect of the income distribution shift also contributes to the increased travel and cannot be ignored.

Figures 25b and 25c show the results from Extended Scenarios 3 (b) and (c). Again, a similar pattern of adoption is observed, but greater in magnitude as environmental awareness increases by 50% per period and 100% per period in the two specifications. New SUV adoption starts at 2.44% in Extended Scenario 3 (b) and increases to 4.64%, 6.14%, 14.49% and 27.26%. In Extended Scenario 3 (c), the adoption is slightly faster at 4.67% in period 2 and 6.22%, 14.66% and 27.54% in the subsequent periods. Comparing between the three specifications of Extended Scenario 3, we observe that when environmental awareness increases at a faster rate, the percentage of households purchasing new SUV actually increases. It may appear to be counterintuitive at the outset, but the difference can be attributed to a small amount of substitution from used vehicles to new vehicles. The percentage of households choosing to purchase new hybrid vehicles also follows a similar pattern as Extended Scenario 3 (a), increasing from 0.45% in the first period to 3.34%, 6.80%, 15.52% and 26.65% in the next four periods in Extended Scenario 3 (b) and to 4.73%, 7.42%, 16.30% and 27.69% in Extended Scenario 3 (c).

Finally, in Extended Scenario 4, we explore the possibility of dramatic increases of 100% per period in both comfort level and environmental awareness to examine how it would affect vehicle adoption. The results shown in Figure 26 are as dramatic as the premises of the simulation. New SUV adoption increases in period 2 to 4.10%, decreases to 3.15% in period 3, again increases to 7.22% in period 4 and then decreases down to 0% in period 5. The adoption of the new hybrid vehicle shows dramatic increases from 0.45% in the baseline period 1, and then takes off to 5.86%, 8.00%, 17.96% and 60.27% in the following periods, equivalent to an average increase of 401.26% per period.

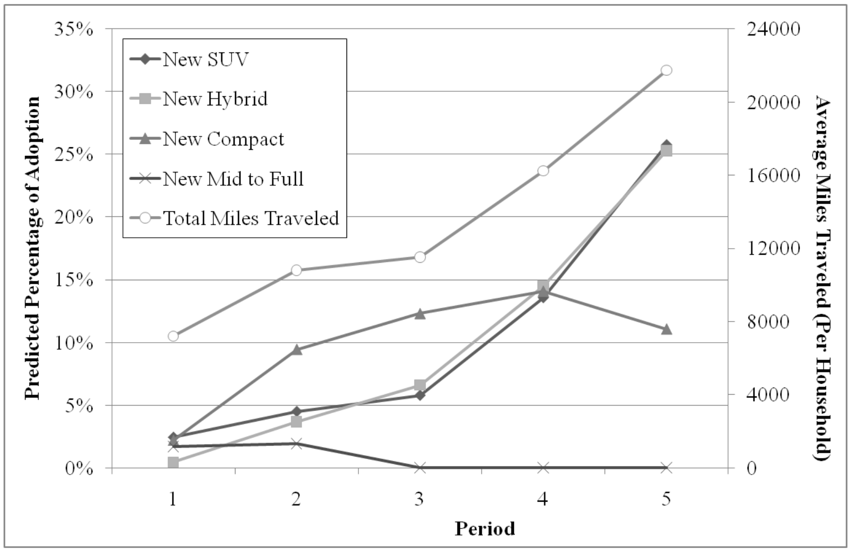
These fluctuations make more sense when each household structure is examined separately. Households with children (h=1) follow a similar pattern of choosing used compact vehicles, used large vehicles and new SUVs for the first four periods, with critical income ranges very close to those in the Main Scenario. In the fifth period, when both overall comfort level and environmental awareness have increased by sixteen-fold, households of this type chooses used compact vehicles, used large vehicles and new hybrid vehicles depending on household income, in this order. Households in the low-income range earning less than $15,050 will choose the used compact vehicle, households in the mid-income range earning between $15,050 and $71,250 will choose the used large vehicle and those in the upper-income range above $71,250 will choose the new SUV in period 5. Senior households (h=3) start out with an adoption pattern similar to that of households with children, choosing between the used compact, used large or new SUV depending on the household income level. In period 3, the pattern changes to choosing between used compact vehicle, used large vehicle or new mid to full-size vehicle, with the critical income levels at $43,150 and $70,500. In period 4, senior households switch between used compact vehicles and new mid to full-size vehicles at a critical income level of $71,850. In period 5, households of this type chooses between used compact vehicles or new hybrid vehicles, switching from the used compact vehicle to the new hybrid at a household income level of $84,750.

Households without children (h=2) choose used compact vehicles, used large vehicles, new compact vehicles, new mid to full-size vehicles, new hybrid vehicles and new SUVs depending on their income levels at the start of the simulation. In the next four periods of this specification, used compact vehicles, new compact vehicles and new hybrid vehicles dominate all other vehicle types for households without children. These three types of vehicles are more energy efficient, providing large gains in utility to households as environmental awareness increases through the periods simulated. In addition, as households travel more miles when the income distribution dynamically shifts up, it makes sense for them to purchase vehicles that involve lower variable cost. The fluctuations (or ups and downs) observed are simply due to the shifting critical income ranges, the different household structures choosing different vehicle types and the income distribution shift. All of these effects combined result in the vehicle adoption patterns that we see in Figure 26.

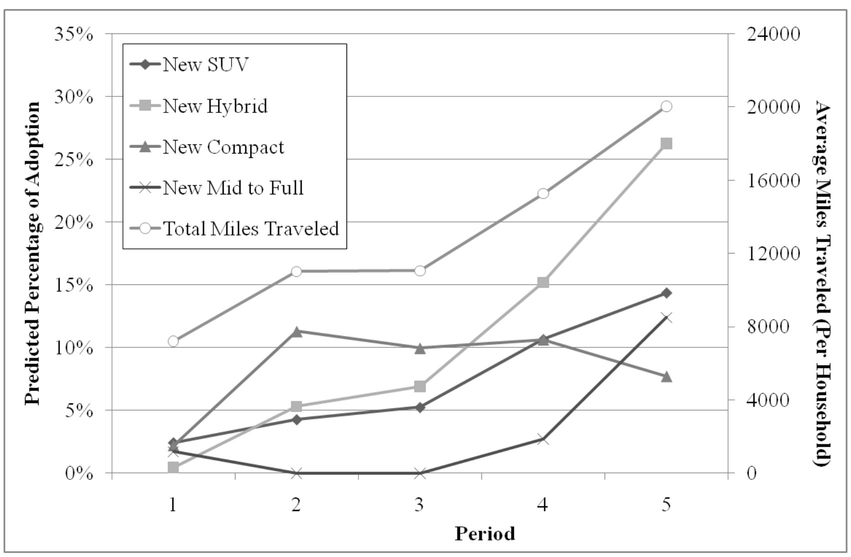
5.1.5 Conclusion and Policy Implications

This case study iterates through a plethora of possibilities that could occur in the context of a developing nation along with dynamic changes in the income distribution. It incorporates rapid economic growth as well as increasing inequality common in these economies. The dramatic changes occurring in developing nations such as China or India coupled with their large population size make them particularly of interest when considering the environmental impacts of vehicle adoption and diffusion. Of course, it would pose an incredible problem to the global society if every household in both China and India choose to adopt vehicles that consume large amounts of fuel and have high emissions as their income levels increase. If we are better able to understand the patterns of vehicle adoption, then we may better be able to devise policies to guide consumers towards better transportation options.

The Main Scenario focuses on these dynamic movements in the income distribution by simulating an increase in overall income levels and an increase in inequality. In such a scenario, we see high adoption of new SUVs along with small increases in the adoption of new hybrid vehicles. We also observe that households travel more miles. The results here are mainly attributed to the Income Distribution Effect, more households moving into the critical income ranges of the higher priced vehicles. Although the Variable Price Effect is present, its effects are dominated by the Income Distribution Effect. The simulation model shows that the dynamic shifts in income distribution leads to a preference for bigger, better (more comfortable) and newer vehicles. However, the percentages predicted only show the flow of vehicle demand. If we were to look at the stock of vehicles, the cumulative stock of larger

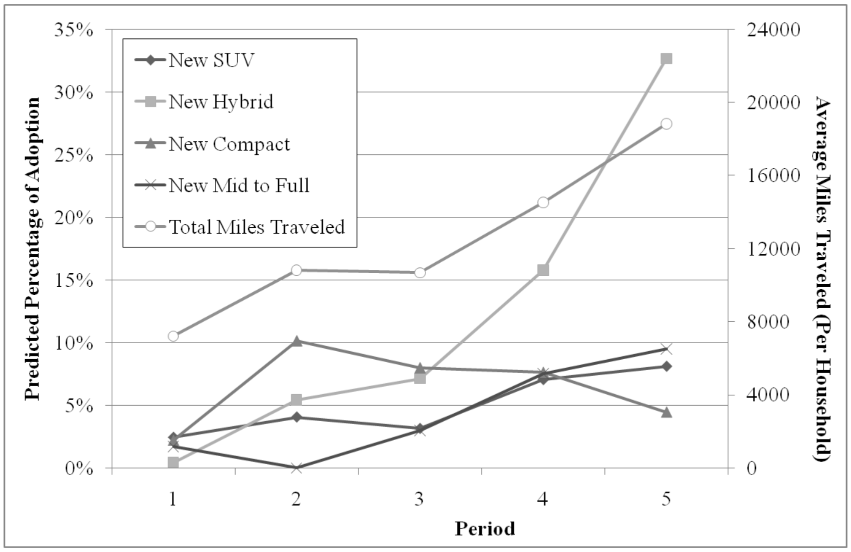


(a) 10% per period increase

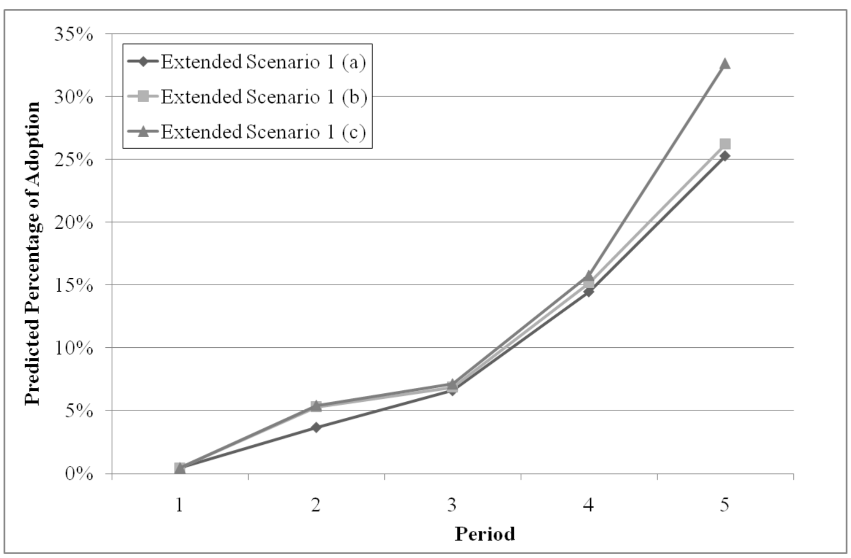


(b) 50% per period increase

Figure 23: Case Study I - Extended Scenario 1: Predicted percentage of all vehicle sales when comfort/quality level increases at different rates per period.

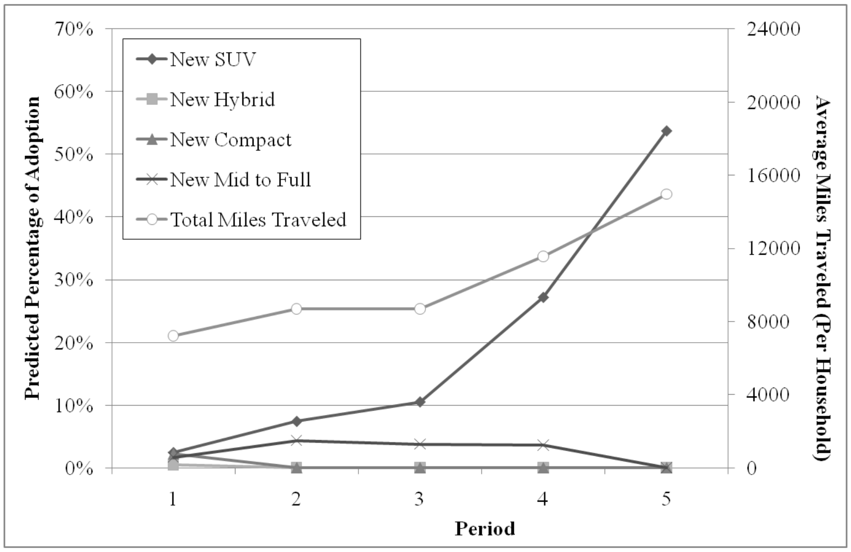


(c) 100% per period increase

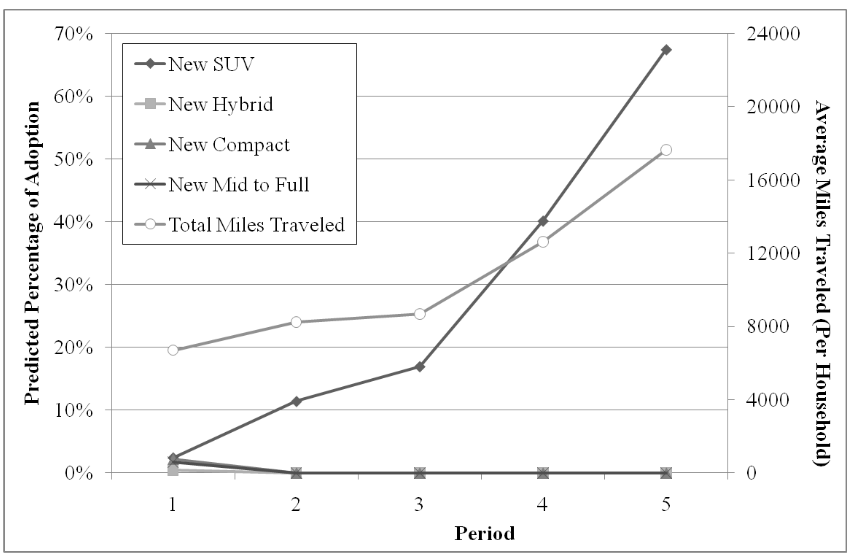


(d) Summary of New Hybrid Vehicle Adoption

Figure 23: Case Study I - Extended Scenario 1: Predicted percentage of all vehicle sales when comfort/quality level increases at different rates per period.

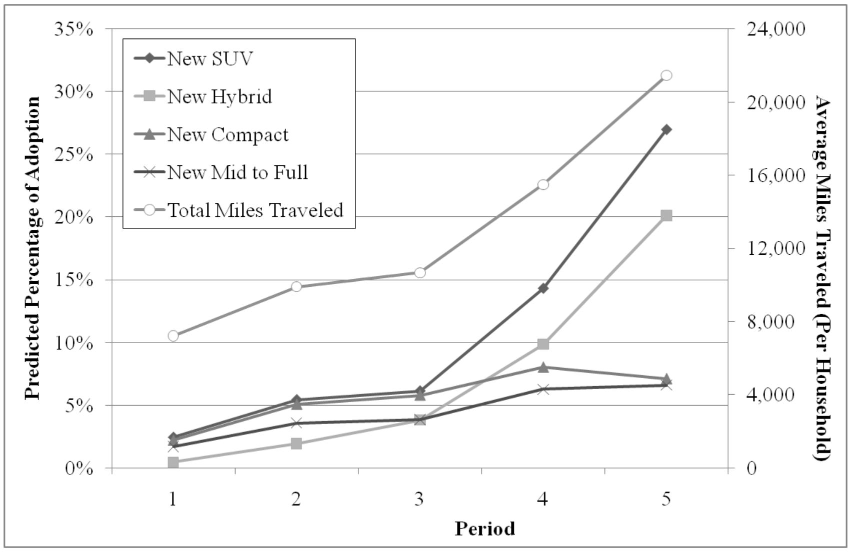


(a) 10% decrease per period

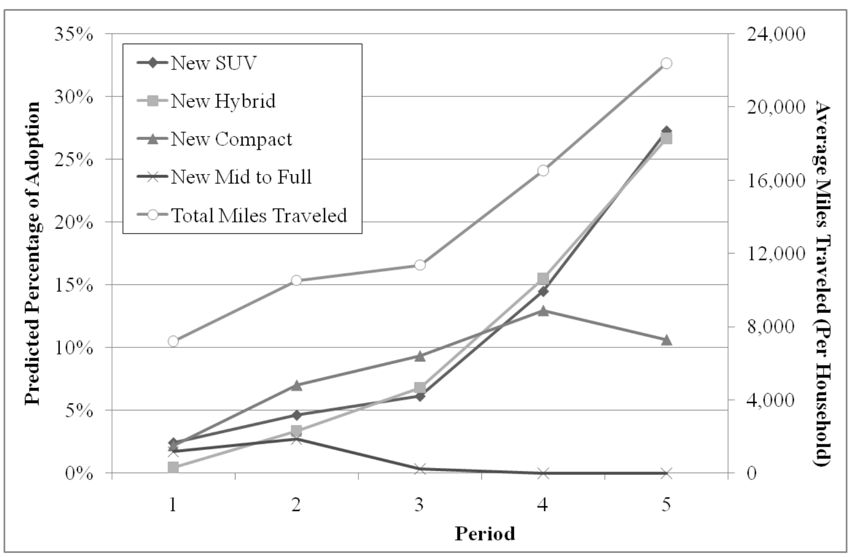


(b) 50% decrease per period

Figure 24: Case Study I - Extended Scenario 2: Predicted percentage of all vehicle sales when comfort/quality level decreases at different rates per period.

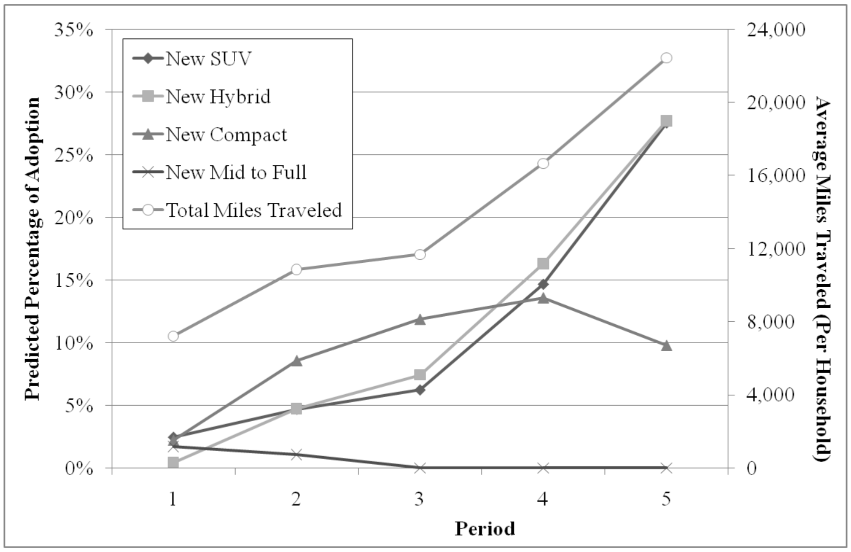


(a) 10% per period increase

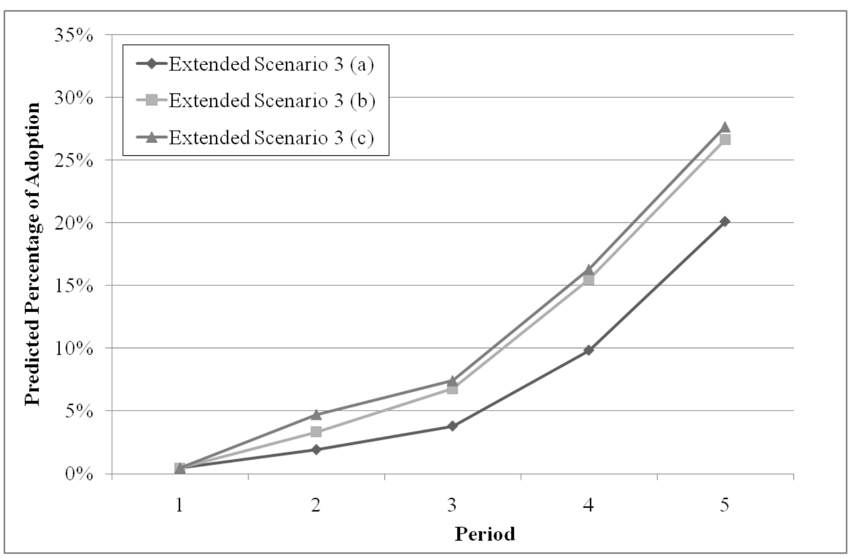


(b) 50% per period increase

Figure 25: Case Study I - Extended Scenario 3: Predicted percentage of all vehicle sales when environmental awareness increases at different rates per period.



(c) 100% per period increase



(d) Summary of New Hybrid Vehicle Adoption

Figure 25: Case Study I - Extended Scenario 3: Predicted percentage of all vehicle sales when environmental awareness increases at different rates per period.

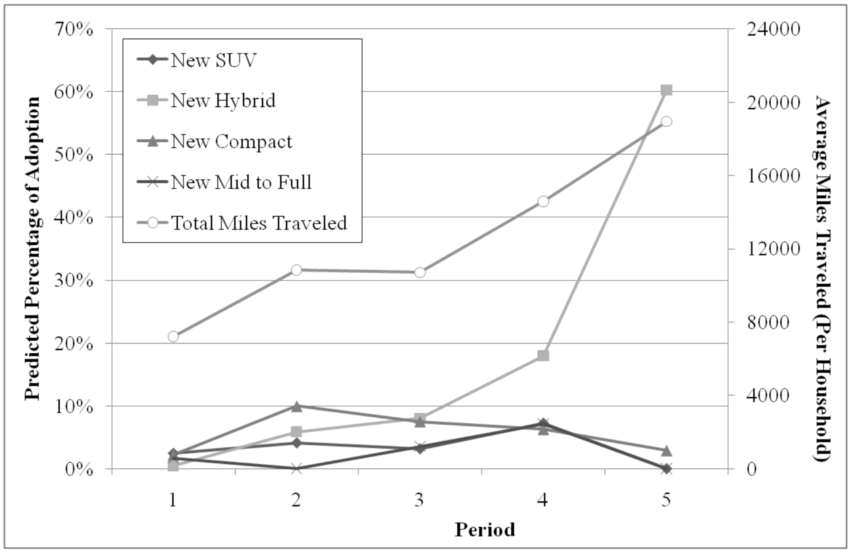


Figure 26: Case Study I - Extended Scenario 4: Predicted percentage of all vehicle sales when both comfort/quality level and environmental awareness increase by 100% per period.

vehicles such as the SUV may look even more impressive.

As transportation infrastructure is being improved and expanded in developing nations, we hypothesized two separate effects: increasing comfort levels due to better roadways and networks of roadways, and decreasing comfort levels due to increasing congestion or pollution caused by the increasing stock of vehicles and miles traveled. If it is the case that comfort levels are increasing (Extended Scenario 1), we would observe faster adoption of new hybrid vehicles and increasing (but at a slower rate) adoption of new SUVs. Overall, households are traveling more miles in this scenario. Four effects contribute to the change in optimal miles traveled: income distribution shift increases miles traveled, substitution towards more energy-efficient vehicles increases miles traveled, higher energy prices decrease miles traveled and the increasing overall comfort levels also decrease miles traveled. On the other hand, if it were true that construction of highways leads to increased congestion and pollution and overall lower comfort levels of travel (Extended Scenario 2), then we observe very rapid adoption of new SUVs. In this case, the decreasing levels of comfort encourages households to opt for more comfortable cars.

We hypothesize that there may be some evidence of the Environmental Kuznets Curve (EKC), meaning that as these developing economies are growing, we may observe an increase in the environmental awareness of the population. It may not be the case, but it is certainly worth considering what would happen if people did start caring more about the environment when they become wealthier. In the Extended Scenario 3, we observe faster adoption of hybrids and compact vehicles because households gain utility from knowing they have purchased a fuel-efficient vehicle. However, there is still significant increases in the adoption of new SUVs from the effects of the income distribution shift. For some households, although buying new hybrids might bring them utility through environmental awareness, the size, comfort and convenience of larger vehicles simply cannot be substituted by smaller vehicles. Another result we see here is that along with the increased adoption of fuel-efficient vehicles, households also travel more because the variable cost of travel is lower.

In the final extended scenario (Extended Scenario 4), we combine large increases in overall comfort with large increases in environmental awareness. The results show that if these dramatic changes did indeed occur, we would see new SUV adoption drop to zero while households would flock to new hybrid vehicles, embracing its high utility from environmental awareness. Unfortunately, this may not be the most realistic scenario of this case study.

In terms of policy, it is clear that simply building transportation infrastructure is not the straight-forward answer to encouraging the adoption of alternative fuel vehicles. Data from China indicates increasing levels of congestion as more money is being poured into transportation construction projects. The reality is possibly closer to the situation presented in Extended Scenario 2, where large portions of the population choose to purchase new SUVs or used large vehicles. Although increasing education in environmental awareness may encourage a certain amount of substitution towards energy-efficient vehicles, it appears that it may not be enough to counteract the effects of the shifting/increasing income distribution and the negatively growing comfort levels. If the emerging economy is left to its own devices and continues to grow at the current speed, the resulting environmental problems from energy consumption and greenhouse gas emissions could be significant. Drastic measures such as direct consumer subsidies for energy-efficient vehicles or research subsidies for manufacturers to encourage learning-by-doing for alternative fuel vehicles may be needed in order to circumvent the current trend both in the percentages of adoption as well as miles traveled in private vehicles shown in this case study.

5.2 Case Study II: Ageing Economies (Japan/Europe)

In developed economies such as Japan or European nations, fertility rates are decreasing, leading to decreasing number of households with children. Data shows that in both of these regions lower fertility rates coupled with longer life expectancy has resulted in a shift in the distribution of household structures to more senior households (head of household older than 65 years old) and more childless households. In this case study, we employ Japanese data from the National Survey of Family Income and Expenditure, Japan Statistical Yearbook and Census to construct several scenarios to simulate vehicle adoption trends. The data shows that from year 1999 to year 2009, real household annual income decreased by 1.624% per year (see Table 16), possibly due to decreased average number of earners per household and the increased number of households in retirement. The Census, conducted every 5 years, further reveals that from 1995 to 2005, households with children decreased on average by 0.65% per year and households with senior household heads increased on average by 1.495% per year (see Table 18). These parameters are applied in all of the case study scenarios described in Table 19. In addition to the parameters specified in Table 19, it is assumed that environmental awareness increases by 1.7% each period (following the same trend as the U.S.). Period 1 of this case study uses the household income distribution and household structure distribution detailed in Table 17 as the baseline starting point. In Scenarios 3 and 4, we generate predicted adoption patterns if income levels were to move in the opposite direction.

Year	**HH Mean Nominal Annual Income**	**HH Mean Real Annual Income (2005 yen)**	**CPI** (Base: 2005)
1999	¥6,494,000	¥6,304,854	103
2004	¥5,887,000	¥5,869,392	100.3
2007	¥5,530,000	¥5,513,460	100.3
2008	¥5,470,000	¥5,378,564	101.7
2009	¥5,350,000	¥5,333,998	100.3

Table 16: Household mean nominal and real annual income. (Source: 1999 and 2004 Japan National Survey of Family Income and Expenditure and 2007-2009 Japan Statistical Yearbook)

Household Income (10000s)	**All HHs**	**w/ Children** $h = 1$	**w/out Children** $h = 2$	**Senior** $h = 3$
¥0 - ¥200	10.44%	3.34%	1.87%	4.64%
¥200 - ¥300	11.59%	4.12%	2.30%	4.65%
¥300 - ¥400	14.87%	5.97%	3.34%	5.13%
¥400 - ¥500	13.41%	6.54%	3.66%	3.20%
¥500 - ¥600	11.09%	6.02%	3.37%	1.90%
¥600 - ¥800	16.49%	9.62%	5.38%	2.01%
¥800 - ¥1000	9.91%	5.98%	3.35%	0.96%
¥1000 - ¥1250	6.29%	3.84%	2.15%	0.56%
¥1250 - ¥1500	2.90%	1.78%	1.00%	0.25%
¥1500 - up	3.02%	1.65%	0.93%	0.50%
Total		48.85%	27.35%	23.80%

Table 17: Japan household income distribution and household structure distribution. (Source: 2004 Japan National Survey of Family Income and Expenditure and 2000 Japan Census.)

Year	**Total HHs**	**w/ Children** $h = 1$	**w/out Children** $h = 2$	**Senior** $h = 3$
1995	43.900	23.065	12.169	8.668
		(52.54%)	(27.72%)	(19.74%)
2000	46.782	22.855	12.795	11.136
		(48.85%)	(27.35%)	(23.80%)
2005	49.062	22.589	9.454	17.020
		(46.04%)	(19.27%)	(34.69%)

Table 18: Changes in Japanese household structure. (Source: 1995 to 2005 Japan Census (millions of households)).

5.2.1 Results and Discussion

Scenarios 1 and 2 both closely follow the pattern of Japan's progression of lower income levels, more senior households and less households with children. As energy price increases and new hybrid vehicles become cheaper through the process of learning-by-doing, we see increasing adoption of the hybrid technology. In all the scenarios, new hybrid vehicle adoption begins in the first periods with an growing rate of adoption (similar to the take-off period of the S-shaped diffusion curve) and then gradually slows down to lower rates of increases as we head into the latter portion of the S-shaped diffusion curve, consistent with the theoretical model.

In each of the scenarios simulated in this case study, we begin from a baseline period 1 that follows the income distribution and household structure distribution from Table 17. In this first period, households with children (h=1) who have high demands for vehicle passenger capacity, vehicle cargo capacity, convenience as well as comfort choose to purchase used compact vehicles, used large vehicles and new SUVs depending their income levels. The critical income at which these households switch from used compact vehicles to used large vehicles (I_c^1) is approximately ¥800,000 (nominal). They will switch over to new SUVs at a critical income (I_c^2) of approximately ¥9,900,000.

Senior households (h=3) are similar to households with children in their higher demands for comfort and convenience, but also have less propensity to adopt newer technology. These households also choose to purchase used compact vehicles if their income is below the critical income level (I_c^1) of ¥1,930,000. Within the critical income range between ¥1,930,000 and ¥9,260,000, senior households maximize utility by choosing used large vehicles. Those who have incomes above ¥9,260,000 will choose new SUVs in this first period.

Households without children (h=2) account for almost 30% of the population in the baseline period 1. This particular household type will adopt the used compact vehicle, used large vehicle, new compact vehicle, new mid to full-size vehicle, new hybrid vehicle and new SUV, in this order from the lowest income level to the highest income level. The households with income levels below the critical income level (I_c^1) of ¥4,430,000 will choose the lowest fixed cost option of used compact vehicles. Between ¥4,430,000 and ¥6,400,000, households without children purchase used large vehicles. Between ¥6,400,000 and ¥7,900,000, the household will choose to purchase a new compact vehicle. The households with income levels above ¥7,900,000 but

	Parameter	Change per period
Scenario 1 (a)	**Household income level**	decrease 1.624%
	New hybrid vehicle price	decrease 1%
	Energy price	increase 1%
Scenario 1 (b)	**Household income level**	decrease 1.624%
	New hybrid vehicle price	decrease 1%
	Energy price	increase 5%
Scenario 2 (a)	**Household income level**	decrease 1.624%
	New hybrid vehicle price	decrease 5%
	Energy price	increase 1%
Scenario 2 (b)	**Household income level**	decrease 1.624%
	New hybrid vehicle price	decrease 5%
	Energy price	increase 5%
Scenario 3 (a)	**Household income level**	increase 1.624%
	New hybrid vehicle price	decrease 1%
	Energy price	increase 1%
Scenario 3 (b)	**Household income level**	increase 1.624%
	New hybrid vehicle price	decrease 1%
	Energy price	increase 5%
Scenario 4 (a)	**Household income level**	increase 1.624%
	New hybrid vehicle price	decrease 5%
	Energy price	increase 1%
Scenario 4 (b)	**Household income level**	increase 1.624%
	New hybrid vehicle price	decrease 5%
	Energy price	increase 5%

Table 19: Case Study II Scenarios

below ¥13,270,000 will adopt the new hybrid vehicle while household with income levels above the critical income level of ¥17,140,000 will choose the new SUV.

By period 10 of Scenarios 1 and 2, the overall household income levels have fallen by a total of 13.7%. This shift in the income distribution means that households are falling into different critical income regions, causing the majority of the adoption pattern changes. We will first look at Scenario 1 where the fixed cost of a new hybrid falls by 1% per period. Comparing between (a) and (b) of Scenario 1 in Figure 27, new hybrid vehicle adoption follows a similar pattern in both of these situations. However, we observe a slightly faster rate of adoption in (b) where energy price increases at 5% per period. As energy price increases, the critical income interval at which households choose to adopt new hybrid vehicles becomes larger, indicating a substitution away from new mid to full-size vehicles first, and then away from new compact vehicles which tend to be less efficient compared to the hybrid. When we reach period 5 in Scenario 1, the utility from purchasing a new hybrid vehicle completely dominates the utility from purchasing new mid to full-size vehicles. The same thing happens for new compact vehicles as new hybrid vehicles take over in period 9 of this simulation. Hybrid technology becomes cheaper through learning-by-doing, lowering the fixed cost of adoption, and energy prices are increasing, increasing the overall variable cost of travel for all vehicle types, but lowering the relative variable cost of traveling by hybrid vehicles. These factors together contribute to the increasing adoption of the technology.

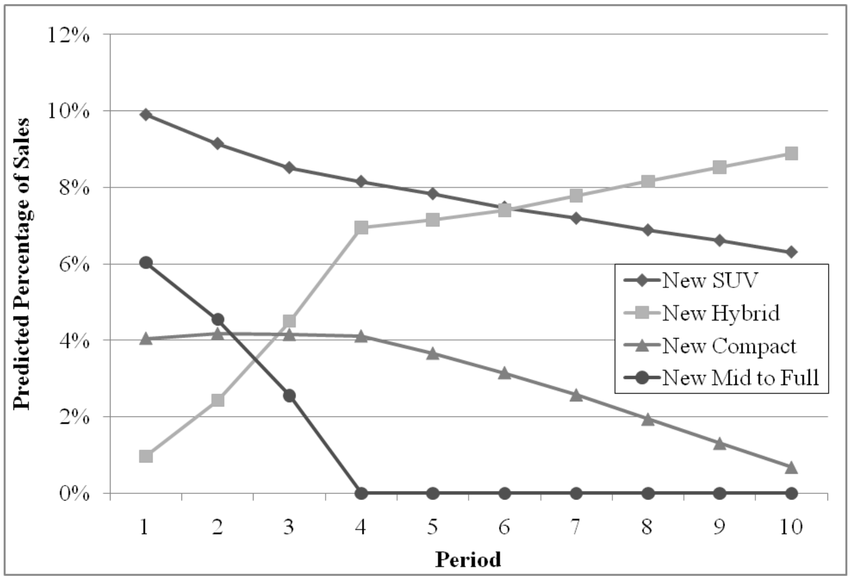
There is also some substitution away from new SUVs that appears to be faster in Scenario 1 (a) than in Scenario 1 (b), ending at 6.31% and 7.18%, respectively. It may seem to be counterintuitive that when energy price increases 5% instead of 1% we do not observe households ditching gas-guzzling SUVs much more quickly. However, it is again important to note that the consumer optimization involves a continuous choice of miles to travel in addition to the discrete choice of vehicles in our model. When households travel less miles as the per-mile variable cost goes up, the marginal utility of comfort/convenience/quality increases, effectively making new SUVs more attractive for some households.

Scenario 2 follows the same specifications as Scenario 1, but includes a 5% learning-by-doing decrease in new hybrid prices per period. It is not surprising that the results shown in Figure 28 are of the same shape and direction as Scenario 1 just discussed, but displays greater magnitude. The movement towards higher levels of hybrid technology adoption is much faster, ending with 21.59% in Scenario 2

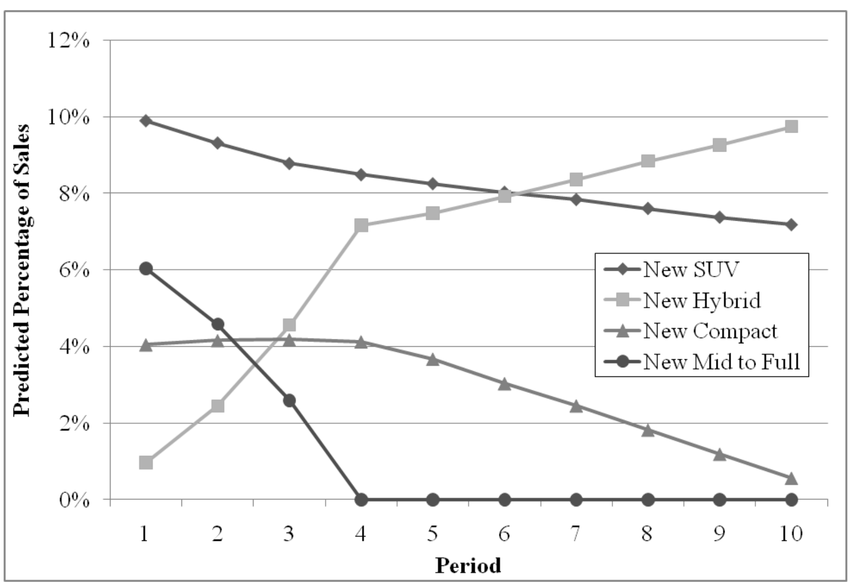
(a) and 22.09% in Scenario 2 (b). In addition, we are able to observe that the growth rate of new hybrid adoption after period 3 appears to be fueled by households substituting towards new hybrid vehicles instead of used vehicles as they become much more affordable. The percentage of households choosing to purchase new SUVs in period 5 is 6.31% and 7.18% in Scenarios 2 (a) and (b), which is exactly the same as the results from Scenario 1. It is not unreasonable to conclude that even when new hybrid vehicles become very cheap and energy prices become very high, a certain number of households would still prefer to purchase new SUVs which provides convenience, capacity and comfort that may not be substitutable by any other type of vehicles. In other words, these households maximize their utility through the choice of new SUVs even at a high fixed cost and high variable cost.

Scenarios 3 and 4 are similar to Scenarios 1 and 2 except they involve a growing (albeit slowly) economy where overall household income increases by 1.624% per period. These specifications may be more similar to developed economies in Europe where income is increasing at a low rate, and the economy is also experiencing the same shifts of household dynamics as Japan (i.e. lower birth rates, less households with children and more senior households). With increasing household annual income levels, we observe even faster adoption of the hybrid vehicle technology in Figures 29 and 30. On the other hand, the predicted percentage of households choosing new SUVs do not decline in these scenarios, increasing to 13.93% in Scenarios 3 (a) and 4 (a) and 15.43% in Scenarios 3 (b) and 4 (b) in the last period. This signifies that more households are moving into the critical income levels for purchasing new SUVs as the overall income distribution shifts to the right each period, and more households are able to afford the more expensive vehicles such as the new SUV and the new hybrid vehicle.

Figure 31 summarizes the predicted percentage of new hybrid vehicle sales in all four scenarios to provide a comparison between the different specifications. Given the parameters that are changing in this particular case study, the figure shows that the cost of new hybrid vehicles is the largest factor contributing to its adoption. In addition, the rightward shift of the income distribution shifts, indicating increasing income or a growing economy, also cause more household to be able to afford the new technology. Finally, energy price fluctuations do play a role in vehicle technology adoption, but can also affect the optimal number of miles traveled and the marginal utility of comfort/quality.

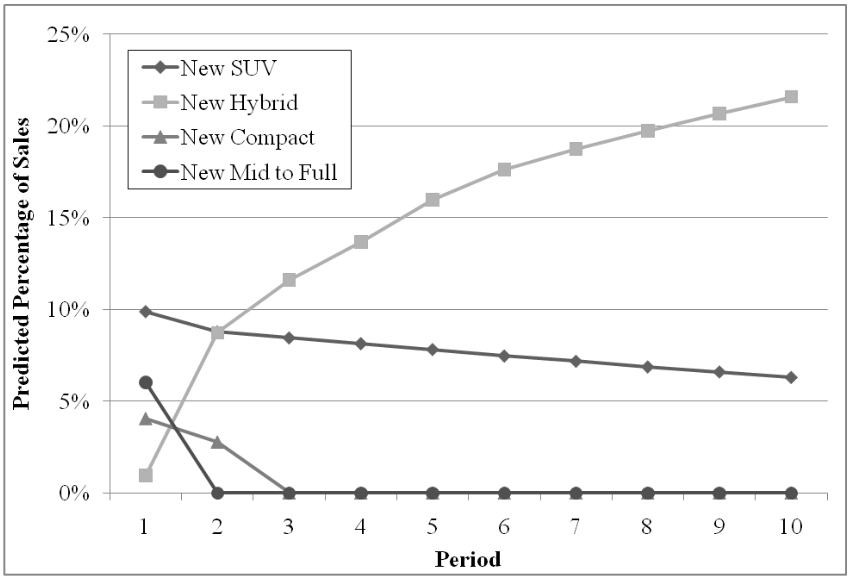


(a) 1% annual increase

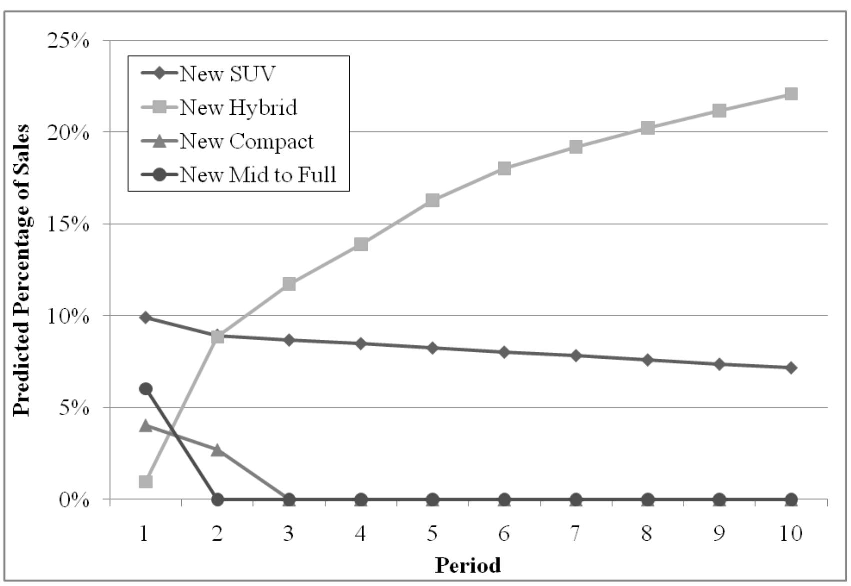


(b) 5% annual increase

Figure 27: Case Study II - Scenario 1: Predicted percentage of all vehicle sales with different annual rates of energy price increases.

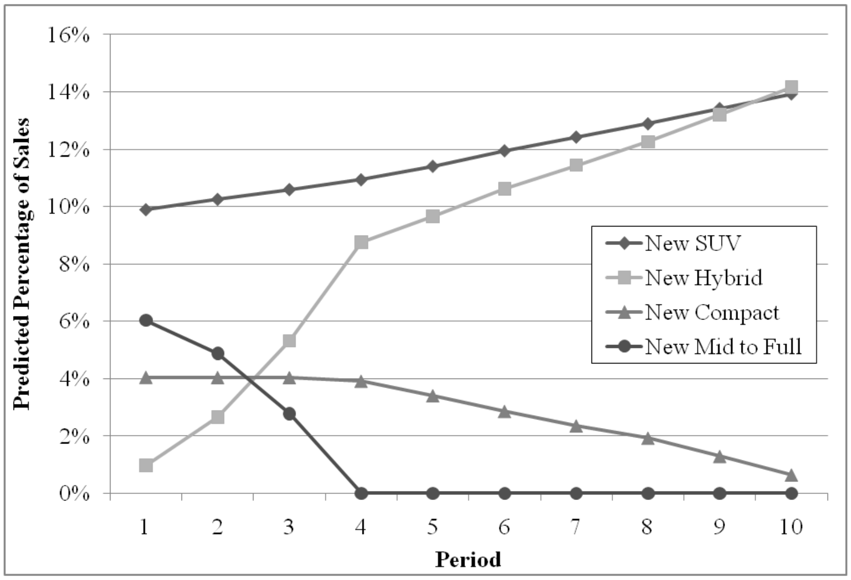


(a) 1% annual increase

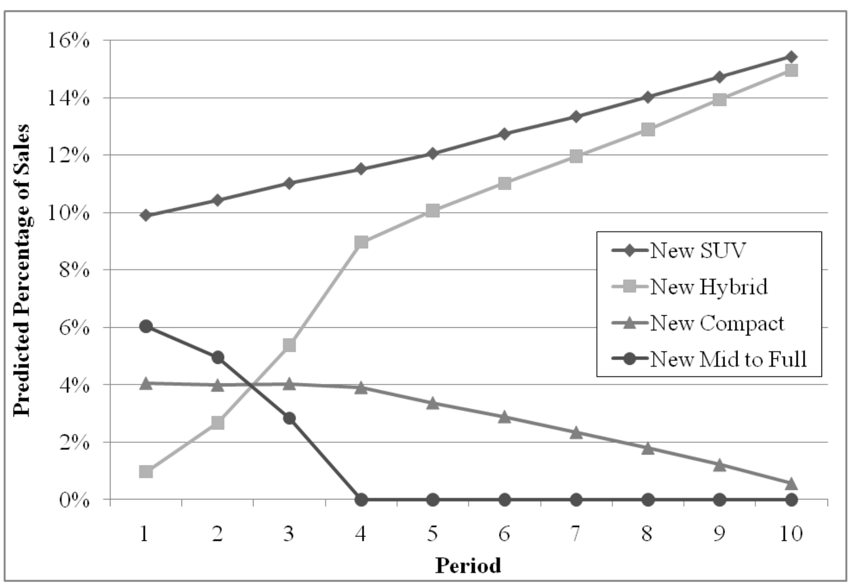


(b) 5% annual increase

Figure 28: Case Study II - Scenario 2: Predicted percentage of all vehicle sales with different annual rates of energy price increases.

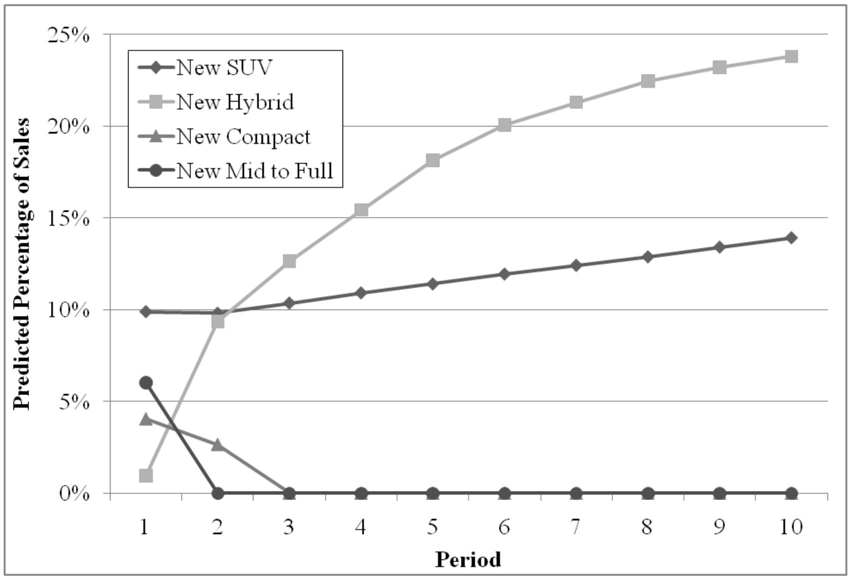


(a) 1% annual increase

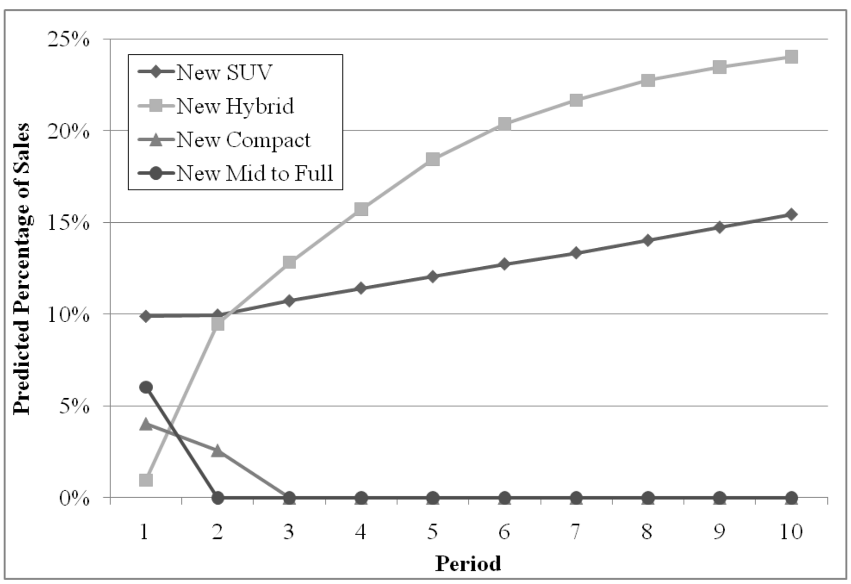


(b) 5% annual increase

Figure 29: Case Study II - Scenario 3: Predicted percentage of all vehicle sales with different annual rates of energy price increases.



(a) 1% annual increase



(b) 5% annual increase

Figure 30: Case Study II - Scenario 4: Predicted percentage of all vehicle sales with different annual rates of energy price increases.

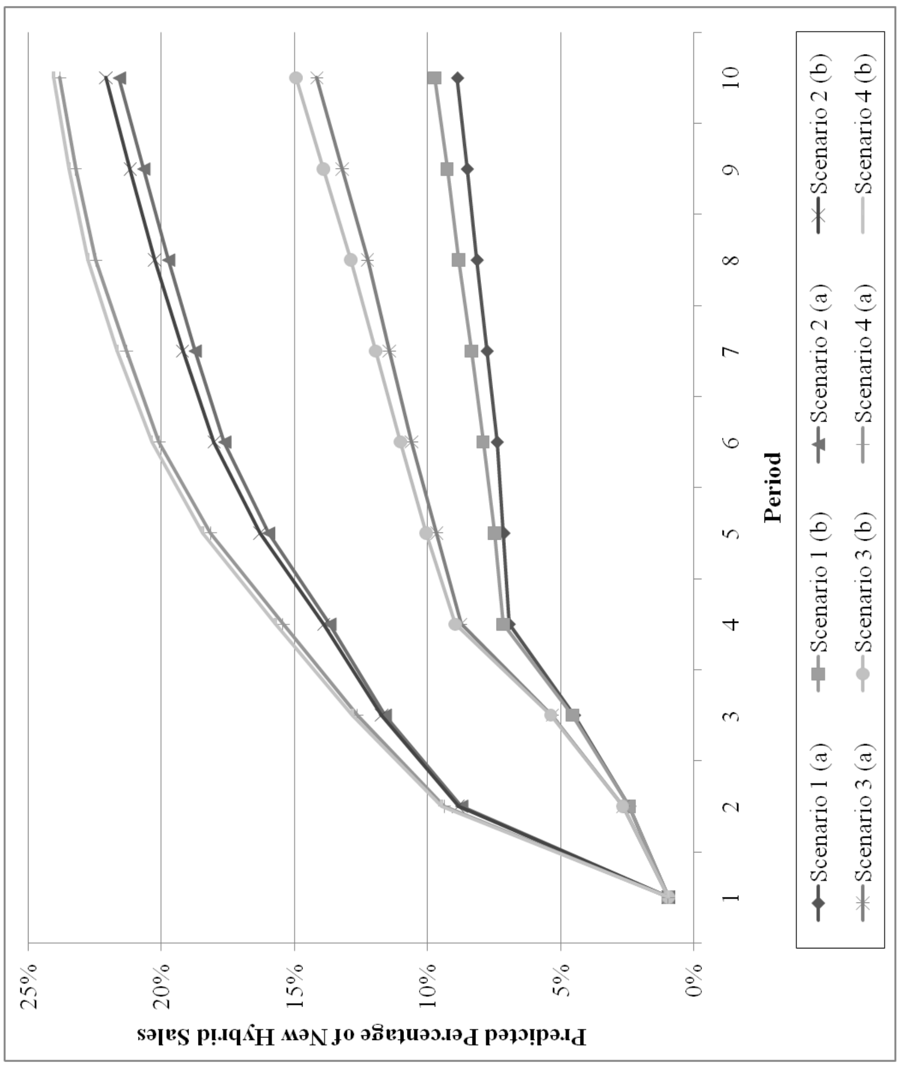


Figure 31: Case Study II: Predicted percentage of hybrid vehicle sales in the various scenarios.

5.2.2 Conclusion and Policy Implications

Ageing economies such as Japan and European nations present an interesting scenario. They are highly developed, which means there are less dramatic dynamic changes, but the composition of the population is gradually evolving towards more senior households and less households with children. Although this is not the current situation in the U.S., there is some evidence that the population is ageing as well. In addition the social welfare concerns and worries of a stagnant economy with an ageing society, vehicle adoption patterns are also gradually changing. This case study provides a look into what may be the future for the U.S. and the patterns of vehicle adoption in such a scenario.

Scenarios 1 and 2 illustrate the situation with a shrinking economy, increasing number of senior households and decreasing number of households with children, increasing energy price and decreasing hybrid vehicle prices due to learning-by-doing. We observe a strong preference for new hybrid vehicles and a decreasing preference for new SUVs. The increase in hybrid vehicle adoption occurs even with the decrease in overall income levels of households. This effect becomes accelerated as hybrid vehicle prices drop at a faster rate or when energy prices are increasing at a faster rate.

Scenarios 3 and 4 illustrate a growing economy with the same specifications of household structure changes, energy price changes and new hybrid vehicle price changes. With a growing economy, households are becoming wealthier, leading to even faster adoption of new hybrid vehicles. New SUVs are also adopted at an increasing rate by households in this scenario.

The results of this case study scenario indicate that although the effects of household structure changes and growing/shrinking economy do affect the overall adoption patterns, the most significant effect is attributed to the fixed cost of any given technology. Since the growth (or shrinkage) of the economy is gradual and not as dramatic in scale as the emerging economies case study, its effects are limited. The amount of effort put into researching and developing the alternative vehicle technology to either decrease the cost of production or to increase the comfort/quality level of hybrid vehicles (or any other alternative fuel vehicle) should have the most significant impacts in these regions of the world.

5.3 Case Study III: Public Transportation

Throughout this paper we assumed the lack of a public transportation option, but the model and simulation both are capable of analyzing such a scenario. Although households that purchase vehicles will likely travel predominantly in their private vehicles, they may choose to utilize public transportation for a portion of their travel needs if doing so maximizes their utility functions. This case study scenario expands upon the previous simulation of U.S. travel, and it also follows many of the same assumptions. We focus specifically on public transportation in this case study and look at what happens to the adoption of vehicles as well as public transportation when the alternative to not own a car exists.

Public transportation is unique because it entails zero private fixed cost but with the tradeoff of higher variable cost per mile traveled compared to driving a private vehicle. According to the Bay Area Rapid Transit (BART), passengers typically pay $0.20 per mile traveled. In this case study, we will assume a variable per mile cost of $0.20 and zero fixed cost for public transportation. It is quite possible to set up a simulation that includes multiple public transportation options with varying comfort levels and variable costs, but for the purpose of demonstrating the capabilities of the simulation model, we will include only one public transportation option. In addition, it is also common to observe increases in public transportation fares from year to year, possibly due to increased maintenance and operation expenses, increased energy prices, ridership changes or decreased public subsidization. This case study will incorporate different rates of public transportation price increases as well.

One additional characteristic of public transportation is the lack of comfort/quality for all types of households, especially for households with young children or households with senior members. Families with young children often need to carry supplies such as diapers, booster seats or extra clothing, or adults may have difficulty supervising or moving multiple children aboard public transportation. Households with either children or senior members may face additional difficulties due to the walking distance or limited accessibility that may be common when utilizing public transportation. Even households without children face difficulties with carrying cargo or shopping bags via public transportation. Moreover, public transportation often does not depart from or arrive at the exact locations where households intend to travel, decreasing the amount of convenience and increasing the amount of difficulty for many users. Therefore, to account for these problems, the comfort/quality parameter for public transportation is assumed to be 0.5 for both households with children

Vehicle Type	Baseline Comfort	w/ Children $h = 1$	w/out Children $h = 2$	Senior $h = 3$
Used Compact	2.25	1.125	2.25	2.25
Used Large	8.1	24.3	8.1	12.15
New Compact	2.5	0.625	2.5	1.25
New Mid to Full	5.5	8.25	5.5	6.6
New SUV	12.5	37.5	12.5	18.75
New Hybrid	2.5	0.5	2.5	2
Public Transportation	1	0.5	1	0.5

Table 20: Heterogeneous Comfort Parameters for Different Household Structures

and senior households and 1 for households without children as summarized in Table 20. These parameters are created because of a lack of critical data that details the comfort/quality of public transportation in relationship to private vehicles.

Another factor in the household utility maximization that plays an important role in the choice process is environmental awareness. As before, this case study simulation uses a proxy that is a combination of vehicle-specific energy efficiency (higher for more fuel-efficient vehicles) and the percentage of people who understand global warming well or fairly well from the Gallup annual Environment poll. Following from the calibration of the simulation model, we assume that the annual increase in environmental awareness is approximately 1.7%. It is also reasonable to assume that public transportation users gain a certain amount of utility from using a mode of transportation that is environmentally friendly, similar to the buyers of hybrid vehicles. Depending on the particular type of public transportation, we observe different levels of energy efficiency and carbon emissions. For simplicity, this case study will assume that energy efficiency is twice that of a new hybrid vehicle when calculating the environmental awareness proxy.

In Scenarios 1 through 4, household structures and income distribution remains constant through each period (approximately 35% households with children, 45% households without children and 20% senior households, see Table 3). Scenario 1 takes place where energy prices are relatively stable, increasing by 1% per period, but in Scenarios 1 (a) through (d), we observe different rates of increase in public transportation prices. Scenario 2 is similar to Scenario 1 except energy price increases more, at 5% per period. In Scenarios 3 and 4, we add on learning-by-doing price decreases for new hybrid vehicles, 1% per period in Scenario 3 and 5% per period in Scenario 4. In Scenario 5, income distribution follows the shift shown in Figure 18 to combine the developing nation scenario of Case Study I with Scenarios 1 and 2 of Case Study III. This particular expansion brings the simulation closer to the current situation in many parts of China or India where the majority of the population within the lower income groups may not choose (or are unable to choose) to purchase a private vehicle. The above hypothesis is consistent with the theoretical model prediction that the households below a certain income threshold will prefer the transportation option with the lowest fixed cost. Scenarios 3 and 4 further expands upon Scenarios 1 and 2 by adding a learning-by-doing decrease in new hybrid vehicle price of 1% and 5% per period. Case Study III scenario parameters are summarized in Tables 21, 22 and 23.

	Parameter	**Change per period**
Scenario 1 (a)	**Energy price**	increase 1%
	Public transportation price	no change
Scenario 1 (b)	**Energy price**	increase 1%
	Public transportation price	increase 1%
Scenario 1 (c)	**Energy price**	increase 1%
	Public transportation price	increase 5%
Scenario 1 (d)	**Energy price**	increase 1%
	Public transportation price	increase 10%
Scenario 2 (a)	**Energy price**	increase 5%
	Public transportation price	no change
Scenario 2 (b)	**Energy price**	increase 5%
	Public transportation price	increase 1%
Scenario 2 (c)	**Energy price**	increase 5%
	Public transportation price	increase 5%
Scenario 2 (d)	**Energy price**	increase 5%
	Public transportation price	increase 10%

Table 21: Case Study III - Scenarios 1 and 2

	Parameter	Change per period
Scenario 3 (a)	**Energy price**	increase 1%
	Public transportation price	no change
	New hybrid vehicle price	decrease 1%
Scenario 3 (b)	**Energy price**	increase 1%
	Public transportation price	increase 1%
	New hybrid vehicle price	decrease 1%
Scenario 3 (c)	**Energy price**	increase 1%
	Public transportation price	increase 5%
	New hybrid vehicle price	decrease 1%
Scenario 3 (d)	**Energy price**	increase 1%
	Public transportation price	increase 10%
	New hybrid vehicle price	decrease 1%
Scenario 4 (a)	**Energy price**	increase 5%
	Public transportation price	no change
	New hybrid vehicle price	decrease 5%
Scenario 4 (b)	**Energy price**	increase 5%
	Public transportation price	increase 1%
	New hybrid vehicle price	decrease 5%
Scenario 4 (c)	**Energy price**	increase 5%
	Public transportation price	increase 5%
	New hybrid vehicle price	decrease 5%
Scenario 4 (d)	**Energy price**	increase 5%
	Public transportation price	increase 10%
	New hybrid vehicle price	decrease 5%

Table 22: Case Study III - Scenarios 3 and 4

	Parameter	Change per period
Scenario 5 (a)	**Energy price**	increase 1%
	Public transportation price	no change
	Income distribution	follows Case Study I see Figure 18
Scenario 5 (b)	**Energy price**	increase 1%
	Public transportation price	increase 1%
	Income distribution	follows Case Study I see Figure 18
Scenario 5 (c)	**Energy price**	increase 5%
	Public transportation price	increase 0%
	Income distribution	follows Case Study I see Figure 18
Scenario 5 (d)	**Energy price**	increase 5%
	Public transportation price	increase 5%
	Income distribution	follows Case Study I see Figure 18

Table 23: Case Study III - Scenario 5

5.3.1 Scenarios 1 and 2 - Results and Discussion

The results from the case study Scenarios 1 and 2 are presented in Figures 32 and 33. In Scenario 1, energy price increases by 1% per period while public transportation prices increase by 0% (Scenario 1 (a)), 1% (Scenario 1 (b)), 5% (Scenario 1 (c)) and 10% (Scenario 1 (d)) per period. In Scenario 2, energy price increases by 5% per period while public transportation prices increase by 0% (Scenario 2 (a)), 1% (Scenario 2 (b)), 5% (Scenario 2 (c)) and 10% (Scenario 2 (d)) per period. We hypothesize that public transportation ridership will benefit from high energy price increases and low public transportation prices, which is consistent with common intuition. These are scenarios that may be of high interest to public transportation agencies during years where energy prices do not fluctuate enough to create waves of people ditching cars for buses/trains. The results will provide insight into how public transportation prices interact with energy price movements.

It is clear from Figures 32 and 33 that public transportation ridership does indeed benefit from high energy price increases and low public transportation prices: the higher energy prices and lower public transportation prices, the greater the increase in public transportation adoption. Figure 34 summarizes the percentage of households who choose public transportation in lieu of purchasing a private vehicle in both Scenarios 1 and 2. Looking at this more detailed figure gives us a clearer picture of how public transportation prices may influence household decisions. The results shown are consistent with the historical trend that saw increasing public transit ridership nationwide during energy price hikes, similar to the situation in 2008. On the other hand, we observe decreasing ridership as public transportation becomes more expensive, even if riding public transportation provides higher environmental awareness utility. In Figure 32c and 32d and Figure 33, when public transportation prices increase faster than overall energy prices, households tend to substitute towards purchasing more used vehicles to satisfy their transportation needs. This result may be significant in the public policy arena where fare increases often cause heated debate, particularly in determining the price elasticity of demand of public transportation.

With regards to the percentage of other vehicle sales, we observe consistent results with the theoretical model and previous simulations. As energy price increases, households substitute towards relatively more fuel efficient vehicles such as the new hybrid vehicle or new compact vehicle and away from larger, more fuel-consuming vehicles. This result is more prominent when energy price increases at a faster rate.

In addition, households also drive less when energy price is higher, due to both the substitution effect (households substitute towards relatively cheaper goods, which are all other goods) and the income effect (households become less wealthy due to the price increase, so they drive less) in consumer theory. For the most part, when the price of public transportation is changing, we see a shift in the critical income level at which households switch between public transportation and used compact vehicles. This means that those who choose other types of vehicles are essentially not affected by the introduction of the public transportation alternative into the scenario, relating to the axiom of independence of irrelevant alternatives in consumer choice theory.

Looking more specifically at Scenario 1 (a) in Figure 32a where energy price increases by 1% per period and public transportation prices remain constant, we observe approximately 0% change in public transportation ridership from period 1 to period 4, remaining stagnant at 1.30%. Then, in period 5, the energy price becomes high enough for some people to switch over to public transportation, causing a 10.00% increase. In this particular scenario, some percentage of households in household structures types of households with children (h=1) and households without children (h=2) choose public transportation. Households with children (h=1) choose public transportation below a critical income level of $5,900 while households without children (h=2) will choose the same below an income level of $6,250 for periods 1 through 4 and $6,500 for period 5. Senior households (h=3) do not choose public transportation at all in the simulation. Those senior households in the lowest income levels will instead choose used compact vehicles. The households that choose to travel using public transportation will each travel approximately 1,055 miles per year on average for periods 1 through 4. In period 5, households travel an average of 1,086 miles via public transportation. This slight increase in the number of miles traveled is due to the additional adoption by households of type 2 (households with children) when the critical income level increased. These households earn slightly more than those who adopted public transportation in the first four periods, and their optimal number of miles traveled is higher.

In Scenario 1 (b) shown in Figure 32b, we observe negligible change in public transportation through the periods when public transportation prices increase in sync with energy prices. The effects of energy price increases and public transportation price increases essentially cancel each other out in this particular case. Although the percentage of households choosing public transportation remains constant, the average number of miles each of these households travels on public transportation starts at 1,055 miles in the first period and drops to 1,046, 1,037, 1,028 and 1,019 miles in the following periods. This means that although the same portion of the population utilizes public transportation through all periods in this scenario, as public transportation prices go up, these households are utilizing public transportation less. Both the substitution effect and the income effect are evident here when households choose to make up for higher fares by taking less rides or shorter rides.

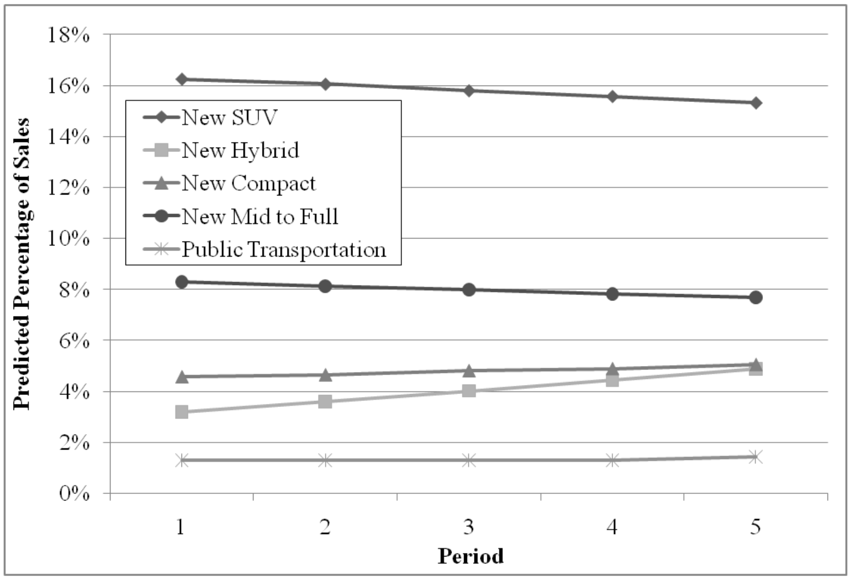
Scenario 1 (c) is set up such that public transportation prices are increasing at a faster rate (5% per period) than energy prices (1% per period). Here public transportation experiences large decreases (Figure 32c), going from 1.30% of households choosing public transportation to 1.09%, 0.89%, 0.68% and 0.55% in following periods. This is equivalent to a per period decrease ranging from 16.15% to 23.60% because investing in a private vehicle that comes with lower variable costs for transportation becomes more attractive when public transportation is more expensive. Households with children (h=1) usually do not find public transportation to be an attractive transportation option compared to private vehicles due to reasons previously discussed. Only households with incomes below $5,900 will choose public transportation in the first period, and this income level drops to $5,300 in the final period. Households without children (h=2) choose public transportation below the critical income level of $6,250 in the first period and $5,500 in the last period. Again, no senior households (h=3) prefer public transportation over other private vehicle options. Within those who choose to travel by public transportation, the average annual miles traveled starts at 1,055 miles and gradually drops to 1,002, 955, 918, 839 miles as public transportation becomes more expensive. The overall conclusion from this particular scenario is that when public transportation prices become too high, it will push consumers towards purchasing low fixed cost private vehicles to lower their per-mile travel cost.

In Figure 32d, Scenario 1 (d) shows the same effects as Scenario 1 (c), only more severe in magnitude. The fare to ride on a bus or the subway is increasing 10% per period, and consistent with public sentiment regarding fare increases, the percentage of people choosing to ride public transportation decreases dramatically. Consequent to fare increases, the variable cost of traveling on public transportation is so high that it becomes attractive to pay the fixed cost for a private vehicle and significantly lower the variable cost of travel. Figure 32d shows that the percentage of households choosing public transportation drops to 0.13% in period 5. The critical income level below which households with children (h=1) choose public transportation drops to $5,300 in period 3. In periods 4 and 5, these households forego public transportation in favor of buying a used compact vehicle to fulfill their travel needs. The critical income level for households without children (h=2) also drops down to $5,100 in period 5. Unsurprisingly, the cost of public transportation dictates the number of households who ride it, highlighting the importance of public transportation pricing decisions. Not only does the number of households decrease as public transportation becomes increasingly expensive, the number of miles traveled by the average household also decreases from 1,055 miles per period to 957, 842, 915 and 826 miles in the following periods. In other words, upping public transportation fares serves a "double-whammy" of sorts, decreasing both the percentage of population who ride and the number of miles or trips made on public transportation.

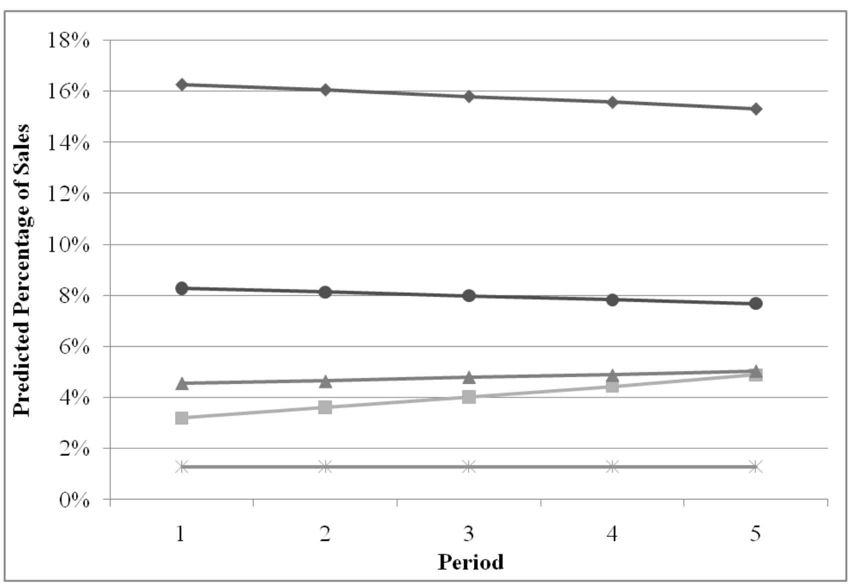
Scenario 2 (a) through (d) display similar results to Scenario 1: as public transportation prices increase faster than energy prices, less households choose to utilize public transportation. First, focusing on the results of Scenario 2 (a) in Figure 33a, as energy price increases by 5% per period and public transportation does not see any price increases, public transportation utilization rises from 1.30% in period 1 to 1.51%, 1.64%, 2.00% and 2.21% in subsequent periods. This is equivalent to an average rise of 14.30% per period compared to an average rise of 2.59% in Scenario 1 (a) when energy price increased by 1% per period. In the fourth period, when energy price has increased by a total of 15.76% from period 1, even some senior households (although a low percentage) start to prefer public transportation. It has become more expensive for them to operate their own vehicle, making it utility-maximizing to go with the public option. The critical income level below which senior households use public transportation is $5,100 for both periods 4 and 5. The results from Scenario 2 (b) shown in Figure 33b indicate that when energy price increases by 5% per period and public transportation increases by 1% per period we still observe some growth in public transportation ridership, increasing from 1.30% in the first period to 1.30% in period 2, 1.51% in period 3, 1.71% in period 4 and 2.00% in period 5. The patterns of adoption are similar to Scenario 2 (a), with households with children (h=1) and households without children (h=2) experiencing higher critical income levels where they switch over to used compact vehicles from public transportation as energy price increases. In addition, senior households (h=3) will utilize public transport in period 5 only if their income level falls below $5,100.

When public transportation prices increase at the same rate as energy prices such as Scenario 2 (c), the outcome is not favorable for public transportation (Figure 33c). The percentage of households adopting public transportation drops down to 1.09% in period 3 and stays at that level to the last period of the simulation. These results are quite similar to that in Scenario 1 (b), the effect of increasing public transit fares (pushing people away from public transportation) practically cancels out the effect of increasing energy prices (driving people towards more fuel efficient modes of travel such as public transportation). Figure 33d shows the results from Scenario 2 (d) and it follows the same pattern of Scenario 2 (c). When public transportation fees are increasing faster (10% per period) than prices at the pump (5% per period), then consumers tend to prefer purchasing private vehicles over public transportation as the public transportation percentage drops to 0.34% in the final period of this case study scenario.

Although households may choose to utilize public transportation for portions of their travel even if they own a private vehicle, the simulation results indicate that households do not utilize public transportation after they buy a private vehicle in all scenarios of this case study. It is reasonable and realistic that when a household buys a car, then they will tend to use the car to drive everywhere they need to travel. However, this may not be the case if there are alternative transportation options with characteristics such as low or zero variable cost (i.e. walking or cheap public transportation) or high satisfaction from environmental awareness combined with low variable cost(i.e. bicycling) available. In these cases, households may purchase a private vehicle for some travel and utilize another mode (i.e. walking or bicycling) for other travel. This may be an area of extended research that can be explored in future studies.

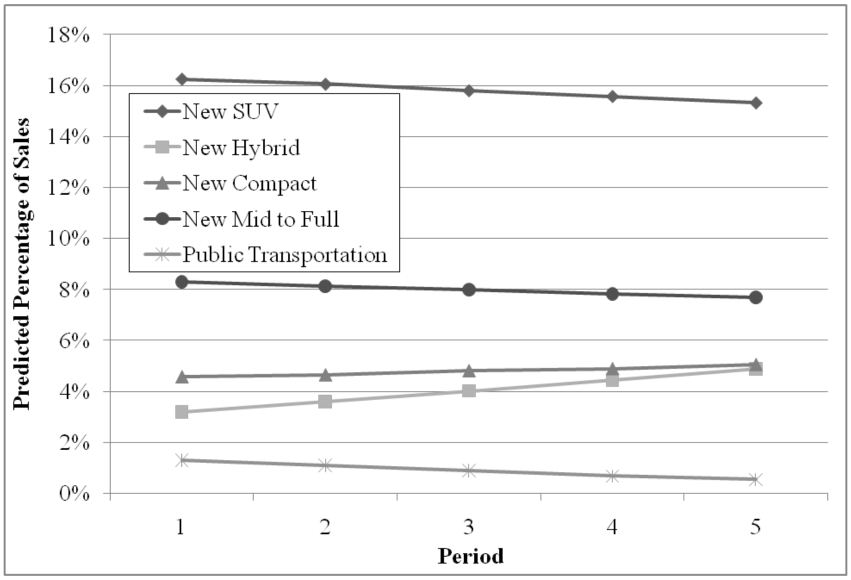


(a) 0% annual increase

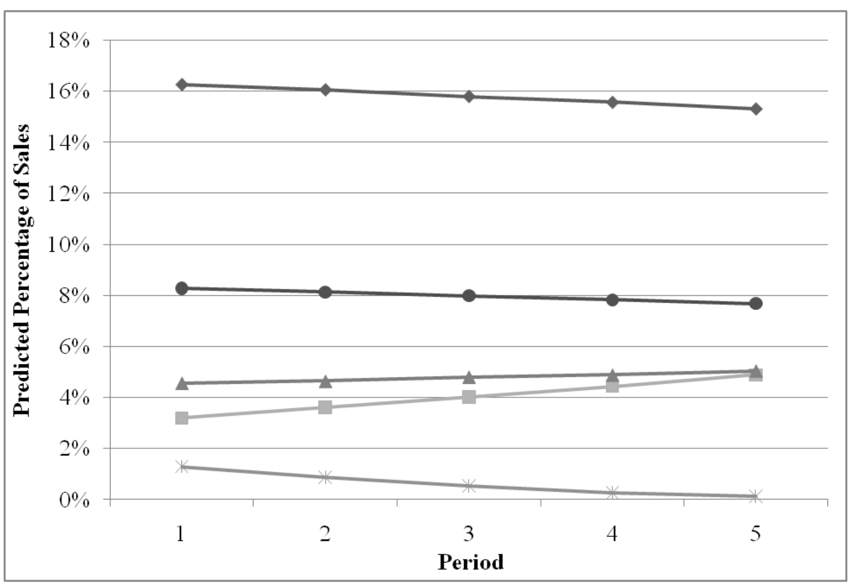


(b) 1% annual increase

Figure 32: Case Study III - Scenario 1: Predicted percentage of all vehicle sales with different annual rates of public transportation price increases.

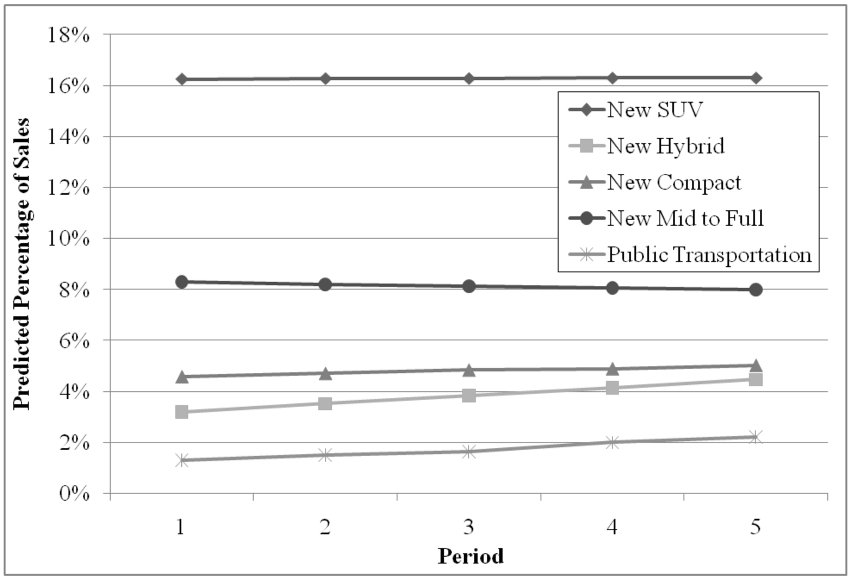


(c) 5% annual increase

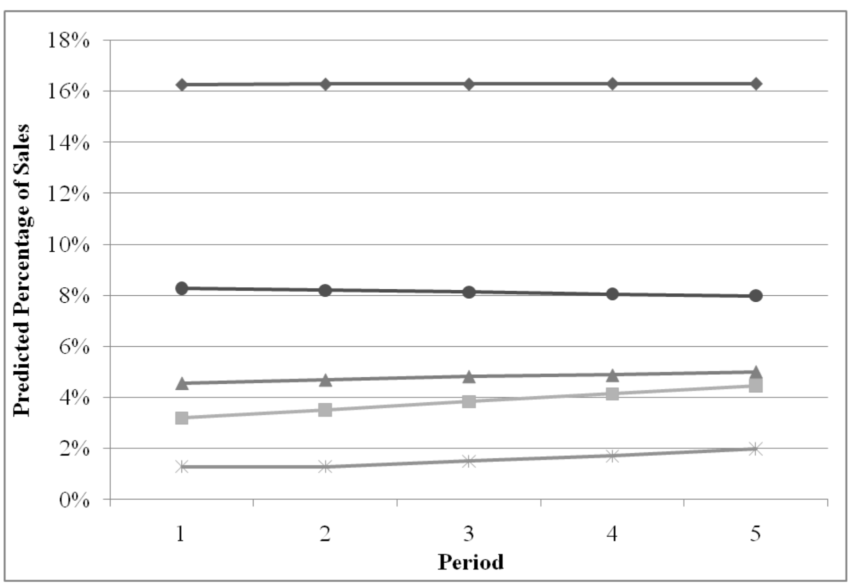


(d) 10% annual increase

Figure 32: Case Study III - Scenario 1: Predicted percentage of all vehicle sales with different annual rates of public transportation price increases.

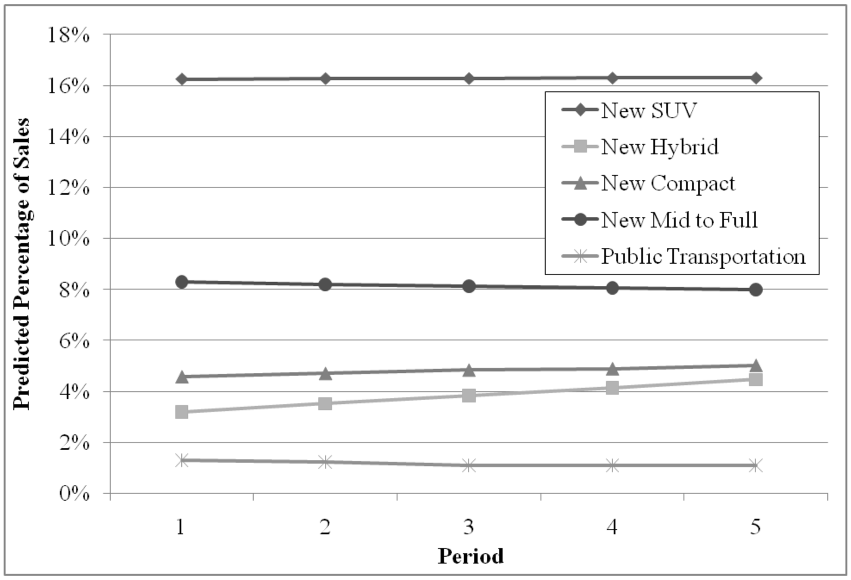


(a) 0% annual increase

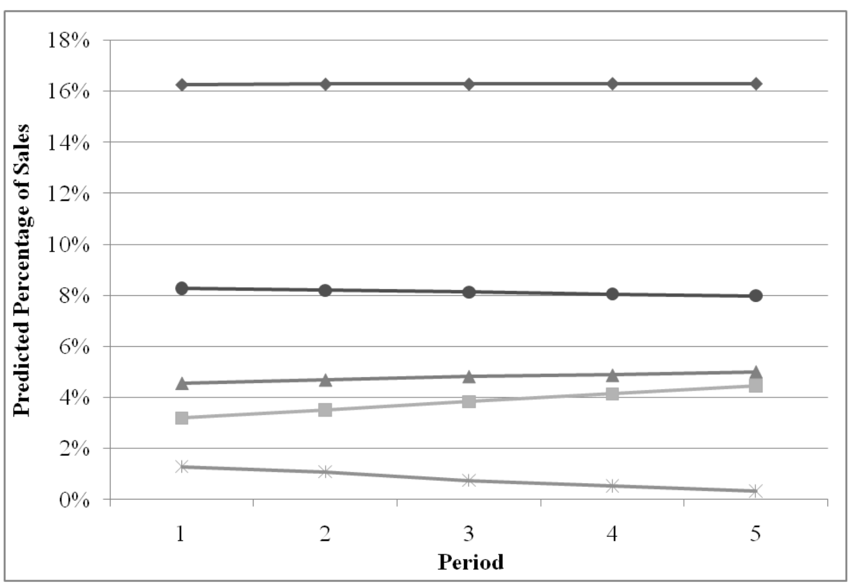


(b) 1% annual increase

Figure 33: Case Study III - Scenario 2: Predicted percentage of all vehicle sales with different annual rates of public transportation price increases.



(c) 5% annual increase



(d) 10% annual increase

Figure 33: Case Study III - Scenario 2: Predicted percentage of all vehicle sales with different annual rates of public transportation price increases.

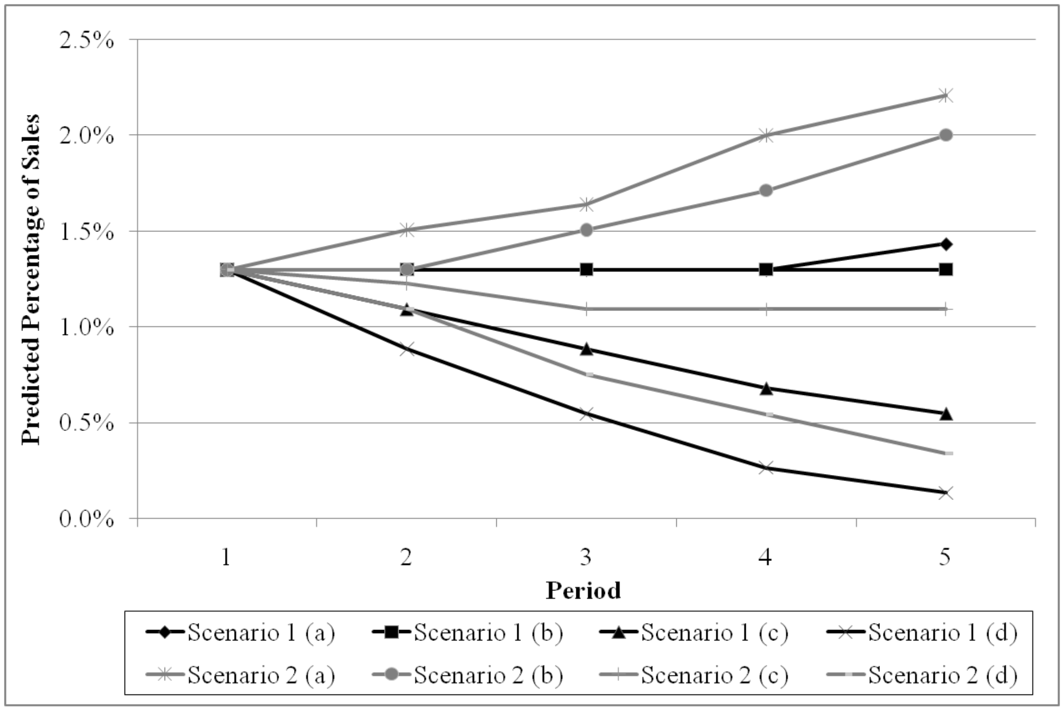


Figure 34: Case Study III - Predicted percentage of households who choose not to purchase a vehicle and only use public transportation in Scenarios 1 and 2.

5.3.2 Scenarios 3 and 4 - Results and Discussion

The results from the case study Scenarios 3 and 4 are presented in Figures 35 and 36. In Scenario 3, in addition to energy price increases by 1% per period, public transportation prices increase from 0% to 10% per period and environmental awareness increase of 1.7% per period, we also incorporate a learning-by-doing new hybrid vehicle price decrease of 1% per period. It is an extension of Scenario 1. Scenario 4 includes energy price increases of 5% per period, public transportation price increases of 0% to 10% per period, environmental awareness increases of 1.7% per period and new hybrid vehicle price decreases of 5% per period. This is an extension of Scenario 2. These are quite plausible scenarios as we are observing more hybrid or alternative vehicle development in many countries. In addition, the learning-by-doing process may not be simply contained in developed nations where more adoption and diffusion is taking place. The benefits of research and development in alternative fuel vehicles may, in fact, spillover into developing nations. When car manufacturers in developed nations are able to manufacture cheaper, more convenient, faster and better hybrid vehicles, they may want to expand their market to developing nations with high sales potential (i.e. China and India where the economy is growing rapidly and the population is large). Therefore, these extended scenarios may have high significance in developing nations even if they are not at the forefront for alternative vehicle development.

Four separate effects interact in Scenarios 3 and 4. Energy price increases cause a Variable Cost Effect that encourages more drivers to adopt energy-efficient vehicles. On the other hand, it may also lead to lower average miles traveled per households, which would increase the marginal utility of comfort/quality and drive households towards more comfortable vehicles such as new SUVs. The second effect present here is the increasing public transportation prices. When public transportation prices increase, as we observed in Scenarios and 2, it shifts the critical income level at which households switch to another type of vehicle, resulting in a lower percentage of public transportation utilization. In addition, with higher bus fares, not only do fewer households utilize public transportation, those who do use public transportation as their sole means of travel will tend to reduce the number of trips or length of trips taken on public transit. The increase of environmental awareness means that people start to place higher importance on whether their vehicle choice is environmental-friendly or not. This effect causes higher adoption of fuel efficient vehicles such as the new hybrid vehicle or new compact vehicle as well as public transportation. However, this means that when households purchase fuel-efficient vehicles, they will drive more miles, ceteris paribus. Finally, the learning-by-doing price decrease of new hybrid vehicles as the technology becomes more mature and gains market share leads to the Fixed Cost Effect which increases the critical income range in which households choose to adopt hybrid vehicles. The resulting percentages of vehicle adoption reflects the interaction of all of these effects.

Public transportation ridership again benefits from high energy price increases and low public transportation prices. We again observe decreasing ridership as public transportation becomes more expensive. However, it is of interest to note that public transportation adoption percentages in Scenarios 3 and 4 are exactly the same percentages we observed in Scenarios 1 and 2 shown in Figure 34. The households in the lowest income brackets are those who choose to utilize public transportation, and are therefore unaffected by the decreasing price of new hybrid vehicles because their income levels are much lower than the critical income level threshold of new hybrid vehicle adopters.

Who are the people that purchase hybrid vehicles, then? The new hybrid vehicle is priced at a level between the new mid to full-size vehicles and the new SUV. As the price of hybrid vehicles become cheaper as more production occurs and it becomes a more mature technology, energy price increases and environmental awareness goes up, the critical income level at which households switch from new mid to full-size vehicles drops significantly and the critical income level at which households switch from new hybrid vehicles to new SUVs increases. The combination of these effects drives out the category of new mid to full-size vehicles and lowers the adoption of new SUVs while leaving the public transportation sector unaffected in the process.

We will look in detail at the results from Scenario 3 (a) shown in Figure 35a where energy price increases by 1% per period, public transportation prices remain constant, environmental awareness increases by 1.7% and new hybrid vehicle price decreases by 1% per period. The percentage of households choosing to purchase new SUVs again starts at 16.26%, but drops to 14.78%, 13.17%, 12.32% and 12.37% in the later periods. Comparing this trend with that from Scenario 1 (a) of Case Study III, we see a similar decrease in the percentage of new SUV adoption, but the rate of decrease appears to be faster in Scenario 3 (a). This is because as new hybrids are becoming cheaper, its combination of attributes becomes more attractive to a larger percentage of households. Looking more specifically at households with children (h=1), we observe that the critical income level above which households start to switch to new SUVs starts at $90,000, but decreases slightly to $89,400.

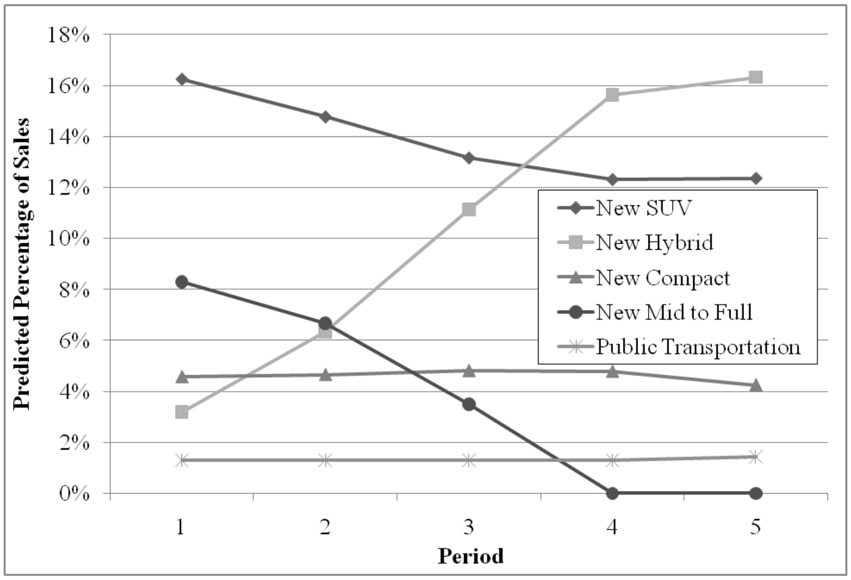
This means more households will fall into this income range. This is due to the effect where increasing energy prices causes less miles traveled and higher marginal utility of comfort in larger vehicles. The effect is also present in senior households (h=3) where the critical income level starts at $84,150 in period 1 and decreases to $83,550 in the final period. For households without children (h=2), the story is bit different because they perceive less relative difference between the comfort of different vehicle types. Originally, those households with incomes above $155,800 will choose to purchase the new SUV. In the second period, only those with income levels above $172,550 will purchase the new SUV and very few households fall into this high income bracket. In the last three periods, the new hybrid vehicle becomes much cheaper and the utility curve for the new hybrid completely dominates the new SUV, and no households without children will spring for the SUV any longer.

New hybrid adoption is greatly encouraged in this scenario by the 1% decrease in fixed cost per period. The percentage of all purchases attributed to the new hybrid vehicle starts out at 3.20% and increases to 6.35%, 11.14%, 15.63% and 16.32% in the next periods. Looking at households without children (h=2), the results show that the critical income range for new hybrid vehicles is between $120,650 and $155,800 in the first period. In period 2, the critical income range for new hybrid vehicles widens to $102,900 through $172,550. In period 3, this critical income range becomes $85,500 to $190,350. In periods 4 and 5, all households without children who have household incomes above $71,450 and $69,100, respectively, will choose to adopt new hybrid vehicles. This increasing trend of new hybrid vehicle adoption for this type of household is driven mainly by the decreasing fixed cost and aided by the increasing energy price and environmental awareness. Households with children (h=10 and senior households (h=3) do not choose to buy any new hybrids in this scenario.

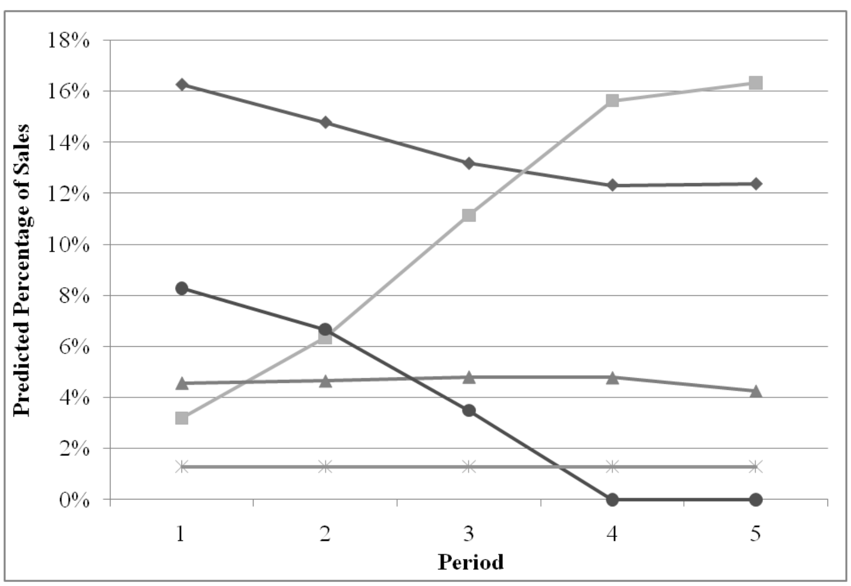
If one looks closely at the results from Scenarios 3 (a), (b), (c) and (d) which include various rates of public transportation price increases (Figures 35a, 35b, 35c and 35d), one will notice that the predicted percentages of sales for new SUVs, new hybrid vehicles, new compact vehicles and new mid to full-size vehicles remain the same for all four specifications. The only difference between these results is the different percentages of households who choose public transportation. When public transportation prices increase, we see a shift in the critical income levels at which households switch between used compact vehicles and public transportation for all household structures. Those who choose other types of vehicles (aside from used compact vehicles) are essentially unaffected by changes in public transportation fares, maintaining the same percentages of adoption and the same optimal number of miles traveled through all specifications of Scenario 3.

Next, we focus on the results from Scenario 4 (a) shown in Figure 36a where energy price increases by 5% per period, public transportation prices remain constant, environmental awareness increases by 1.7% and new hybrid vehicle price decreases by 5% per period. The percentage of households choosing to purchase new SUVs starts at the same 16.26%, but decreases to 15.00%, 13.70%, 12.65% and 12.80% in the next periods, equivalent to an annual decrease of 5.73%. If we compare these results with Scenario 3 (a), we see that the decreasing trend of new SUV adoption is actually slower when energy prices are increasing at 5% per period instead of 1% per period. This phenomenon occurs when households optimize by choosing to travel less miles when energy prices are increasing at a faster rate. For some households, the increase in the marginal utility of comfort from lower optimum number of miles may be enough to sway them towards larger vehicles such as the SUV. However, if we compared with Scenario 2 (a), we observe that the learning-by-doing decreases in hybrid vehicle prices causes lower adoption of new SUVs as well.

Turning our focus to new hybrid adoption, we can observe that the percentage of households who purchase new hybrid vehicles starts at 3.20% and quickly increases to 16.78% in the final period. The trend is quite similar to Scenario 3, but the effects are hastened by the larger increase in energy prices and larger decrease in hybrid prices. Results from Scenarios 4 (b), (c) and (d) (Figures 36b, 36c and 36c) all display the same percentages of adoption for all vehicle types as Scenario 4 (a) except for used compact vehicles and public transportation. This is because when public transportation prices increase at different rates, it only affects the critical income level at which households start to substitute the lowest priced private vehicle for public transportation. Again, the resulting percentages of public transportation adoption in all specifications of Scenario 4 are identical to those in Scenario 2 because changing hybrid prices do not affect those in the lowest income group who utilize public transportation.

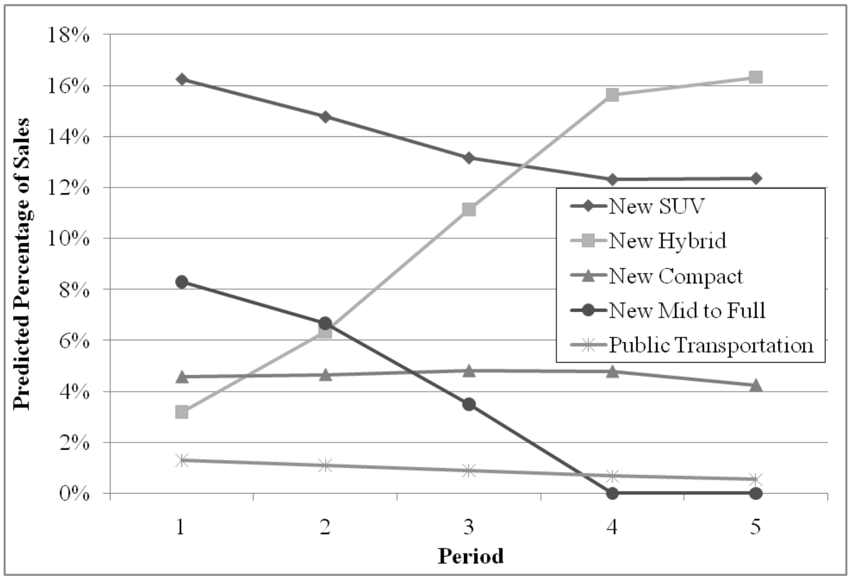


(a) 0% annual increase

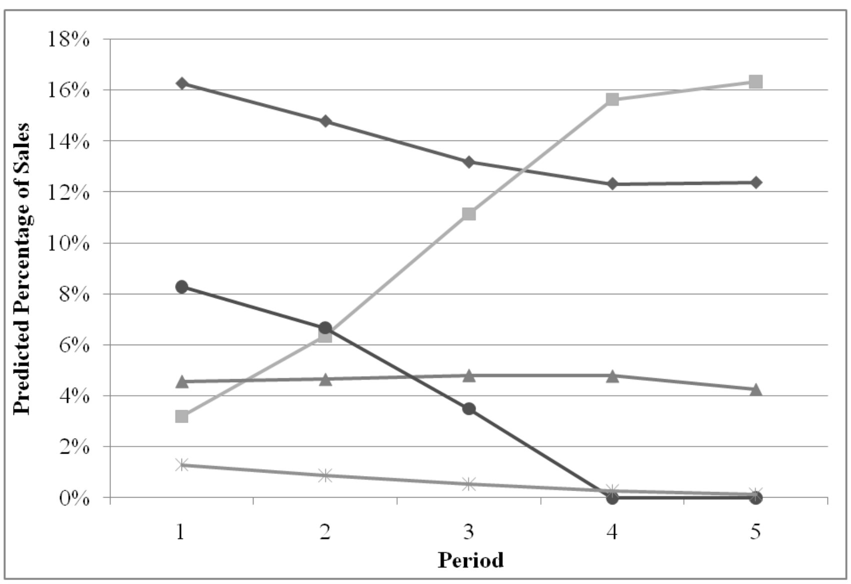


(b) 1% annual increase

Figure 35: Case Study III - Scenario 3: Predicted percentage of all vehicle sales with different annual rates of public transportation price increases with new hybrid vehicle price decrease of 1% per period.

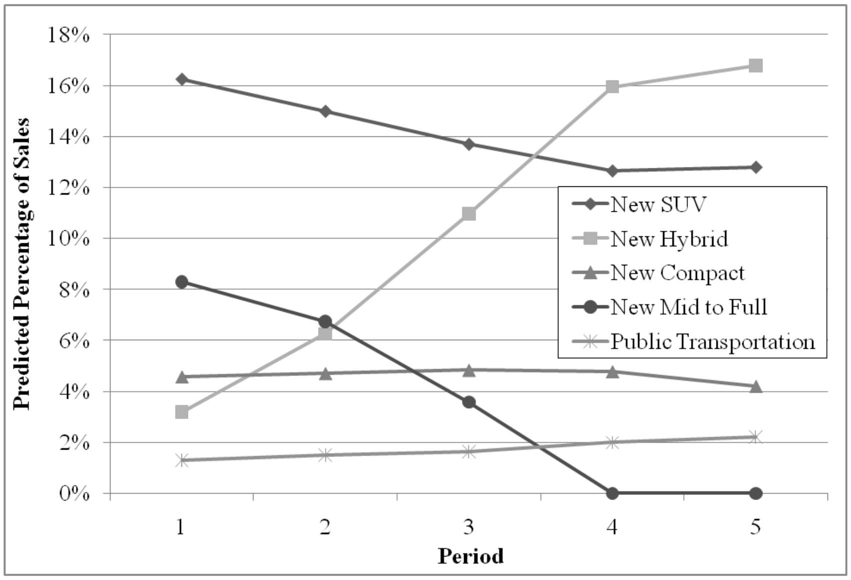


(c) 5% annual increase

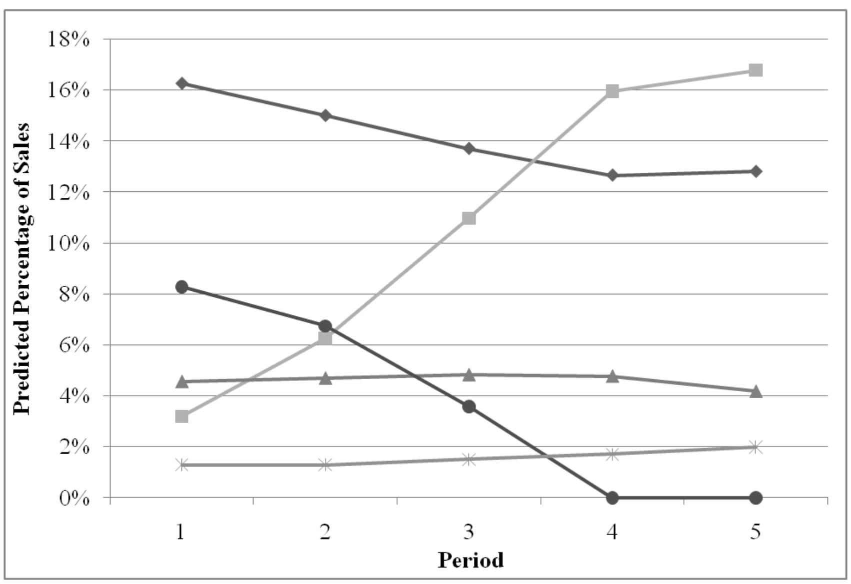


(d) 10% annual increase

Figure 35: Case Study III - Scenario 3: Predicted percentage of all vehicle sales with different annual rates of public transportation price increases with new hybrid vehicle price decrease of 1% per period.

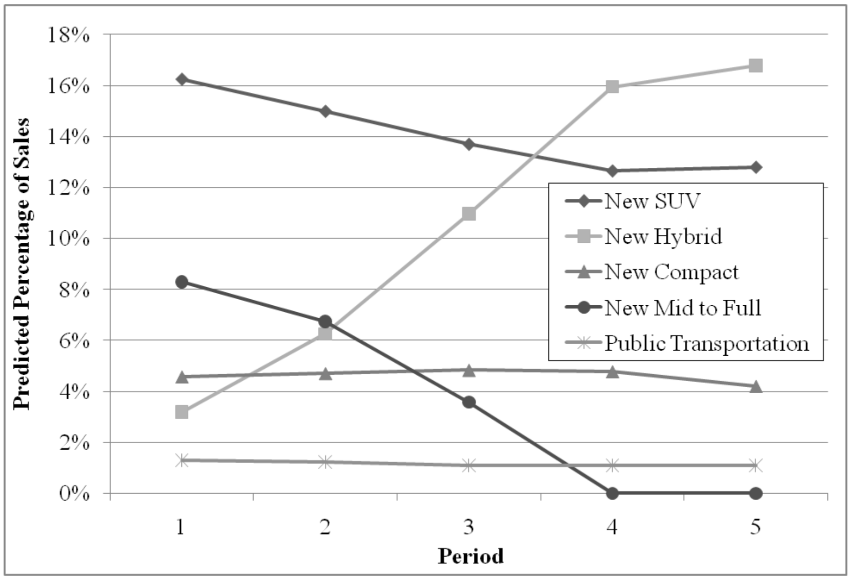


(a) 0% annual increase

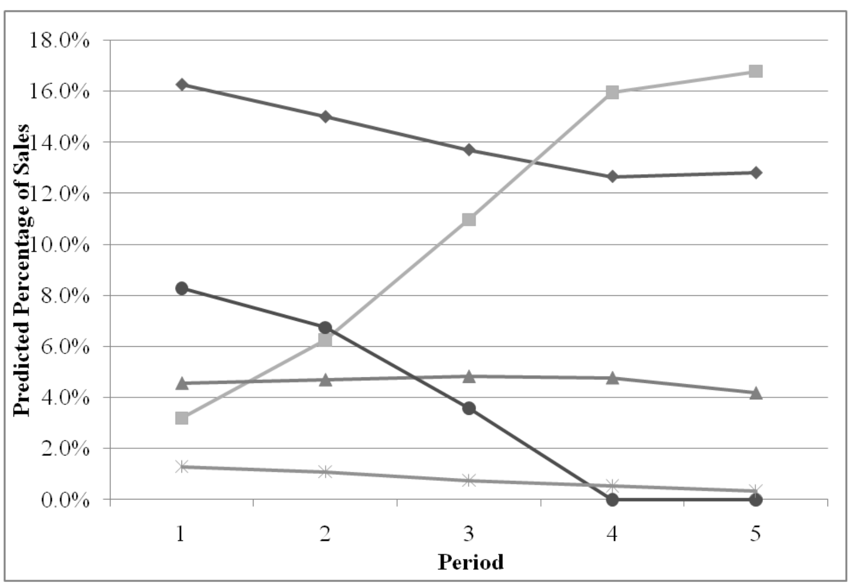


(b) 1% annual increase

Figure 36: Case Study III - Scenario 4: Predicted percentage of all vehicle sales with different annual rates of public transportation price increases new hybrid vehicle price decrease of 5% per period.



(c) 5% annual increase



(d) 10% annual increase

Figure 36: Case Study III - Scenario 4: Predicted percentage of all vehicle sales with different annual rates of public transportation price increases with new hybrid vehicle price decrease of 5% per period.

5.3.3 Scenario 5 - Results and Discussion

In Scenario 5, we take Scenarios 1 (a), 1 (b), 2 (a) and 2(c) in this case study one step further and apply the developing nation income distribution trend of Case Study I shown in Figure 18. Although this income distribution trend does not take into account the drastically lower income levels (we use the same income brackets as the calibrated U.S. simulation) or different types of vehicle categories (we use the same vehicle categories and parameters throughout this paper) that may be available in developing nations, it can still illustrate the dramatic trend of vehicle or public transportation adoption. This scenario setup brings the simulation model one step closer to the reality in developing nations such as India or China where public transportation is often the only type of travel affordable to a large percentage of households.

Four different parameters are changing in Scenarios 5 (a) through (d): energy price, public transportation price, environmental awareness and income distribution shape. The parameter changes are summarized in Table 23. Each of these parameters have different effects on both the discrete choice of vehicle type as well as the continuous choice of miles to travel. First, energy price increases (1% per period in Scenarios 5 (a) and (b) and 5% per period in Scenarios 5 (c) and (d)) will cause critical income levels to change due to the Variable Cost Effect, which also means households will optimally choose less miles to maximize utility. Public transportation price fluctuations change the relative variable cost of travel between public transportation and private vehicles. As public transportation price increases, households will prefer private vehicles over public transportation. Additionally, the effects of public transportation price increases are relative to energy price increases and can potentially cancel each other out as illustrated in Case Study III Scenarios 1 through 4.

Next, environmental awareness increases by a constant rate of 1.7% per period in all Scenario 5 specifications. Increasing environmental awareness is one of the driving forces that results in higher adoption of fuel-efficient vehicles because people feel good (and gain utility) from the fact that they are behaving in a way that is environmentally-friendly. Finally, the income distribution shift pattern follows the shape of China's income distribution change in the past two decades (the same as Case Study I). We know from the theoretical model that the Income Distribution Effect will cause households to move into the critical income range for the various vehicle categories. This particular income distribution shift shows more concentration of households at the two extremes of the distribution as well as a rightward shift in the economy (households becoming richer). The effect of this is that more households will be able to purchase more expensive vehicles and also be able to travel more given their vehicle choice. Scenario 5 combines all of these separate effects to show what would happen when an economy is quickly growing, energy price and public transportation prices are changing and environmental awareness is also on the rise.

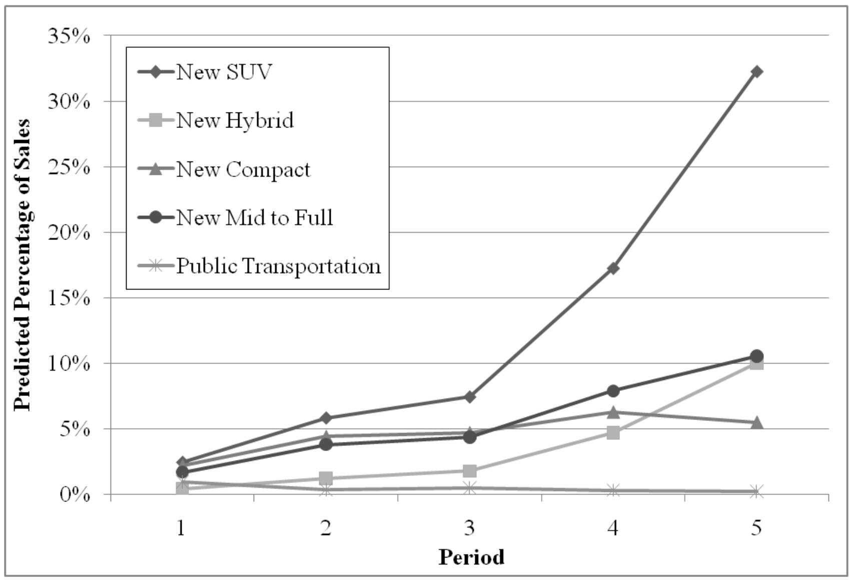
As more households are concentrated in the upper and lower regions of the income distribution (M-shaped income distribution), the trend towards bigger, better (more comfortable) and newer vehicles seen in Figure 37 becomes even more apparent and presents larger environmental and political implications in these populous developing areas of the world. In the baseline period 1, we observe 2.44% of households choosing new SUVs, 1.70% choose new mid to full-size vehicles, 2.21% choose new compact vehicles, 0.45% choose new hybrids, 0.96% choose public transportation while the rest prefer used vehicles. Note that these numbers are quite close to the baseline period 1 results from the main scenario of Case Study I. Again, this reiterates the independence of irrelevant alternatives as the introduction of public transportation attracts only those in the lowest income bracket and does not influence the choices and preferences of other households.

Scenario 5 (a) depicts a scenario where three forces should contribute towards more adoption of energy efficient transportation options. Higher energy price (1% increase per period), constant public transportation price and increasing concern for the environment all encourage households to purchase new hybrids or new compacts or utilize public transportation, depending on the household income level. However, we observe that the percentage choosing public transportation falls to 0.23% in the final period while new SUV purchases increase to 5.83%, 7.43%, 17.25% and 32.28% in the last four periods. New hybrid adoption appears to be faster in this specification compared to the situation where no income distribution shift is occurring, growing to 10.04% in the final period at an incredible average annual growth rate of 124.16%. If we compare these results to the main scenario in Case Study I, we see greater percentage of the population opting or new hybrid and new compact vehicles, but less opting for new mid to full-size vehicles and new SUVs. This result can be attributed to the rising environmental awareness factor. On the other hand, comparing these resulting percentages with Scenario 1 (a) where the only difference is the income distribution shift, we observe a general shift towards higher fixed cost vehicles and new vehicles instead of used vehicles or public transportation. Therefore, we can conclude that the availability of public transportation, the increasing energy price and the increase in environmental awareness each period are dominated by the shift in the shape of income distribution. The trend towards bigger, more comfortable, newer modes of travel is persistent, although slight curbed by increasing environmental concern.

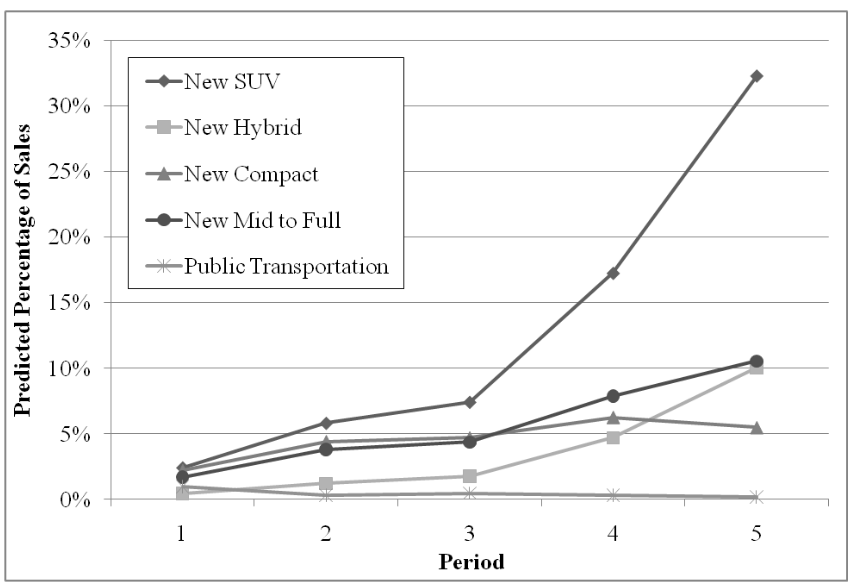
Scenario 5	**(a)**	**(b)**	**(c)**	**(d)**
Period 1	0.96%	0.96%	0.96%	0.96%
Period 2	0.34%	0.34%	0.40%	0.32%
Period 3	0.49%	0.49%	0.61%	0.41%
Period 4	0.32%	0.32%	0.48%	0.26%
Period 5	0.23%	0.21%	0.36%	0.18%

Table 24: Predicted percentage of public transportation using Case Study I income distribution shifts.

Table 24 summarizes the projected percentage of households choosing public transportation in each of the four situations. Although it has been shown that the income distribution shift speeds up the adoption of larger vehicles, the lower income segment of the population still relies on public transportation even with the income distribution shift. In Scenarios 5 (b) and 5 (d), the situation is bleaker still for public transportation as the price to ride public transit increases at the same rate as energy price. Scenario 5 (c) shows a slower decline in public transportation ridership compared to the other three specifications here, but the percentage still drops to a low 0.36% in the final period. The dominance of the Income Distribution Effect is undeniable in the results of this simulation scenario.

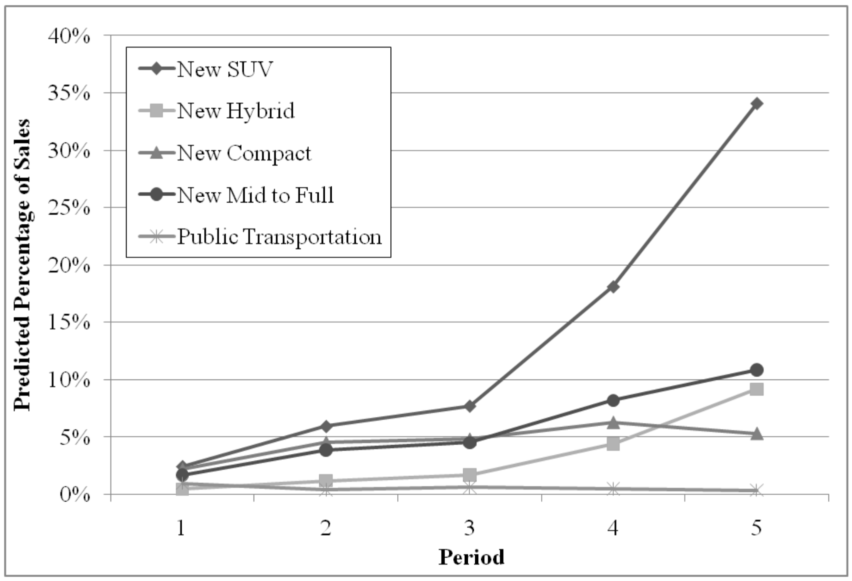


(a) Energy price: 1% annual increase; Public transportation price: no change

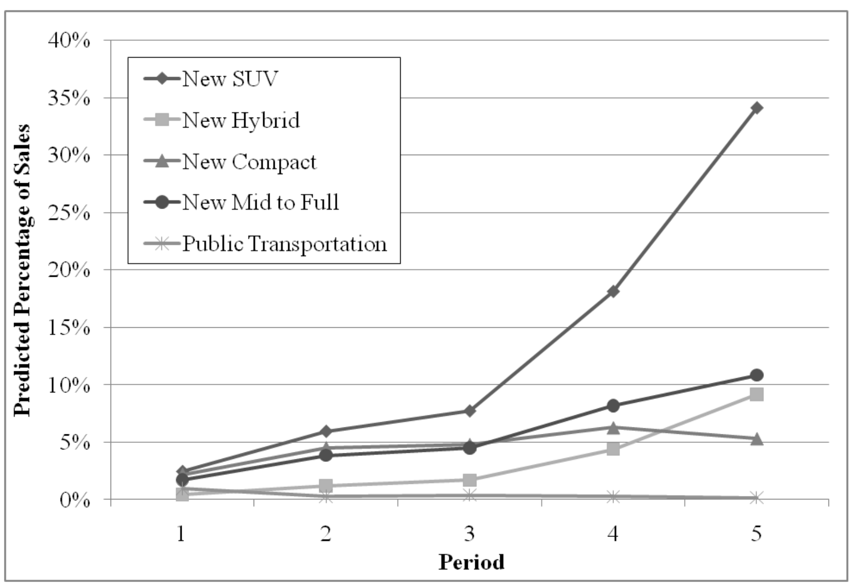


(b) Energy price: 1% annual increase; Public transportation price: 1% annual increase

Figure 37: Case Study III - Scenario 5: Predicted percentage of all vehicle sales with different annual rates of energy price and public transportation price increases.



(c) Energy price: 5% annual increase; Public transportation price: no change



(d) Energy price: 5% annual increase; Public transportation price: 5% annual increase

Figure 37: Case Study III - Scenario 5: Predicted percentage of all vehicle sales with different annual rates of energy price and public transportation price increases.

5.3.4 Conclusion and Policy Implications

Case Study III demonstrates the capability of the simulation model by including a public transportation option. Although a few major metropolitan areas in the U.S. do have extensive public transportation networks (i.e. New York City), the majority of regions do not offer such an option (i.e. Los Angeles). However, when public officials are considering the possibility of developing public transportation networks or improving existing networks, the case study presented in this section can provide some insight into how different factors may influence public ridership and the adoption of other vehicle options. The simulated results will illustrate the percentage of households choosing to utilize public transportation and forecast the number of miles that these households will travel on public transportation as well. The unique characteristics of public transportation that includes zero fixed cost, higher variable cost and tradeoffs in comfort/quality are all considered in this case study.

We iterate through several combinations of energy price increases and public transportation fare increases in Scenarios 1 and 2. It becomes clear from these two scenarios that public transportation benefits from increasing energy prices and constant (or decreasing) fares. In addition, we observe from the results that when public transportation prices increase faster than overall energy prices, then fewer households will choose to utilize public transportation, and they will travel less miles or take fewer trips on public transit. The introduction of public transportation as an alternative travel mode only affects those in the lowest income groups in our simulation as the vehicle adoption choice of households in higher income brackets are unaffected by the introduction of an irrelevant alternative. In Scenarios 3 and 4, we expand upon the first two specifications by adding price decreases to new hybrid vehicles from learning-by-doing. Again, public transportation usage is at exactly the same levels as Scenarios 1 and 2 because those households that are affected by the change in the fixed cost of hybrid vehicles are not the same ones that utilize public transportation. New hybrid vehicle adoption increases with the drop in its fixed cost, but is unaffected by the changes in public transportation fares.

Public transportation clearly benefits from high energy price increases. When consumers observe uncertainty and large fluctuations in energy prices, they will prefer to utilize public transportation which provides them with certainty in pricing as well as a relatively cheaper travel alternative. It is also quite possible that during times of energy price fluctuations, the operating costs of public transportation agencies also increase, leading to the discussion of increasing public transportation fares. The results of the simulation show that when public transportation fares increase at or more than the rate of energy prices, a lower percentage of households will ride public transportation, and they will reduce the length and frequency of trips taken as well. The combined magnitude of these effects and how much they will influence the revenue generated by public transportation agencies can provide some guidance in public policy regarding the pricing of public transportation. Additionally, it is important to keep in mind that as much as energy prices may increase or as cheap as public transportation may get, some households will still choose to purchase private vehicles because they possess attributes of convenience and quality that may not be substitutable by public modes of transportation.

Finally, in Scenario 5, we combine the dramatic income distribution shifts (including both a dramatic rise in income levels as well as a shift in the shape of the income distribution towards higher inequality) from Case Study I with the public transportation case study. This is a step closer to the reality in these emerging economies such as China or India where the majority of the population are still utilizing public transportation or other types of non-motorized modes of travel (i.e. walking or cycling). The results are a stark reminder that the effects of large shifts in the income distribution dominates most other movements that may affect vehicle adoption. With the addition of public transportation into the picture, the emerging market sees large increases in new SUV adoption as well as new mid to full-size vehicle adoption. The usage of public transportation is decreasing in all specifications of this scenario because households are becoming wealthier and are able to afford private vehicles that provide them with both lower per-mile variable cost and higher levels of comfort. If one's priority is to discourage the "bigger is better" mentality of vehicle choice and reduce fuel consumption and environmental degradation, then perhaps more has to be done rather than depending on the growing economy and increasing wealth of the population.

Chapter 6

Conclusion

The framework consisting of the theoretical model and simulation presented in this paper provides a novel approach to understanding the household adoption of transportation technology. This chapter will summarize the findings and contributions of this dissertation, and the next section will discuss future research that may be undertaken as extensions of this study.

First, this dissertation starts out with the threshold model of diffusion introduced by David (1969) [25] and Sunding and Zilberman (2001) [82], applying the theoretical foundation commonly used in analyzing modern irrigation technology adoption to household vehicle adoption. Households are assumed to be heterogeneous and utility-maximizing through a discrete vehicle choice and a continuous choices of miles traveled, and they adopt the technology that provides the highest utility given the optimal number of miles chosen for that particular technology. Then, the theoretical model is extended to include both parameters of comfort and environmental awareness in the choice process. Comfort is a general parameter that represents some combination of vehicle passenger capacity, vehicle cargo capacity, seating comfort, quality of travel and convenience of operation for each type of vehicle. Environmental awareness is a parameter that represents the higher utility gained by a household by the adoption of energy-efficient or environmentally-friendly transportation technology. Another extension of the theoretical model is to include household heterogeneity through the inclusion of household structures where each household structure may have their own preference set. We then derive the comparative statics for all extensions of the theoretical which show that the optimal number of miles traveled decreases with energy price increases (e_j), fixed cost increases (F_j), comfort increases (q_j), and increases with income level increases (I). These derivations provide insight into the disaggregate vehicle adoption behavior of individual households.

On the aggregate level, we derive the effects that influence the overall diffusion of different vehicle technologies: Population Effect, Income Distribution Effect, Variable Cost Effect and Fixed Cost Effect. This conceptual derivation is crucial to the conclusions and results later presented in the case study scenarios. In summary, the aggregate flow demand of vehicles at time t ($Q_j(t)$) is determined by the combination of these effects: the population growth rate, the shift of income distribution within the population and the movement of the critical income levels for each type of vehicle (affected by characteristics of each vehicle technology as well as preferences of households).

In Chapter 3, we develop a computer simulation model with the theoretical household vehicle choice threshold model as foundation. Utilizing a CES utility functional form as the starting point, we calibrate the simulation model using data from various sources, including data of income distribution, vehicle attributes and pricing, vehicle sales data in the U.S. and environmental awareness factors. The purpose of the calibration is to ensure that the parameters of the simulation model yield accurate predicted sales percentages and trends comparable to historical data. Through this calibration exercise, we were able to finalize a specification that yielded an R^2 equal to 0.9595, indicating the simulated results explains approximately 95.95% of the variance in historical vehicle sales data. One of the major contributions of both the theoretical model and the simulation model is the ability to incorporate complex changes in the income distribution shape and location in predicting aggregate diffusion of vehicle technologies.

Chapter 4 utilizes the simulation model to examine the effects of various movements in parameters such as energy price, governmental policy, vehicle price, environmental awareness and income distribution. We find that the results are often surprising and more complex than what the derivatives can tell us. The patterns of vehicle adoption is a combination of individual household choices (both the discrete vehicle choice as well as the continuous choice of miles to travel) and the composition of the population in terms of household structure type and income distribution. We would like to refer the reader to Chapter 4 for detailed discussions of the various scenarios. The main conclusion here is that as parameters are changing, households are not only changing what type of vehicle they prefer to purchase, they also adjust how much they would like to travel. We find that two of the largest contributors to the adoption of different vehicle technologies are the fixed cost of the vehicle and shifts in the income distribution, although other factors such as changes in gas price or environmental awareness also contribute.

The theoretical model and the simulation model culminate in Chapter 5 where three very different case studies illustrating potential scenarios in emerging markets, ageing economies and public transportation are presented. Case Study I presents the scenarios of rapidly growing economies with rapidly changing population dynamics such as China or India. The results from this case study illustrate the potential trend towards the adoption of bigger, better (more comfortable) and newer vehicles which are less fuel-efficient and more polluting as the economy experiences high income growth and increases in inequality. These results are further exacerbated by the population increases in these regions that contribute to the Population Effect. In other words, if these economies were to continue growing at the current rate, the vehicle adoption trends may signify much broader impacts in terms of climate change, fuel prices and fuel-shortage problems in the long run.

The extended scenarios presented in Case Study I incorporates the increasing trend of transportation infrastructure construction. Two effects are hypothesized in this extension: increasing comfort levels due to better roadways and networks of roadways, and decreasing comfort levels due to increasing congestion or pollution caused by the increasing stock of vehicles and miles traveled. The other extension in this portion proposes increasing environmental awareness in a developing economy as it is growing, possibly due to the Environmental Kuznets Curve. Both increasing overall comfort levels and increasing environmental awareness lead to the high rates of adoption of energy-efficient vehicles such as the new hybrid vehicle or the new compact vehicle. However, the reality is probably closer to the hypothesized decreasing comfort levels due to increased congestion and pollution, which results in extremely rapid adoption of new SUVs and used large vehicles. Therefore, drastic measures such as direct consumer subsidies for energy-efficient vehicles or research subsidies for manufacturers to encourage learning-by-doing for alternative fuel vehicles may be needed in order to circumvent the current trend both in the percentages of adoption as well as miles traveled in private vehicles shown in this case study.

Case Study II of Chapter 5 examines the ageing economies of Japan and Europe. The population dynamics are also shifting in these regions, although at a slower rate, towards a larger percentage of childless households and senior households. If one were concerned about the damaging effects of the adoption of larger vehicles in Case Study I on the environment, then one may find some comfort in this case study where the results indicate a faster adoption rate of new hybrid vehicles. The substitution towards energy-efficient vehicles is driven by a combination of increased environmental concern, increasing energy prices, decreasing cost of new hybrid vehicle technology as well as increasing income levels. The effects caused by the larger percentage of childless households and senior households depend on the magnitude of each as well as on the income distribution shape within each household structure.

Case Study III takes the simulation model one step further by introducing public transportation as an alternative travel mode. Public transportation is unique because it entails zero fixed cost but with the tradeoff of higher variable cost per mile traveled compared to driving a private vehicle. In addition, public transportation provides lower levels of comfort/quality/convenience for all types of households, but especially for households with children or senior households. Environmental awareness also comes into play here because public transportation is regarded as an environmentally-friendly method of travel, thus providing households with higher utility when they choose to travel by public transit. Unsurprisingly, we find that public transportation ridership benefits from high energy price increases and low public transit fares. The case study further illustrates the two implications of adjusting public transportation fares: the percentage of households who utilize public transportation and the number of miles traveled on public transportation. In other words, increasing public transit fares not only decreases the overall number of households who ride public transit, but also induces them to ride less. This case study is extended to incorporate the income distribution shifts in economies such as China. One can imagine that in developing economies, public transportation is one of the main methods of travel for large portions of the population due to lower household income levels. We find that public transportation usage declines and new SUV adoption rapidly increases as the population experiences income increases, demonstrating the dominant effect of the income distribution shift on the adoption of vehicle technologies.

6.1 Future Research Directions

The theoretical model and simulation model set forth in this dissertation provide a basic framework on which numerous extensions can be applied and various scenarios can be analyzed. The following are some future research directions that directly expand on the capabilities of our models.

One source of heterogeneity in our model comes from differences in household structures. Each household structure type has different preferences which is expressed through a series of comfort parameters. Additional sources of heterogeneity can be incorporated into the model, such as a random distribution of preferences for comfort/quality or for environmental awareness for each individual household within a specific household structure type. This extension would mean that critical income levels at which households switch from one type of vehicle technology to the next becomes individualized. Furthermore, the distribution function of the random variables may also change depending on the overall conditions of the economy from period to period to account for the changes in public sentiment towards, for example, climate change. Another consideration may be the differing vehicle replacement rate within each type of household structures. Perhaps senior households keep their vehicles longer or households with children switch vehicles more often due to growing children and growing family size. Or it may be that wealthier households display a faster rate of replacement compared to those in the lower income groups. In addition, although we assume in our model that each household only purchases one vehicle, in reality different types of households may choose to purchase more than one car, possibly one type of vehicle for commuting and another for leisure. This may significantly impact the pattern of adoption of hybrid or alternative fuel vehicles in particular. These additional sources of heterogeneity can be incorporated into future research.

The prospect of the simulation model to forecast vehicle adoption and diffusion in developing nations is one of the main features of the model. However, the accuracy of the forecast heavily depends on the proper calibration of the parameters specific to the region or nation. In particular, it would be prudent to collect specific data of the available vehicle types, pricing, characteristics as well as income distribution data in these regions. In addition, there is a larger percentage of the population in developing nations that utilize their non-motorized methods of travel. By calibrating the model for these regions, we should be able to examine the determining factors that shift these households from travel by foot to travel using two-wheeled methods (both motorized and non-motorized) to travel using four-wheeled methods.

One of the most intriguing areas of vehicle adoption choice involves household decisions. Aside from using different functional forms of utility functions in addition to the CES functional form used in this dissertation, it is important to examine the allocation of decision power within the household. Studies by Manser and Brown (1980) [55], Browning et al. (1994) [17] and Zhang et al. (2002) [88] among others have delved into devising models to better explain household decisions. In addition to vehicle purchasing decisions, the intra-household allocation of transportation resources (i.e. how is it decided who drives which vehicle and who has priority to drive to work?) carries significant policy implications. With more knowledge of how households make their decisions, we can expand our theoretical model of vehicle choice to more accurately reflect the actual choice mechanism and household dynamics. In addition, studies by Bhat et al. (2009) [12] and Salon (2009) [69] have shown significant effects of household location and neighborhood characteristics (i.e. urban versus rural or residential density) on vehicle choice. It would be particularly useful to consider the interaction of residential choice with vehicle choice in an extension of our model using urban economics models by Alonso (1960) [1], Muth (1969) [61], Mills (1972) [58] and Brueckner (1987) [19].

New plug-in electrical vehicle models such as the all electric Nissan Leaf or the electric hybrid Chevrolet Volt roll out onto the U.S. market in 2010 and 2011. These vehicles possess limited driving range (40 miles on Chevrolet Volt and 100 miles on Nissan Leaf according to manufacturer's estimates) on each electrical charge, which makes the infrastructure for charging stations particularly important. The positive-feedback nature of charging networks/infrastructure will be key in the spread of this vehicle technology which can be incorporated in our model as one of the many dynamic processes that lead to adoption and diffusion (Katz and Shapiro 1994 [45], Struben 2008 [81] and Liebowitz and Margolis 1994 [49]).

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