Quantifying the Benefits of the Introduction of the Hybrid Electric Vehicle*

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Abstract

This study models demand and supply in the market for new automobiles to estimate the economic benefits generated by the introduction of the hybrid electric vehicle. We estimate our model using all new vehicle registrations in California along with detailed demographic data. Our counterfactual analysis of the removal of hybrids reveals a gain in social surplus that peaks at just over $900 million in 2007, but environmental benefits make up less than 1% of the net benefits. We further show that all income groups benefit from the introduction of the hybrids due to the re-equilibration of prices in the market.

Keywords: automobile markets, new products, consumer benefits.
JEL classification codes: L9, L6, R4, Q4

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1 Introduction

Hybrid electric vehicles were first introduced to the United States in 2000 and by April 2016 over 4 million hybrid vehicles were sold, with a peak in market share of over 3% of the total light-duty vehicle market in 2013. By including an electric motor and regenerative braking, hybrids offer greater fuel economy than equivalent non-hybrid models, and have been an important contributor to firm compliance with Corporate Average Fuel Economy (CAFE) standards. Moreover, national policymakers took a keen interest in hybrids, incentivizing them with federal income tax deductions prior to 2006 and income tax credits that phased out with the number of hybrid vehicles sold for each manufacturer, before finally being eliminated in December 31, 2010. The core technologies in hybrids also laid the foundation for plug-in hybrid electric vehicles and electric vehicles, both of which are currently being subsidized with tax credits up to $7,500. The introduction of these technologies have been heralded by policymakers and reporters as a way to reduce carbon emissions, local air pollutant emissions, and dependency on imported oil. What has been less discussed, however, are the overall welfare effects of these new technologies.

In addition to any possible benefits from reduced environmental and energy security externalities, the welfare effects of the introduction of hybrid vehicles also include changes in consumer and producer surplus after accounting for the substitution patterns in new vehicle sales associated with the new equilibrium in the market. The welfare effects of the introduction of new technologies have long been of broad interest to economists (Bresnahan and Gordon, 1997), with notable work estimating the consumer benefits from many different new products, including cellular phones (Hausman, 1999), health care technology (Trajtenberg, 1989), computers (Bresnahan, 1986), and automobiles (Feenstra, 1988; Berry, Levinsohn, and Pakes, 1993; Fershtman and Gandal, 1998; Petrin, 2002). This body of previous work has shown that the consumer surplus gains from new technologies can be quite large, a benefit of the Schumpeterian process of firms innovating to gain a first-mover advantage and transitory market power.

This study estimates a structural model of demand and supply in the automobile market to estimate the total consumer surplus effects of the introduction of hybrid vehicles. We use data on the complete set of new vehicle registrations from California over the period 2001-2008, along with household-level income and zip code-level demographics, to estimate substitution patterns in this market, which is the largest in the United States. The market is sufficiently large that automakers are even willing to develop technologies and trims primarily to serve this market.[1] We perform a counterfactual analysis removing hybrid vehicles to compute a new equilibrium in the market and the welfare consequences of the introduction of the hybrid. The compensating variation is estimated at -$14 (all values are in real 2017 dollars) for each new vehicle purchaser in 2001 and $395 in 2008, and is mostly driven by the success of the Toyota Prius. We find mixed results on compensating variation based on income, with high-income households requiring $248 to be compensated in 2008 and low-income households needing $236, but middle-income households requiring $468. We also estimate an upper bound for the carbon dioxide emissions reduction benefits from the introduction of the hybrid, and find that these environmental benefits are less than 1% of the total market benefits. This result is striking, considering the attention that has been focused on the environmental benefits of hybrids. These findings demonstrate that the welfare gains from the introduction of the new product and the increased competition it engendered far outweigh the environmental benefits that received the most attention.

Our methodology combines elements of the estimation strategies from Petrin (2002) and Berry, Levinsohn, and Pakes (2004) to fully take advantage of our rich data. Just as in Berry, Levinsohn, and Pakes (1995), we posit a structural oligopoly model for the automobile market to estimate demand and supply, incorporating unobservable vehicle quality in the estimation to allow for highly flexible substitution patterns. We add further moments based on demographic data, as in Berry, Levinsohn, and Pakes (2004) ("micro-BLP"), but in our case these moments are at the zip code level. Petrin (2002) uses a similar approach to

[1] For example, it is common for the most efficient new models to only be sold in California first–sometimes for several years–before they are offered elsewhere in the United States.

examine the market benefits generated by the introduction of the minivan in 1984. Our estimation and counterfactual mirrors Petrin (2002) in that we also simulate the removal of the new product and calculate the consumer benefits for different demographic groups. Our work differs in using a much richer dataset and being a setting with substantial policy interest and environmental implications.

Several recent papers have examined different aspects of the introduction of the hybrid vehicle. Berensteanu and Li (2011) is perhaps the closest to our work methodologically; they use a modification of the Petrin (2002) estimation strategy, aggregate data on vehicle sales in 22 Metropolitan Statistical Areas (MSAs) from 2001-2006, and survey data from a cross-section (2001 NHTS) to examine the impact of policies to promote hybrids on the market equilibrium. Our study differs from Berensteanu and Li (2011) in the research question, exact methodology, data available, and results. We bring to bear all new vehicle registrations in the state of California over an eight-year period and demographic information for approximately 2,000 zip codes based on the location of vehicle registration, allowing for more precise micro-level moments in our estimation.

Our work also contributes to the small, but growing literature on hybrids. In addition to Berensteanu and Li (2011), Gallagher and Muehlegger (2010) and Chandra, Gulati, and Kandlikar (2010) also examine the effects of different policy instruments to subsidize hybrids. Gallagher and Muehlegger (2010) show that sales tax waivers are more effective than income tax credits. Chandra, Gulati, and Kandlikar (2010) finds that that a rebate policy in Canada induced 26% of the hybrids sold during that rebate period. Sallee (2011) estimates the incidence of tax credits for the Toyota Prius, finding that they were fully captured by consumers. Our work differentiates between the consumer and producer benefits from the introduction of the hybrid, and is the first to demonstrate that the benefits from the introduction of the new technology far exceed the environmental benefits, a result that may be surprising given the attention focused on the environmental benefits. We also demonstrate that through the re-equilibration of prices in the vehicle market, the introduction of hybrids benefitted households across the entire income distribution. This result is an important contribution, as a common critique of high efficiency and alternative fuel vehicles is that the wealthy disproportionately benefit from them (and from subsidies on them).[2]

The next section provides some brief background on hybrid vehicles and describes our data. Section 3 lays out the model and discusses our estimation approach. Section 4 presents the results. Section 5 provides several counterfactual analyses that simulate the following scenarios: the automobile market without hybrids; the automobile market where hybrid cars are introduced but lack hybrid technology and the corresponding gain in fuel economy; and the automobile market where hybrid cars are introduced, lack hybrid technology, and yet retain their fuel economy. In each scenario, we measure the corresponding changes in consumer utility and market share. Using these changes, we estimate the compensating variation as the market benefit of hybrids, and the change in carbon emissions as the social benefit of hybrids, as well as the aggregate benefits. Section 6 concludes.

2 Background and Data

2.1 Background on Hybrid Vehicles

Hybrid-electric vehicles contain a standard gasoline engine that is supplemented with an electric motor that can offset some of the burden on the gasoline engine to improve performance and/or fuel economy. The electric motor runs off a battery that is recharged by regenerative brakes that convert some of the vehicle's kinetic energy to electricity.[3] Because of the potential for improved fuel economy and reduced emissions, hybrids have become known as a symbol of "conspicuous conservation" (Sexton and Sexton, 2014).

[2]For example, see https://www.greencarreports.com/news/1078350_toyota-prius-hybrid-popular-among-very-very-wealthy-americans/

[3]There are several different variants of hybrid vehicles, including different variants of "full hybrids" (vehicles that can run entirely in electric-only mode), "mild hybrids" (an electric motor allows that gasoline engine to be turned off when coasting, breaking, or stopped, but there is no electric-only mode of propulsion), and "plug-in hybrids" (full hybrids that can be plugged in to charge). This article examines full hybrids only.

The first hybrid car was the Toyota Prius, sold in Japan beginning in 1997. The Honda Insight and Toyota Prius were introduced to the United States in 1999 and 2000 respectively, with low sales to start. However, the improvement in fuel economy of these vehicles over previously available options was dramatic, with the Honda Insight EPA mileage rating of 61 miles per gallon city and 70 miles per gallon highway.[4] In 2002 Honda introduced the Civic Hybrid, while in 2004 Ford introduced the Escape Hybrid. By 2004, sales of hybrids had grown beyond expectations, led by the Prius. In 2007, GM and Nissan also began offering hybrid models, and by this time there were already 15 hybrid models offered and hybrid sales had exceeded 300,000 vehicles and 2% of total vehicle sales. Our study focuses on the effects on the automobile market in the early years of the introduction of the hybrid.

2.2 Data

The data for this research comes primarily from R.L. Polk and covers all new personal vehicle registrations in California from 2001 to 2008. Each vehicle in the data is uniquely identified by its Vehicle Identification Number (VIN), allowing us to decode the VINs and obtain detailed attribute information. For this study, we use vehicle make, model, model year, trim, weight, displacement (a measure of power), and the manufacturer's suggested retail price (MSRP). Prices, and all other dollar amounts in this article, have been adjusted to 2017 dollars.[5] Fuel economy ratings (in miles per gallon) are obtained from the U.S. Environmental Protection Agency, and safety ratings are gathered from the National Highway Transportation Safety Administration. We also observe whether each vehicle is leased or purchased. Most importantly, we identify if a vehicle is a hybrid or not, even if a vehicle and its hybrid counterpart share the same model name. Summary statistics on vehicle attributes are reported in Table 1.

We differentiate vehicles by model year, make, model, whether or not the vehicle is a hybrid, and body type. Different trims that are otherwise the same across these five

[4] See http://www.hybridcars.com/history-of-hybrid-vehicles/.

[5] Income brackets are defined by endpoints expressed in the data's native 2010 dollars.

categories are averaged together using observed purchases to weight the average. Across eight time periods, we observe 2,639 different vehicles, where a vehicle is defined as a specific make-model year-model-hybrid-body type. Consumers choose from among approximately 300 different vehicles in each year, or they can choose to not purchase a new vehicle. Table 2 gives the number of purchases for some of the more popular options across different types over the years in California.

The purchases show hybrids following a common diffusion pattern for new technologies. Hybrids began with a lackluster appearance in the market. The Honda Insight, which arrived in 1999, had all but disappeared by 2002. The Toyota Prius, though selling much better than the Insight, only made up 0.4% of all new vehicle purchases in California in 2002 and had a quarter of the share of the Toyota Corolla. Over time, however, the technology improved, and hybrids–especially the Toyota Prius–became more mainstream. Over the next six years, new vehicle market shares of the Toyota Prius more than doubled every two years, from 0.4% in 2002, to 0.8% in 2004, 1.4% in 2006, and finally 3.11% in 2008. This is especially striking in 2008, a year when the economy was in recession. Despite total new vehicle purchases dramatically decreasing, readily observable in sales of the highly popular Toyota Corolla and Ford F-Series, Prius sales actually increased. Undoubtedly, this was in part due to the higher gasoline prices at this time.

The registration data also contains the zip code in which each new vehicle was registered, and the household income of most of the registrants (about 70% of the observations, which total to over 12 million). This household income is collected by R.L. Polk and is based on data aggregation from multiple sources. Outside of income, further zip-code level demographics are gathered from the U.S. Census Bureau (2005-2007 American Community Survey). The unemployment rate at the county-month level in California is obtained from the Bureau of Labor Statistics, and average retail gasoline price at the county-month level is acquired from the Oil Price Information Service. We use zip-code level income for any missing household-level incomes to complete the sample.

Given that we have zip code-level demographic information for several of our key variables, we treat each zip code as our unit of observation in our estimation. This modeling choice also dramatically improves the computational speed of estimation and makes estimation feasible. Accordingly, we treat each zip code as a representative individual and weight each zip code by its population for all of our California-wide market analyses. In the traditional micro-BLP framework, one would typically observe a household's vehicle choice as the unit of observation, and would use these observations to estimate a household vehicle choice probability distribution function. Instead, as we observe a number of vehicle choices for each given zip code, we aggregate to construct zip code-level vehicle choice distributions, and use these to estimate a zip code-level vehicle choice probability distribution function. In our data, we observe 1,655 distinct zip codes in the state of California for each year from 2001-2008.[6] Although most of the demographic variables do not vary over time, the unemployment rate and gasoline prices do. Gasoline prices in particular are useful for our analysis, as fuel costs can be expected to influence the demand for hybrids. Table 3 reports summary statistics for demographic variables, where all are at the zip-code level, except income, which is at the household level.

There is a substantial amount of variation in mean income across zip codes (recall that we are using the mean over households that bought new cars as we observe household-level incomes). Population density varies greatly as well, from congested cities to sparsely populated rural areas, reflecting the heterogeneity of California. Figure 1 shows the changes in gasoline prices and the unemployment rate over time, along with the market share of hybrids.

There is very little cross-sectional variation in gasoline prices, but the prices are increasing over time, reaching peak levels in 2007. Unemployment rates were slowly declining for most of the period, but we can see an increase as the recession in 2008 began after the financial

[6]The raw data give us 2,111 zip codes for each year in this period, but they contain groups of small zip codes with the same demographics for all zip codes in that group. For each such group, we aggregate and treat it as a single zip code, leaving us with 1,655 observably varying zip codes.

crisis of 2007. The market share of hybrids begins very low and rises over the period, reaching a peak at just above 8% just before the peak in gasoline in 2008. It then drops down to close to 4%, but remains at that level. These time series emphasize the importance of including gasoline prices in our empirical analysis.

3 Model and Estimation

We proceed with a model of demand and supply, motivated by micro-BLP, to estimate how consumers and firms respond to one another in the U.S. automobile market. We define a market to be all new vehicles available for purchase in California in a given year. The outside option captures all alternatives available for transportation in a given year that do not involve the purchase of a new vehicle (e.g., buying a used car, renting a vehicle, exclusively using public transportation, etc.). In our model, the representative consumer from each of the 1,655 zip codes chooses from a range of different vehicles and the outside option in each year. Each year offers the consumer between 302 and 370 different vehicle choices, depending upon the year. Vehicle choices are exogenously provided by 20 competing suppliers, who compete in a simultaneous price-setting game with differentiated products, arriving at a (static) Nash equilibrium.

3.1 Demand

The utility that the representative consumer from zip code i obtains from purchasing new vehicle j in period t is separated into three components: an average utility component (δ_{jt}), a consumer-specific component (μ_{ijt}), and an idiosyncratic error (ϵ_{ijt}):

$$u_{ijt} = \delta_{jt} + \mu_{ijt} + \epsilon_{ijt}. \tag{1}$$

The average utility that all consumers gain from purchasing vehicle j in period t is denoted by δ_{jt}, and it is derived from observable characteristics X_{jt}, such as weight, safety ratings, and vehicle type; and unobservable characteristics ξ_{jt}:

$$\delta_{jt} = X_{jt}\beta + \xi_{jt}. \tag{2}$$

Consumer-specific utility is captured by μ_{ijt}. Zip-code demographics Z_{it}, such as population density and gasoline prices, are interacted with vehicle characteristics X_{jt}. We estimate normally distributed random coefficients for three key variables in the model: vehicle fuel consumption (measured in gallons per mile), vehicle weight, and a hybrid indicator variable. Averaging over the standard normal distribution draws ν_i allows us to estimate the standard deviation of the random coefficients' distributions σ. Finally, we denote price as p_{jt} and we measure disutility from price with the parameter α_i, which varies by income bracket. These measures allow for consumers in different geographical regions to have different preferences. For example, consumers in more rural areas may prefer less expensive vehicles, whereas high-income zip codes may be more likely to purchase highly priced vehicles. Thus, we model the consumer-specific utility as:

$$\mu_{ijt} = X_{jt}Z_{it}\beta^o + X_{jt}\nu_i\sigma + \alpha_i p_{jt}. \tag{3}$$

Finally, we assume an idiosyncratic error term ϵ_{ijt}, which follows a Type I extreme value distribution, and we normalize all utility with respect to the outside option, giving it a utility of zero for all consumers.[7] Given this assumption, we can calculate the probability that the representative consumer purchases any of the available new vehicles. Because each consumer in this market represents a particular zip code, we can interpret this probability as the zip-code-specific market shares for new vehicles. Each zip-code specific share is given by:

$$s_{ijt} = \frac{\exp(\delta_{jt} + \mu_{ijt})}{\sum_{j'} \exp(\delta_{j't} + \mu_{ij't})}. \tag{4}$$

[7]The choice of the outside option only indicates that the consumer did not choose to purchase a new vehicle; the consumer may indeed still own a vehicle.

The zip code-specific market shares allow us to estimate the consumer-specific utility component μ_{ijt}. By then weighting each share with the zip code's population w_i, we can calculate the state-wide market share of each vehicle:

$$s_{jt} = \frac{\sum_i w_i s_{ijt}}{\sum_i w_i}. \tag{5}$$

These state-wide market shares will allow us to estimate the average utility component δ_{jt}.

3.2 Supply

On the supply side, we model F firms in a Nash equilibrium, following the approach used in Berry, Levinsohn, and Pakes (1995) and also used in more recent papers, such as Jacobsen (2013). Firms choose prices to maximize profits, given their products J_{ft} and their competitor's products. Profits are denoted by:

$$\Pi_{ft} = M \sum_t \sum_{j \in J_{ft}} (p_{jt} - mc_{jt}) s_{jt}, \tag{6}$$

where the total population across all zip codes is represented by M and mc_{jt} is the marginal cost of producing the vehicle. The J first order conditions for profit maximization give us solutions for the equilibrium prices:

$$s_{jt} + \sum_t \sum_{l \in J_{ft}} (p_{lt} - mc_{lt}) \frac{\partial s_{lt}}{\partial p_{jt}} = 0. \tag{7}$$

We can estimate marginal costs by solving for them using the above equations:

$$\mathbf{mc} = \mathbf{p} - \Delta^{-1}\mathbf{s}. \tag{8}$$

The matrix of own-price and cross-price market share derivatives is Δ, where Δ_{jl} is equal to $\frac{\partial s_j}{\partial p_l}$ if products j and l are produced by the same firm, and equal to zero otherwise. Following

Berry, Levinsohn, and Pakes (1995), we assume marginal costs are a log-linear function of cost variables C, which include the non-price vehicle attributes X and additional cost-side variables, such as the number purchased and whether or not the vehicle is imported.

$$\ln(mc_{jt}) = C_{jt}\gamma + \omega_{jt} \tag{9}$$

3.3 Estimation

We follow Berry, Levinsohn, and Pakes (1995) and Petrin (2002) and use GMM to estimate both demand and supply parameters. We use three sets of moments. As in previous studies, some of these moments are aggregate moments and some of these moments are micro moments, estimated at the zip code level. This both facilitates estimation and allows us to leverage our rich data.[8]

First, we use the BLP contraction mapping process to estimate δ as a function of the individual-specific demand parameters θ; this is done by setting predicted aggregate market shares to exactly match observed aggregate market shares s^0:

$$G_0 = s(p, X, Z; \delta(\theta), \theta) - s^0 = 0. \tag{10}$$

Once δ is solved to satisfy these moments by setting $G_0 = 0$, we can express δ as a function of θ and calculate partial derivatives of market share with respect to price. This allows us to compute the matrix of partial derivatives Δ, and we can solve for the vector of marginal costs using Equation 8.

The second set of moments we use are the traditional BLP market-level disturbance moments. We assume that ξ and ω, the unobserved product-specific disturbance terms, are uncorrelated with observed vehicle attributes relating to demand and cost, and form the

[8]We considered estimating the market share moments at the zip code level, so there would be a zip code-specific δ, but this would remove the variation identifying the micro-moments, so we viewed this as a net loss, rather than gain. By including the micro moments, we are able to leverage the richness of our data.

corresponding moments:

$$G_1 = \frac{1}{J \cdot T} \sum_{j,t} IV_{jt} \xi_{jt}, \tag{11}$$

$$G_2 = \frac{1}{J \cdot T} \sum_{j,t} IV_{jt} \omega_{jt}. \tag{12}$$

Having solved for δ and mc as functions of θ, we can use a linear regression to solve for both β and γ, and then extract estimates of the disturbance terms. Both ξ and ω are correlated with price, so we must use an instrumental variable regression. Following Berry, Levinsohn, and Pakes (1995) and Petrin (2002), we use the non-price characteristics and cost factors of product j as instruments for themselves, and we instrument for each product's price using the sum of the characteristics across other own-firm products ($\sum_{l \in J_{ft}, l \neq j} x_{lt}$) and the sum of the characteristics across competing firms ($\sum_{l \notin J_{ft}} x_{lt}$).[9]

Second, we use the micro moments from Berry, Levinsohn, and Pakes (2004), where we seek to match the covariance between vehicle characteristics and consumer characteristics in our model with that observed in the data. Note that for these moments, we use the zip code-specific market shares to take advantage of variance in consumer characteristics. We proceed as follows:

$$G_3 = \frac{\sum_i xz_i(w_i s_i(p, X, Z; \delta(\theta), \theta))}{\sum_i w_i s_i^0} - \frac{\sum_i xz_i(w_i s_i^0)}{\sum_i (w_i s_i^0)}, \tag{13}$$

$$G_4 = \frac{\sum_i \tau_{ik} p(w_i s_i(p, X, Z; \delta(\theta), \theta))}{\sum_i (w_i s_i^0} - \frac{\sum_i \tau_{ik} p(w_i s_i^0)}{\sum_i (w_i s_i^0)}, \tag{14}$$

where τ_{ik} is an indicator variable for consumers in income bracket k.

We use the non-linear optimization solver fmincon in MATLAB to minimize the GMM

[9] We also run a robustness check with the instruments suggested in Reynaert and Verboven (2014) and while we have some trouble with convergence, the coefficient estimates upon solution are extremely similar.

objective function and solve for $\hat{\theta}$:

$$\mathbf{G}(\theta)' = [G_1 G_2 G_3 G_4], \tag{15}$$

$$\hat{\theta} = \arg\min_{\theta \in \Theta} \mathbf{G}(\theta)' W \mathbf{G}(\theta). \tag{16}$$

The GMM estimator uses the weight matrix W, which weights the sets of market-level demand and supply moments independently using $(\mathbf{IV}'\mathbf{IV})^{-1}$, and weights the sets of zip-code-level moments using the identity matrix.[10] We obtain standard errors by bootstrapping over both demand and supply.[11]

4 Results

The demand-side parameter estimates are shown in Table 4. These results are sensible and broadly consistent with the existing literature. We find consumers prefer more powerful vehicles and dislike vehicles with high fuel consumption. The large negative constant associated with a new vehicle purchase indicates that the outside option is a highly popular option, as it contains used vehicle purchases and no vehicle purchase at all. The random coefficient estimate for the hybrid dummy has a negative but insignificant mean, with a large and significant standard devation. This result suggests that unobservable attributes of hybrids beyond fuel efficiency are literally a matter of taste, with strong preferences for and against them depending upon the consumer. One may hold a preference for new technology while the other finds comfort in a more traditional design. Our model explains the increase in the share of hybrids over time through consumer preferences for lower prices, greater safety, and increased fuel economy. Over its eight-year run in the data, the Toyota Prius improved substantially in all three of these attributes, especially in price, with a drop of $2,778 from

[10] We also attempted to estimate the model with an optimal two-step GMM estimator, but the solver failed to converge onto a solution when using the inverse of the estimated variance-covariance matrix of the moments.

[11] Currently we are using 25 bootstraps, as each bootstrap takes at least several days to run on our server.

2004 to 2008.

In zip codes where the population is made up of fewer people under 18, we see increases in demand for new cars, likely due to eligibility to drive. Increases in population density decrease demand for new cars, likely because higher densities are correlated with cities and better public transportation options. Increases in the unemployment rate also imply decreased demand for new cars, likely because less expensive transportation options are available in the outside good (e.g., used cars, public transportation, etc.). All consumers dislike higher prices, but consumers with high incomes are roughly just as averse to higher prices than those with low incomes. Increases in gasoline price decrease consumer demand for new vehicles, as the cost of operating a vehicle increases. The estimated effect of gasoline price on demand is insignificant, for which there are several potential explanations. One possibility is that consumers consider fuel economy and gasoline price jointly when making their decision, such that gasoline price has an insignificant effect on demand once fuel economy is controlled for. Another possibility is that after controlling for gasoline consumption, which varies by vehicle, gasoline price does not play a significant role in influencing demand for new vehicles considered as a whole relative to the outside option.

Table 5 presents the estimates from the supply side. Increases in power, weight, and safety lead to higher costs. Hybrids are more expensive to manufacture, all else equal. Imported vehicles cost more to manufacture and deliver to the market, and the log quantity of vehicles produced has a small but statistically significant negative impact on marginal cost, consistent with economies of scale in automobile production.

Table 6 shows substitution patterns for select vehicles in 2008, showing that the implied substitution patterns are quite reasonable. An increase in a given vehicle's price leads to a large decrease in sales for the vehicle and modest substitution to other new vehicles, in part due to the attractiveness of the outside option. We find that the two most popular hybrids, the Toyota Prius and Honda Civic (hybrid), are strong substitutes for one another. Our model produces this result despite the large standard deviation in the random coefficient for hybrids. Consumers' idiosyncratic preferences for hybrids are relatively widely spread, resulting in substantial groups of consumers who greatly desire hybrids and consumers who are highly averse to them. These groups of consumers substitute within hybrids and traditional vehicles, respectively, in response to a price increase.

5 Counterfactual Analyses

5.1 Market Benefits

With the estimates for the demand and supply models complete, we can proceed with the counterfactual analysis. In our first counterfactual analysis, we remove hybrids from the choice set in all years, so that consumers no longer have them as an option for purchase. Under this new choice set, we use the demand and supply models to find the new market equilibrium. We find small changes in prices from the removal of hybrids, on the order of tens of dollars. This is most likely due to the small market shares of hybrids, so that removing them from the market does not significantly increase demand for other vehicles. Indeed, changes in market shares of other vehicle classes are quite small. Table 7 shows that changes in vehicle type shares, as a percentage of new vehicle purchases, make up 1-3% of the total market.

Table 7 reports changes in the share of new vehicle purchases due to the removal of hybrids in two ways. First, including hybrids in our calculations, we see that hybrids made up 2.75% of all new vehicle purchases. The share of SUVs decreased 0.17% due to the removal of hybrids, but by looking at the calculation from excluding hybrids when measuring changes in shares, we see that this decrease is due to the removal of hybrid SUVs rather than consumers substituting away from SUVs. Indeed, shares of traditional SUVs increase by 0.22%. Traditional smaller cars (which fall into the "Other" category) are the most popular substitute for hybrids, with an increase of 0.43%, which is reasonable given both their popularity in the market and their relative similarity to hybrids (compared to other vehicle types). The "Other" category includes any coupes, sedans, or convertibles, such as the Ford Taurus, Toyota Corolla, and Honda Civic.

Having calculated the changes in shares and prices, and having previously estimated the marginal cost for each vehicle, we can calculate the changes in manufacturer new vehicle profits. Table 8 displays the estimated change in profits from the removal of hybrids by automaker. The results indicate that Toyota, Honda, and Nissan are negatively affected the most, as they sell hybrids (Nissan after 2006). GM is a large manufacturer and while it sold a hybrid starting in 2007, it appears that the overall gain in market share from the absence of the Toyota and Honda hybrids more than made up for the loss of the single GM hybrid in most years. Indeed, GM would have been the greatest beneficiary had hybrids not been on the market.

Once prices are solved for, we calculate the expected utility for each zip code under the counterfactual and compare it to the observed expected utility, similar to the analysis in Petrin (2002). We then calculate the level of price reduction each individual zip code would need to experience across all offered vehicles in order for it to be indifferent between the two markets. We interpret this value as the compensating variation.[12] We perform this analysis both at the mean and at different zip code income brackets. Examining the results by income brackets is especially useful because of the common critique that it is mostly wealthy households who purchase hybrids, and thus the benefits primarily accrue to these households. For example, 26% of hybrids are purchased by households that live in zip codes with the median household income over $70,000.

Table 9 displays the results for this analysis. At the start of the period, there is not much of a difference between the observed and counterfactual. Only a few hybrids were available on the market, and they were not popular vehicles. As such, they did not substantially impact consumers' choices and did not create competitive pressure on the prices of other vehicles.

[12]This interpretation deserves a caveat in that the existing policies for hybrids complicate the analysis. For example, one could scale down our estimate by the social cost of public funds from the federal tax incentives used to encourage hybrid sales.

Compensating variation per vehicle purchased during this period is about -\$14. Over the next two years, compensating variation slowly increases, but in 2004, the new model of the Toyota Prius enters the market, and rapid changes are observed. Benefits increase from \$42 in 2004 to \$179 in 2005. By 2008, hybrids are exerting enough competitive pressure and creating enough demand to warrant an average compensating variation of \$395.

From a distributional perspective, we find that compensating variation from the availability of hybrids is fairly evenly dispersed. For instance, in 2008, households in the highest income bracket have a compensating variation of \$248, whereas for those in the bottom bracket the compensating variation is \$236.[13] The model results thus suggest that in equilibrium, all households benefit–even those in the lowest bracket. The structural approach taken in this article, whereby the new equilibrium in the market in obtained, is especially useful for allowing such insights to emerge.

5.2 Carbon Emissions Reduction Benefits

We can also calculate a back-of-the-envelope estimate of the direct emissions reduction benefits. These estimates should be viewed cautiously in light of a binding Corporate Average Fuel Economy (CAFE) standard. Specifically, if automakers face a binding nationwide fuel economy constraint, then the introduction of the highly fuel efficient hybrids would simply provide additional leeway under the constraint to sell more lower fuel economy vehicles. This issue is analogous to the leakage issue discussed in Goulder, Jacobsen, and van Benthem (2012). Of course, one could also argue from a political economy perspective that the existence of new technology that allows for major gains in fuel economy could spur regulators to adopt more stringent standards. It is possible this occurred with the setting of the model year 2012-2016 standards, which were proposed in 2009. Parsing these effects is outside the scope of this article, so we calculate the direct emissions reductions from the introduction of

[13]Note again that these estimates are based on zip code-level means using the household-level data on incomes of all new car purchasers, so they are more accurate than zip code means taken over the entire population in the zip code.

hybrids to give a sense of an upper bound of the magnitude of the effect.[14]

Using data from the 2009 National Household Travel Survey, we calculate average vehicle-miles-traveled (VMT) given a household's chosen vehicle's type, model year, make, and whether or not it is a hybrid vehicle. We match these averages to the vehicles in our analysis, and calculate an average VMT for purchasers of new vehicles in each zip code, using the vehicle distribution as weights for the average. We do the same to calculate a weighted average MPG rating for each zip code. Combined, we can derive the average number of gallons of gasoline a new vehicle purchaser consumes each year.

A gallon of gasoline, when combusted, releases 18.9 pounds of CO_2. The U.S. Government Interagency Working Group on the Social Cost of Carbon estimates the social cost of carbon to be roughly \$45/ton of CO_2 when converted to real 2017\$ (IWG, 2015). Using these estimates, we convert gallons of gasoline to the social cost of carbon which a new vehicle purchaser imposes on society each year.

We calculate the difference in the social costs of carbon emissions between the observed data and the counterfactual. We compute two sets of estimates, under two different assumptions. First, we assume that VMT for each consumer is fixed; in other words, a consumer's vehicle reveals information about their VMT but the vehicle itself does not influence their VMT. Second, we allow consumers to change their driving based on their vehicle, accounting for the well-known rebound effect (Gillingham, Rapson, and Wagner, 2016). The idea behind this response is that if a vehicle costs less per mile to drive due to the higher efficiency, the consumer would be expected to drive it more. We thus recalculate the expected VMT for each consumer in the counterfactual using a -0.15 elasticity of driving with respect to the price per mile of driving based on Knittel and Sandler (2018).[15] Table 10 displays the carbon

[14] It is possible that there are also local air pollutant benefits, however, the sufficiently stringent standards for emissions control equipment in new vehicles means that it is unlikely that hybrids would have substantially different local pollutant emissions than the substitute vehicles for many years (until the emissions control equipment degrades). Accordingly, we do not model these potential benefits. Similarly, there are very slightly larger carbon emissions associated with production of hybrids (from the production of batteries) that a life-cycle analysis would capture, but that we do not model.

[15] We also examine other estimates of the rebound effect, such as -0.10, which is the value EPA uses in the Regulatory Impact Analysis of CAFE standards and may perhaps be more appropriate because Knittel and

emissions reduction benefit in each calculation.

Results under fixed VMT and adjusted VMT are as expected, increasing as hybrids make up greater shares of the market, with adjusted estimates coming in slightly lower as we account for the rebound effect.

5.3 Aggregate Benefits

Having estimated the individual market and (upper bound) carbon emissions reduction benefits for new vehicle purchasers, we can calculate the expected total benefit of hybrids as a choice in the market. Note that the compensating variation we have calculated is the required price reduction of new vehicles in order to equate utility between the observed and counterfactual markets for new vehicle purchasers. In order to accurately measure aggregate benefits, we must multiply the compensating variation by the probability that the representative consumer of each zip code will purchase a new vehicle. Table 11 reports the expected total benefit of hybrids for the state of California. We find that the greatest gains in welfare were made in 2007 at $917 million, when new vehicles were in high demand and hybrids were well-established in the market.[16]

A key finding is that relative to the market benefits, the environmental benefits from carbon emissions reductions are very small–and the estimates presented here should be considered an upper bound on the environmental benefits. Consumer market benefits alone are at least 60 times greater than upper bound for carbon emissions benefits in every year in our sample. Thus, despite the vast attention given to the environmental benefits of hybrids, our calculations indicate that the real story is the very large market benefits from the introduction of the new desired technology.

Sandler (2018) do not include newer vehicles in their study and newer vehicles tend to be less elastic. The main qualitative story does not change.

[16] There is a decrease in benefits in 2008, likely due to the economic downturn and the market-wide reduction in new vehicle purchases that came with it.

5.4 Related Counterfactual Scenarios

One concern about our counterfactual that entirely removes hybrids from the choice set is that while it is useful for understanding the effects of the introduction of the hybrid, it may not be a very realistic counterfactual. If automakers did not develop hybrids, it is possible that they would have developed similar vehicles to hybrids. Accordingly, we also examine two additional, related counterfactual scenarios that can be thought of as scenarios for the introduction of "hybrid-like" vehicles. In both counterfactuals, we allow hybrids to remain in the market, but we remove the underlying technology in one of two ways. In the first scenario, we remove the hybrid technology, treating the vehicle as a standard vehicle, but leave all other vehicle characteristics unaltered, including the fuel economy rating. In the second scenario, we remove the hybrid technology and adjust the vehicle's fuel economy accordingly, but leave the other characteristics unaltered.[17]

In Table 12, we report the aggregate measures of benefits for each of our three counterfactual analyses in 2007, the point in our observed period at which benefits reach their peak. We find that the addition of hybrid technology, even without the benefits it confers upon fuel economy, creates total benefits in 2007 of $565 million; however, we note that this estimate comes with a relatively high standard error of $396 million, likely due to the high variance on the random coefficient for hybrid preference. After accounting for the gains in fuel economy, benefits in 2007 rise to $601 million, though with a standard error of $388 million. Once we account for the benefits that hybrids provide relative to their absence from the market, benefits rise to $917 million, and the standard error drops to $170 million. While variance from the utility directly provided by a hybrid is high, all customers benefit from the presence of hybrids as additional vehicles in the market. These additional counterfactual scenarios generally confirm our primary results and show how the quantitative values in those results

[17] Many hybrids enter the market alongside a vehicle with the same make and model but no hybrid technology. For these hybrids, we replace the hybrid's fuel economy rating with that of its standard counterpart. For all other hybrids, we replace the hybrid's fuel economy with a vehicle of the same make that is most similar to the hybrid in engine displacement and weight, two characteristics strongly correlated with fuel economy.

might change under alternative counterfactuals.

5.5 Robustness Checks

We run several analyses to explore the robustness of our results to different assumptions.[18]

First, we examine the effect of holding vehicle prices fixed to help us better understand the importance of equilibrium in the market relative to the direct effects of hybrids. In this run, manufacturers cannot adjust price after the removal of hybrids, so we would expect higher prices. However, we did not find very large price changes in our primary results, so we would not expect too large of a difference. Indeed, we find that total benefits are similar and are 0.5% higher at peak when prices are held fixed.

Second, we hold vehicle prices and gasoline prices fixed at their 2001 levels. Here, we expect to see large increases in market benefits. Lower gasoline prices will increase demand for all vehicles in general, which increases demand for hybrids. Notably, there is no change in individual-specific compensating variation conditional on the purchase of a vehicle. Because gasoline prices do not interact with any vehicle characteristics in our utility specification, all vehicles are impacted uniformly by the fixed gas prices, resulting in no relative change in utility between vehicles. If we also interact gasoline prices (not shown) with vehicle characteristics we would see a substitution away from hybrids countering the benefits of lower gasoline prices.

Finally, we hold vehicle prices fixed but remove federal subsidies from hybrids, effectively increasing their price. From 2001-2005, we increase prices by $500, an approximation of the $2,000 tax deduction applied at the median marginal tax rate of 25%. From 2006-2007, we use the annualized tax credit granted to the Toyota Prius, as documented in Sallee (2011). We expect total benefits to decrease as consumers are disincentivized from purchasing hybrids, and this is what we observe. However, when we calculate the saved federal subsidies and add these back into our total benefits, we find that total benefits actually increase relative to the

[18]These checks were inspired by Berensteanu and Li (2011). See Appendix Table A.1 for the total benefits under each run by year.

counterfactual where vehicle prices are held constant and federal subsidies are applied.

6 Conclusion

This study estimates a model of demand and supply in the automobile market using comprehensive vehicle registration data from the state of California from 2001-2008. During this period, we see the introduction of hybrids to the U.S. market, and we investigate the welfare effects of this introduction in terms of increased competition amongst vehicles, better matches for consumer demand, and reduced carbon emissions. Because we observe all new vehicles registered, we can accurately capture the relatively small market shares of hybrids and calculate compensating variation for consumers if we removed hybrids from the market.

Due to limited demand for hybrids shortly after their introduction to the U.S. automobile market, we find compensating variation for new vehicle purchasers is -$14 in 2001, suggesting that early adopters who thought they would prefer a hybrid had second thoughts after purchasing the vehicle. Over time, hybrids become a more attractive substitute for conventional vehicles, and compensating variation increases to $42 in 2004. In 2004, the Toyota Prius undergoes a model revision and becomes the first commercially successful hybrid on the market, and its appeal drives compensating variation estimates up to $179 in 2005. Market shares of the Prius double each year over the next few years, and in 2008, new vehicle purchasers would have had to be compensated $395 for the loss of hybrids from their choice set. In contrast to critiques of high efficiency cars only benefiting the wealthy, by modeling the re-equilibration in the market, we find that the addition of hybrids provides benefits across the income distribution and that households at each income level benefit fairly equally. The benefits from hybrids can be expected to be even larger today, although their market share has leveled off with the recent introduction of plug-in hybrid electric vehicles and dedicated battery electric vehicles.

Although we find that carbon emissions were reduced by the introduction of the hybrid, the social benefit from these reduced carbon emissions is dwarfed by the market benefit of new, differentiated products being introduced to the market. Thus, despite hybrids being widely viewed as a "green" good, this article puts these benefits in context, reminding us of the large welfare benefits new products can have regardless of their environmental friendliness.

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Tables and Figures

Table 1: Average Characteristics for Selected Vehicle Types, 2001-2008

Characteristic	All Vehicles	SUVs	Trucks	Hybrids
Fuel economy rating (mi/gal)	19.2	16.5	16.2	35.0
	(4.7)	(3.2)	(2.2)	(10.7)
Displacement (liters)	35.1	39.9	42.6	21.5
	(12.9)	(11.4)	(11.6)	(10.3)
Weight (pounds)	5,286	5,728	5,846	4,582
	(1,124)	(1,069)	(1,037)	(746)
Safety rating (out of 5)	4.3	4.3	4.1	4.3
	(0.46)	(0.47)	(0.46)	(0.34)
Price	$44,092	$42,815	$30,937	$29,151
	($39,314)	($16,891)	($11,326)	($8,264)

$J = 2,639$; a vehicle is a make-model-model year-hybrid-body type. Standard deviations in parentheses.

Table 2: New Vehicle Purchases for Selected Vehicles (in 1000s), 2001-2008

Vehicle	2002	2004	2006	2008
Honda Civic (sedan)	54.7	41.2	47.9	38.6
Toyota Corolla (sedan)	19.2	41.2	50.5	23.4
Ford F-Series	56.1	64.3	53.1	23.0
Chevrolet Suburban	16.8	13.3	3.0	2.9
Toyota RAV4	12.9	9.3	12.2	12.7
Ford Focus (sedan)	11.1	7.4	5.9	8.6
Mercedes-Benz C-Class (sedan)	10.6	9.3	6.4	9.1
Audi A6	0.8	0.3	0.7	0.3
Toyota Prius	5.4	11.7	21.3	32.8
Honda Civic (hybrid)	—	5.0	7.4	6.0
Honda Insight	0.46	0.09	0.16	—
Total New Purchases	1,328.9	1,409.0	1,304.2	891.3

Figure 1: Average Gasoline Price, Unemployment Rate, and Hybrid Market Share

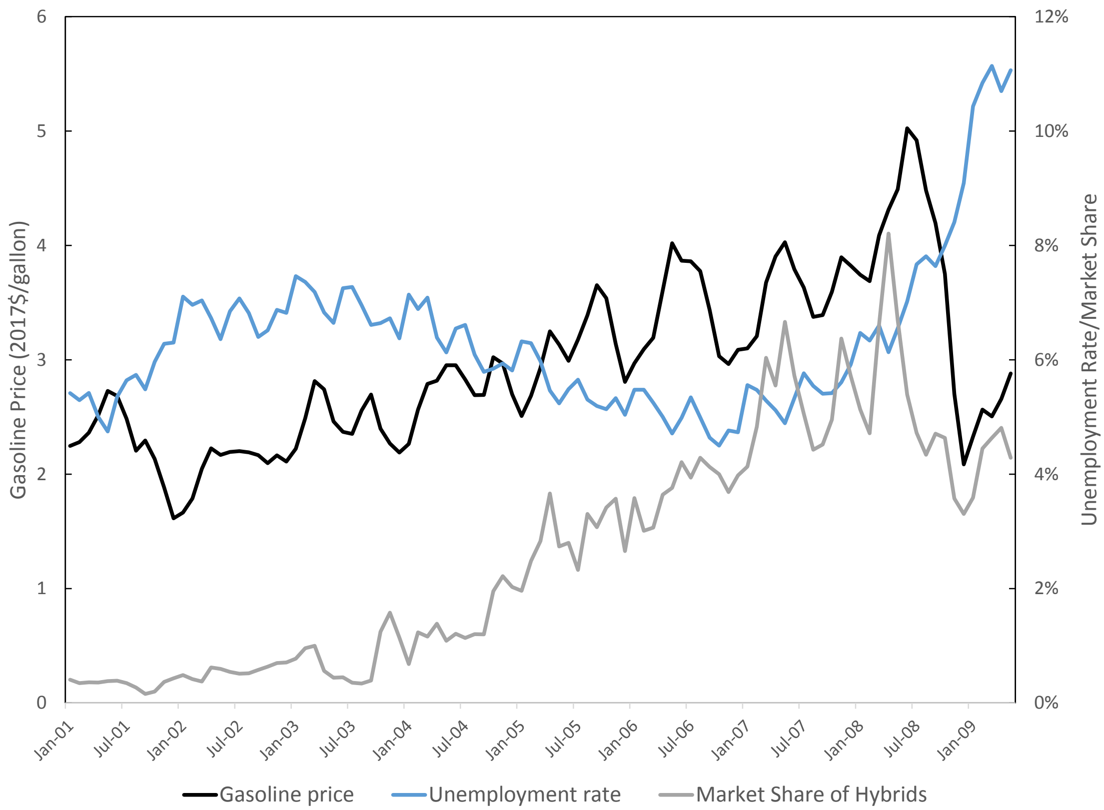

Table 3: Selected Mean Demographics

Characteristic	Mean (Std. dev.)
Income (2017$)	70,438 (28,146)
Population density (per mi^2)	5.8 (6.5)
% over age 65	10.6 (5.0)
% under age 18	26.6 (6.3)
$N \cdot T = 1,655 \cdot 8 = 13,240$. An observation is a zip code-year.	

Notes: $N \cdot T = 1,655 \cdot 8 = 13,240$. An observation is a zip code-year. For income we have household-level, based on R.L. Polk data aggregation, so the mean income is over households that have purchased a new car. Means are taken over zip codes and years and weighted by population. Standard deviations are in parentheses.

Table 4: Demand Model Estimates: Utility

Characteristic	Mean	Std. Err.	Characteristic	Mean	Std. Err.
Constant	-6.88	(2.84)	% over age 65	0.02	(0.01)
Fuel consumption (gal/10 mi)	-0.93	(0.13)	% under age 18	-0.04	(0.01)
Fuel consumption: s.d.	0.43	(0.19)	Unemployment rate	-0.13	(0.03)
Weight (1000s)	-0.36	(0.38)	Population density	-0.03	(0.01)
Weight (1000s): s.d.	0.35	(0.16)	Gasoline price	-1.37	(1.04)
Displacement (liters in 10s)	1.01	(0.01)			
Safety rating (5-star)	1.15	(0.01)			
SUV	-0.11	(0.02)			
Truck	-1.21	(0.03)	Price (in \$10000s)		
Minivan	-1.12	(0.04)	Income: under \$30K	-1.48	(0.03)
Wagon	-1.28	(0.004)	Income: \$30K-\$50K	-1.49	(0.01)
Hybrid	-1.33	(1.30)	Income: \$50K-\$70K	-1.50	(0.01)
Hybrid: s.d.	1.77	(0.76)	Income: over \$70K	-1.49	(0.01)

$J = 2,639$, $N \cdot T = 1,655 \cdot 8 = 13,240$. An observation is a zip code-year.
Bootstrapped s.e. in parentheses.

Table 5: Supply Model Estimates: Log(Marginal Cost) (in \$10,000s)

Characteristic	Mean	Std. Err.
Constant	8.05	(0.02)
Fuel consumption (gal/10 mi)	0.50	(0.01)
Displacement (liters in 10s)	0.30	(0.002)
Weight (1000s)	0.03	(0.001)
Safety rating (5-star)	0.21	(0.001)
SUV	-0.10	(0.001)
Truck	-0.49	(0.004)
Minivan	-0.15	(0.001)
Wagon	0.07	(0.002)
Hybrid	0.19	(0.01)
Import	0.28	(0.005)
Log(quantity)	-0.05	(0.0003)

$J = 2,639$, $N \cdot T = 1,655 \cdot 8 = 13,240$. An observation is a zip code-year.
Bootstrapped s.e. in parentheses.

Table 6: Substitution Patterns for Select Vehicles in 2008

Vehicle	Civic	Corolla	F-Series	Silverado	Prius	Civic (hybrid)
Honda Civic (sedan)	-95,277	71	644	523	292	88
Toyota Corolla	92	-15,503	173	127	441	137
Ford F-Series	1,280	265	-111,137	1,859	821	325
Chevrolet Silverado	906	169	1,620	-90,251	548	208
Toyota Prius	373	435	529	405	-102,023	536
Honda Civic (hybrid)	88	105	164	120	418	-14,866

We show the quantity change resulting from a 1% increase in the price of the row vehicle.

Table 7: Change in Shares of Vehicle Types from Removing Hybrids, 2001-2008

	Incl. Hybrids		Excl. Hybrids	
Type	Mean	Std. Dev.	Mean	Std. Dev.
Sport Utility	-0.17	(0.10)	0.22	(0.08)
Pickup	0.16	(0.07)	0.16	(0.07)
Van	0.05	(0.02)	0.05	(0.02)
Station Wagon	0.01	(0.003)	0.01	(0.002)
Other	0.05	(0.17)	0.43	(0.16)
Hybrid	-2.75	(0.62)	—	(—)
All Vehicles	-1.92	(0.58)	0.82	(0.27)

Shares are expressed in terms of the market for new vehicles.

Table 8: Change in Manufacturer New Vehicle Profits from Removing Hybrids (in Millions \$), 2001-2008

	2001	2002	2003	2004	2005	2006	2007	2008
Aston Martin	—	—	—	—	—	—	0.017	0.012
BMW AG	-0.073	-0.039	-0.025	0.065	0.415	0.907	0.908	1.471
Chrysler	—	—	—	—	—	—	—	4.744
Daewoo Group	-0.011	—	—	—	—	—	—	—
Daimler AG	—	—	—	—	—	—	—	2.186
DaimlerChrysler	-0.466	-0.233	-0.197	0.295	2.958	4.113	4.430	—
Fiat	-0.0004	-0.0003	-0.00001	0.001	0.012	0.020	0.034	0.045
Ford	-0.726	-0.298	-0.141	0.612	-10.100	-22.302	-18.233	-29.501
GM	-0.824	-0.389	-0.306	0.722	4.653	5.572	9.613	8.895
Honda	-6.709	-3.694	-58.143	-38.408	-72.229	-58.582	-54.255	-38.317
Hyundai	-0.131	-0.100	-0.049	0.097	0.848	1.054	1.541	1.692
Isuzu	-0.016	-0.008	-0.002	0.002	0.009	0.012	0.015	0.008
Mitsubishi	-0.066	-0.053	-0.014	0.031	0.157	0.314	0.260	0.408
Nissan	-0.224	-0.106	-0.023	0.297	2.595	3.125	-23.972	-26.263
Proton	-0.00004	-0.00001	-0.000001	—	0.010	0.006	0.005	0.001
Subaru	-0.025	-0.025	-0.003	0.029	0.284	0.368	0.373	0.467
Suzuki	-0.010	-0.007	-0.0008	0.014	0.088	0.117	0.104	0.075
Tata Motors	—	—	—	—	—	—	—	0.655
Toyota	-22.751	-43.022	-21.992	-90.125	-231.266	-255.031	-422.405	-313.553
Volkswagen	-0.145	-0.074	-0.025	0.070	0.474	0.763	1.162	1.473
Total	-32.177	-48.048	-80.921	-126.297	-301.093	-319.545	-500.405	-385.503

Table 9: Compensating Variations by Year and Income Bracket

Year	Average	By Income Bracket			
		<\$30K	\$30K-\$50K	\$50K-\$70K	>\$70K
2001	-\$14	-\$16	-\$12	-\$15	-\$13
	(\$11)	(\$17)	(\$11)	(\$12)	(\$13)
2002	-\$8	-\$9	-\$22	-\$17	\$8
	(\$14)	(\$18)	(\$18)	(\$33)	(\$14)
2003	\$12	\$10	\$28	\$0	-\$1
	(\$16)	(\$21)	(\$15)	(\$13)	(\$38)
2004	\$42	\$30	\$44	\$36	\$56
	(\$19)	(\$42)	(\$17)	(\$34)	(\$27)
2005	\$179	\$212	\$157	\$126	\$206
	(\$41)	(\$96)	(\$116)	(\$60)	(\$43)
2006	\$189	\$256	\$131	\$211	\$195
	(\$42)	(\$108)	(\$38)	(\$57)	(\$54)
2007	\$349	\$267	\$360	\$366	\$303
	(\$52)	(\$158)	(\$88)	(\$103)	(\$83)
2008	\$395	\$236	\$416	\$484	\$248
	(\$37)	(\$225)	(\$46)	(\$110)	(\$109)

$J = 2,639$, $N \cdot T = 1,655 \cdot 8 = 13,240$. An observation is a zip code-year. Bootstrapped s.e. in parentheses.

Table 10: Carbon Emissions Reduction Benefit from Hybrids, 2001-2008

	Fixed VMT		Rebound Effect		Adjusted VMT	
Year	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
2001	0.77	(0.24)	-0.12	(0.04)	0.65	(0.20)
2002	0.55	(0.12)	-0.08	(0.02)	0.46	(0.10)
2003	1.39	(0.23)	-0.22	(0.05)	1.18	(0.19)
2004	2.76	(0.62)	-0.44	(0.12)	2.31	(0.51)
2005	5.57	(0.85)	-0.90	(0.15)	4.67	(0.70)
2006	4.05	(0.86)	-0.67	(0.15)	3.38	(0.71)
2007	7.57	(1.47)	-1.26	(0.25)	6.32	(1.23)
2008	8.71	(1.29)	-1.50	(0.18)	7.21	(1.12)

$N \cdot T = 1,655 \cdot 8 = 13,240$. An observation is a zip code-year. Units are \$/vehicle. Results assume a -0.15 rebound and \$45/ton CO_2 social cost of carbon.

Table 11: Expected Benefits from Hybrids in California (in Millions \$), 2001-2008

Year	Market Benefit	Carbon Benefit	Producer Benefit	Total Benefit
2001	-13.54	0.41	32.18	19.05
	(15.06)	(0.09)	(9.70)	(20.16)
2002	-11.20	0.69	48.05	37.54
	(24.64)	(0.16)	(10.14)	(31.45)
2003	17.06	1.20	80.92	99.18
	(30.97)	(0.20)	(22.99)	(45.41)
2004	59.03	2.10	126.30	187.42
	(33.39)	(0.39)	(29.25)	(58.04)
2005	236.72	4.47	301.09	542.28
	(58.52)	(0.69)	(65.37)	(121.27)
2006	240.44	3.78	319.54	563.77
	(59.87)	(0.74)	(60.82)	(112.83)
2007	410.71	6.08	500.40	917.20
	(67.36)	(0.92)	(110.61)	(170.41)
2008	335.27	5.20	385.50	725.97
	(43.80)	(0.95)	(99.09)	(118.34)

$J = 2,639$, $N \cdot T = 1,655 \cdot 8 = 13,240$. An observation is a zip code-year. Bootstrapped s.e. in parentheses.

Table 12: Expected Benefits from Hybrids in California in 2007 (in Millions $)

Counterfactual Scenario	Market Benefit	Carbon Benefit	Producer Benefit	Total Benefit
Hybrid tech removed,	231.93	3.51	329.56	565.00
no MPG adjustment	(194.61)	(2.09)	(202.24)	(395.50)
Hybrid tech removed,	249.89	4.91	346.54	601.34
MPG adjusted	(178.39)	(0.94)	(212.33)	(387.70)
Hybrid vehicles removed	410.71	6.08	500.40	917.20
	(67.36)	(0.92)	(110.61)	(170.41)

$J = 2,639$, $N \cdot T = 1,655 \cdot 8 = 13,240$. An observation is a zip code-year.
Bootstrapped s.e. in parentheses.

A Online Appendix

The following table shows the results of our robustness checks. Column (1) fixed vehicle prices. Column (2) fixes both vehicle prices and gasoline prices. Column (3) fixes vehicle prices and performs an illustrative simulation mimicking the removal of the federal tax credit for hybrids.

Table A.1: Robustness: Total Benefits from Hybrids in California (in Millions $)

Year	(1) Fixed Veh Prices	(2) +Gas Price Fixed	(3) +Sub. Removed
2001	50.58	50.58	48.69
2002	78.97	97.93	76.11
2003	137.88	209.76	132.99
2004	222.24	396.07	214.50
2005	558.34	1098.12	539.41
2006	577.13	1143.49	475.57
2007	910.03	1880.83	864.89
2008	716.18	1304.80	716.18

$J = 2,639$, $N \cdot T = 1,655 \cdot 8 = 13,240$. An observation is a zip code-year. Bootstrapped s.e. in parentheses.