Gasoline Savings from Clean Vehicle Adoption

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November 30, 2017

Abstract

Without the option to purchase plug-in electric and/or hybrid vehicles, conventional counterfactuals used in the literature may underestimate the fuel savings from clean vehicle adoption, thus overestimating the costs of securing associated environmental benefits. Using a nationally representative sample of new car purchases in the U.S., we propose a vehicle choice model-based counterfactual approach that allows us to predict what consumers would purchase if these clean vehicles were unavailable. The choice model results suggest that the gasoline consumption under a no clean vehicle scenario increases by 1.71 percent, compared to a 1.14 percent increase based on a conventional counterfactual. Many pivotal buyers would instead purchase premium brands and larger vehicles, leading to an increase in the share of light trucks, which are subject to less stringent, but more difficult to meet, standards. Lastly, we estimate the cost of demand-side policies in the form of financial incentives to encourage plug-in electric vehicle adoption. Assuming a vehicle lifetime of 10 years, the conventional counterfactual overestimates the cost of gasoline savings at $8.75 per gallon compared to $6.90 per gallon estimated from the choice model-based counterfactual.

Keywords: fuel efficiency; clean vehicles; air pollution; transportation policy

JEL Classification Numbers: Q48; R40

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1 Introduction

The goal of many transportation policies is to increase clean vehicle market share. However, evidence suggests that consumers most likely to purchase advanced clean vehicle, such as plug-in electric vehicles (PEVs), are early adopters and environmentally conscious (e.g., Sheldon, DeShazo, and Carson (2017); Dua (2017)). These consumers may therefore be more likely to “trade up” from a hybrid to a PEV, resulting in considerably lower gains than replacing a standard, internal combustion engine (ICE) vehicle with a PEV. On the other hand, luxury PEV consumers may otherwise purchase high emitting, high performance vehicles. Achieving greenhouse gas (GHG) and pollution reduction goals depends not only on clean vehicle market share but also on which vehicles are taken off the road as a result of clean vehicle sales. Failure to account for such counterfactuals may result in significant over- or underestimates of environmental benefits of clean vehicles.

Complicating the analysis of a counterfactual fleet is the impact of Corporate Average Fuel Economy (CAFE) and Environmental Protection Agency’s recent Greenhouse Gas (GHG) standards, which regulate carbon dioxide emissions from automobiles under the Clean Air Act. The CAFE and GHG standards set specific sales-weighted fuel economy and GHG emissions targets for automakers with the goal of improving energy use and reducing emissions. PEV sales help auto manufacturers meet CAFE standards. In a counterfactual world without PEVs, auto manufacturers would still have to meet CAFE and GHG targets, meaning that in theory, fleet fuel economy could not decrease below the targets, at least in the medium and long run. Nevertheless, since CAFE standards vary by vehicle size, a change in the vehicle class mix could still impact fleet fuel economy. Additionally, gasoline savings from PEV adoption depends not only on which ICE vehicles are taken off the road, but also on how much those vehicles are driven.

In this paper, we estimate fuel savings from clean vehicle adoption. Our nationally representative sample of nearly 275,000 new vehicle purchases in the U.S. in 2015 includes household level demographic and attitudinal variables. Linking these data to a database of vehicle characteristics, we estimate an innovative vehicle choice model that incorporates consumer heterogeneity, resulting in more precise market share estimates. Using this model, we predict national vehicle sales at the make-model level assuming unavailability of 1) PEVs and 2) PEVs and hybrid vehicles (HEVs). We use these predictions to construct counterfactual fleet fuel economy and gasoline consumption for both scenarios.

Results suggest that if PEVs, which account for 0.81 percent of the 2015 market share, were not available, fuel economy of cars would decrease nearly 1 percent and that of light trucks would decrease by 0.23 percent for a total decrease in fleet fuel economy of 0.60 percent. If PEVs and HEVs, which jointly account for 3.38 percent of the 2015 market share, were not available, fuel economy of cars would decrease 2.49 percent and that of light trucks would decrease by 0.37 percent for a total decrease in fleet fuel economy of 1.68 percent. Since many would-be PEV and HEV purchasers would otherwise purchase a larger vehicle, an absence of PEVs and HEVs would lead to a shift in the vehicle class mix towards light trucks, which are subject to less stringent, perhaps difficult to meet, fuel economy standards. Lastly, since PEV and HEV consumers also tend to drive more miles, in the absence of clean vehicles gasoline consumption increases 1.71 percent, greater than the decrease in fleet fuel economy. Together, these results imply that clean vehicle technology has still led to a significant reduction in gasoline consumption. Furthermore, we estimate greater increases in fuel economy and decreases in gasoline consumption relative to counterfactuals relied upon in existing literature ("conventional counterfactuals"). A back of the envelope calculation in Section 5.1 estimates that the cost of the gasoline savings resulting from PEV adoption incentives to be \$6.90 per gallon, assuming a vehicle life of 10 years. While relatively expensive, it is significantly less than the \$8.75 per gallon we estimate using conventional counterfactuals.

2 Background

Federal, state, and local governments offer a variety of incentives to promote clean vehicle adoption. There is a federal tax credit for PEVs and a dozen states offer additional financial incentives to PEV purchasers in the form of rebates, tax credits, and sales tax exemptions. Local incentives include subsidized battery recharging stations, preferred parking, and access to high occupancy vehicle lanes. These policies are generally intended to decrease carbon dioxide emissions as well as to decrease local air pollution such as sulfur dioxide and nitrogen oxides.

An emerging literature attempts to quantify environmental benefits of PEVs. Archsmith, Kendall, and Rapson (2015) estimate adoption of a PEV results in a \$425 environmental benefit (in western states) in terms of a reduction in greenhouse gas emissions. Holland et al. (2016) estimate environmental benefits of PEVs, including both reductions in local air pollution as well as reductions in greenhouse gas emissions. They find benefits as large as $2,800 per PEV, depending on the carbon intensity of electricity generation, which varies by region. To estimate these pollution reductions, both studies must rely on a counterfactual to PEVs. For example, Archsmith, Kendall, and Rapson (2015) use average values for midsize vehicles to calculate their counterfactual gas mileage. Holland et al. (2016) use the ICE vehicle that is most similar to each PEV model in the analysis. The counterfactual for the Ford Focus PEV is the conventional Ford Focus and the counterfactual for the Tesla Model S is the BMW 740.

Graff Zivin, Kotchen, and Mansur (2014) estimate marginal emissions of electricity demand to assess impacts of PEVs on carbon emissions. They also find that PEVs are associated with lower carbon emissions in western states than ICEs, but higher emissions in other regions, since PEVs tend to charge during off-peak hours when marginal emissions are larger. The authors compare PEVs to two alternatives: a “comparable” economy car and a hybrid. The comparable ICE has the average fuel economy, 31 mpg, of the Toyota Corolla, Honda Civic, Chevrolet Cruze, and Ford Fiesta. The HEV counterfactual is the Toyota Prius.

Lacking revealed preference data, these are logical counterfactuals. However, estimated environmental benefits from the PEV purchase may be overstated if the consumer would otherwise purchase an HEV or highly fuel efficient vehicle. Likewise, estimated environmental benefits from the PEV purchase may be understated if the consumer would otherwise purchase a higher-emitting larger or premium vehicle.

To encourage the development of clean vehicle technologies, the CAFE/GHG standards are less stringent for manufacturers who produce alternative fuel vehicles such as PEVs. Jenn, Azevedo, and Michalek (2016) find that each alternative fuel vehicle sold in place of a conventional vehicle therefore weakens the fleet efficiency standards, resulting in an increase of up to 60 tons of carbon dioxide and 7,000 gallons of gasoline consumption. Existing work to estimate environmental benefits of PEVs tends to overlook the point made by Jenn, Azevedo, and Michalek (2016) that if there were no PEVs, the counterfactual fleet would still have to comply with CAFE/GHG standards. For example, if PEVs were no longer available, the average fuel economy of midsize sedans might increase or else the auto manufacturers might lower prices of compact cars to increase their relative sales in order to be in compliance.

3 Data

The primary dataset, which was purchased from Strategic Vision Incorporated, is from a survey of households who purchased a new vehicle in the year 2015. It is a representative sample of the U.S. national new vehicle market and includes approximately 275,000 observations along with weights that correspond to the ratio of the number of buyers for each make and model in the national market to the number of respondents for the same make and model in the survey. The survey collects information on household characteristics and attitudes, as well as information on the new vehicle purchased, including the vehicle identification number (VIN). Household characteristics include respondent's age and education level, household income, and the number of miles the respondent intends to drive his or her new vehicle each month. Although the dataset is not state-wise representative, we do know each respondent's state of residence as well as whether he or she lives in a metropolitan, suburban, rural, or farming area.

Although some households self-report new vehicle characteristics, to ensure accuracy of vehicle attributes, we match new vehicles to their characteristics on VIN using Edmunds database of vehicle characteristics. Vehicle characteristics include MSRP (price), fuel economy,[1] horsepower, fuel capacity, curb weight, wheel base, track width, and body type. For PEVs, fuel economy is reported in miles per gallon equivalent, which is the average distance traveled per unit of energy consumed normalized to the energy content of a gallon of gasoline. EPA calculations assume that in terms of energy use, one gallon of gas is equivalent to 33.7 kilowatt-hours of electricity. For PEVs data also include electric range.

In our analysis, we use several constructed variables. For ICEs, range is calculated as the product of fuel capacity and fuel economy. Range is equal electric range for BEVs. For PHEVs, range is calculated as the product of fuel capacity and fuel economy, plus electric range. Performance is defined as horsepower over curb weight.

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[1] For the vehicle choice model, we calculate fuel economy as the harmonic mean of city fuel economy and highway fuel economy, which are weighted by 55 percent and 45 percent, respectively. This is consistent with the EPA's unadjusted/laboratory combined fuel economy calculations, which are used for compliance standards and for the fuel economy labels that consumers see. However, in our counterfactual analysis of fleet fuel economy, we use city and highway weights of 43 percent and 57 percent, respectively, which is consistent with EPA methodology for adjusted fleet fuel economy calculations. Adjusted fuel economy is the best estimate of real world performance. For more details see EPA (2015).

Table 1 shows summary statistics of the new vehicles purchased by nationally representative sample, as well as mean monthly vehicle miles traveled (VMT). For VMT calculations, we replace missing observations with the sample-weighted mean monthly VMT of 1,116 miles. In our analysis, PEVs include both battery electric vehicles (BEVs), which are all-electric, as well as plug-in hybrid vehicles (PHEVs), which have both an electric battery and an internal combustion engine.

Table 1: Summary Statistics

	Mean	StDev
Price ($)	30,581	12,335
Fuel Economy (mpg)	25.06	8.96
Horsepower	232	85
Fuel Capacity (gal)	18.4	5.3
Curb Weight (lbs)	3831	896
Wheel Base (in.)	113	13
Track Width (in.)	63.7	3.2
Range (mi)	426	77
HEV	2.57%	15.81%
PHEV	0.29%	5.41%
BEV	0.52%	7.21%
Convertible	0.74%	8.57%
Coupe	3.33%	17.94%
Full-Size	0.18%	4.22%
Hatchback	5.01%	21.82%
Mini-Van	2.98%	17.00%
Pickup	12.55%	33.13%
SUV	32.79%	46.94%
Sedan	34.06%	47.39%
Wagon	8.35%	27.67%
Monthly VMT	1,116	843

4 Vehicle Choice Model

The purpose of our vehicle choice model is to predict vehicle choices when certain alternatives are unavailable. A standard conditional logit model exhibits the independence of irrelevant alternatives (IIA) property, meaning that the odds of choosing one vehicle over another are independent of the choice set for all other pairs. For example, if the PEV alternative is removed from the choice set, the probability that had previously been allocated to choosing the PEV is split equally across remaining alternatives. This could lead to unrealistic substitution patterns, especially if PEV consumers are more likely to purchase an HEV or an SUV, for example.

The foundation of our model is the following mixed logit model. Consumer n consumer choose the vehicle that maximizes her utility of choosing vehicle i, U_{ni}. Utility is a linear function of a vector of vehicle characteristics, $\mathbf{X}_i$, as follows:

$$U_{ni} = \mathbf{X}_\mathbf{i}'\boldsymbol{\beta}_{\boldsymbol{n}} + \varepsilon_{ni.} \tag{1}$$

Assuming ε_{ni}'s are independently distributed Type-I extreme value errors, the probability of individual n selecting vehicle i can be written as:

$$\pi_{ni} = \int \frac{exp(\mu_n \mathbf{X}_\mathbf{i}'\boldsymbol{\beta})}{\sum_{j=1}^{J} exp(\mu_n \mathbf{X}_\mathbf{j}'\boldsymbol{\beta})} f(\boldsymbol{\beta}|\boldsymbol{\theta})\partial\boldsymbol{\beta} \quad , \tag{2}$$

where μ_n is a scale parameter commonly assumed to equal 1 and where $f(\beta|\vartheta)$ is the density function of β.

In contrast to the conditional logit model that assumes fixed parameters, the mixed logit allows for random parameters. When we estimate the mixed logit model, we estimate the distribution of the random parameters. However, the mixed logit does not inform how consumer characteristics correlate with the parameter distributions. While in theory we could interact the mean and/or variance of mixed logit parameters with consumer characteristics, such models tend not to converge to a well-defined maximum value due to numerical instability. We encountered similar issues attempting to estimate latent class models on this large dataset.

In order to more accurately identify heterogeneity in preferences across consumers, we utilize a "mesh" strategy where we divide the sample into subsamples (or "meshes") and for each subsample, estimate a mixed logit on aggregate market shares for that subsample. The choice sets are at the make-model-engine type level, where engine type is either ICE, HEV, BEV, or PHEV. For example, the conventional Ford Focus and the Ford Focus Electric appear as separate alternatives. This results in approximately 400 alternatives.

Table 2 shows the three variables that we use to divide the sample into meshes: 1) socio-economic group, which is a function of age, income, and education, 2) pro-environmental attitude, and 3) residential location. We generate a separate "mesh" for each socio-economic by pro-environment by residential location group of consumers, for a total of 90 meshes. Table 3 shows summary statistics of the number of observations and weighted observations in each mesh. For computational ease, we aggregate household level data to market share level within each mesh, summing frequency weights for each make-model-engine observation such that the sample remains representative. Since each household within a mesh who chooses a particular make-model-engine is identical with respect to variables used in the estimation, estimating the mixed logit model on aggregate market shares using frequency weights is equivalent to estimating the model on individual level data.

Table 2: Mesh Categories

Socio-economic Group	Pro-Enviro[†]	Residential Location
Age < 35 / Income > $70K / College	No or Missing	Metropolitan City
Age < 35 / Income > $70K / No College	Yes	Suburban Community of a Large City
Age < 35 / Income ≤ $70K / College		Small Town or Rural City
Age < 35 / Income ≤ $70K / No College		Farming Area
Age 35 + / Income > $70K / College		Missing
Age 35 + / Income > $70K / No College		
Age 35 + / Income ≤ $70K / College		
Age 35 + / Income ≤ $70K / No College		
Missing		

[†] Individual indicated he or she agrees somewhat or strongly with "I would pay significantly more for an environmentally friendly vehicle."

Table 3: Mesh Sizes

	Observations	Frequency (Weighted)
Minimum[†]	5	111
Second Min[†]	12	731
25th Percentile	378	15,308
Median	1,174	57,390
75th Percentile	2,967	138,907
Maximum	38,981	1,733,866

[†] The smallest mesh includes observations with age < 35 / income > $70K, no college, pro-environmental, and missing residence. The second smallest mesh is similar except college educated. Given the limited sample sizes for these two meshes, for each we utilize the estimates from the most similar mesh. That is the mesh that has identical characteristics except rather than missing residence, includes observations from suburban residences.

For most mesh estimates, vehicle characteristics in the utility function include price, fuel economy, range, performance, engine type indicators (HEV, PHEV, or BEV, with ICE as the omitted category), make indicators, and body type indicators (convertible, coupe, full-size car, hatchback, minivan, pickup, SUV, and wagon, with sedan as the omitted category). We exclude ultra luxury brands to avoid skewing our estimates, since though representing a tiny market share, their prices may be outliers. These brands are also not represented by most meshes. These ultra luxury brands include Alfa Romeo, Aston Martin, Bentley, Ferrari, Jaguar, Lamborghini, Lotus, Maserati, McLaren, and Rolls-Royce. Due to collinearity amongst the variables, we construct a variable that is the product of fuel economy, range, and performance, scaled by price. This variable is specified to have a random parameter. To better characterize body type substitution patterns, the SUV indicator (which is the second most popular body type after sedan) is also specified to have a random parameter. A minority of mesh estimates do not converge when attempting to estimate this model, particularly for meshes with fewer observations. In these cases, we simplify the model first by considering SUV a fixed rather than a random parameter, and, if convergence is still not achieved, then by excluding the make indicators. Table 4 summarizes the three utility functions utilized in our analysis. Lastly, due to collinearity between the BEV indicator and other attributes, in a first stage we fit the utility function excluding the BEV and Tesla make indicators. Then, in a second stage we re-estimate the utility function constraining the fuel economy-range-performance-price coefficient to equal that from the first stage and including the BEV and Tesla indicators.

Table 4: Utility Function

Utility Function	Fixed Parameters	Random Parameters	Number of Meshes
1	Makes, Bodies, HEV, PHEV, BEV	SUV, (Fuel Economy*Range*Performance)/Price	58
2	Makes, Bodies, HEV, BEV, PHEV	(Fuel Economy*Range*Performance)/Price	22
3	Bodies, HEV, BEV, PHEV	(Fuel Economy*Range*Performance)/Price	10

Note: Body indicators (Bodies) include convertible, coupe, full-size car, hatchback, minivan, pickup, SUV, and wagon, with sedan as the omitted category. Make indicators (Makes) are included for all makes except ultra luxury brands, which are omitted from the sample as outliers. These ultra luxury brands include Alfa Romeo, Aston Martin, Bentley, Ferrari, Jaguar, Lamborghini, Lotus, Maserati, McLaren, and Rolls-Royce. Due to collinearity between the BEV indicator and other attributes, in a first stage we fit the utility function excluding the BEV and Tesla make indicators. Then, in a second stage we re-estimate the utility function constraining the fuel economy-range-performance-price coefficient to equal that from the first stage and including the BEV and Tesla indicators.

For PEV prices, we adjust MSRP by state and national incentives. Specifically, for PHEV and BEV purchase observations from states with incentives, we reduce MSRP by the maximum incentive amounts shown in Figure 1 of DeShazo (2016). These state incentives range from \$500 to \$7,500, with most falling in the \$2,000-\$3,000 range. The federal tax credit varies by vehicle, with a maximum amount of \$7,500. A household cannot claim more than it pays in federal income tax. For example, if a household purchases a PEV eligible for a \$7,500 tax credit but only pays \$5,000 in federal taxes, it will get to offset the full \$5,000 of federal taxes, but will not receive an additional rebate or benefit on top of that. The PEV tax credit does not roll over and thus cannot be used to offset future taxes. Due to the complexity of estimating household federal taxes owed and the lack of necessary data to do so (e.g., precise pre-tax income, mortgage and student loan information, number of dependents, etc.), we make the simplifying assumption that all PEV purchases in the data are eligible for the maximum federal tax credit. Given the observation that most PEV buyers are high income, we feel this is a reasonable assumption. Therefore, in addition to any state level subsidies, we adjust PEV prices downwards by the maximum amount of the federal tax credit available for each model.[2]

Table 5: Actual versus Predicted Market Shares

	BEV	PHEV	HEV
Actual	0.52%	0.29%	2.57%
Predicted	0.52%	0.29%	2.57%

In an effort to move inventory, many vehicle manufacturers have been offering cash rebates and special lease offers for their PEVs on top of government incentives. While these vary across vehicle, manufacturer, and location, the cash rebates average around 9 percent of MSRP (Campbell et al., 2016). Therefore, for all PEVs, we reduce MSRP by 9 percent before subtracting federal tax credit and any state incentives. When we collapse individual data to aggregate market share, we take the weighted average price across individuals.

After estimating mixed logit models for each mesh, we use estimation results to predict consumer vehicle choices separately for each mesh. Using consumer weights we aggregate the separate mesh

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[2] See https://www.fueleconomy.gov/feg/taxevb.shtml

predictions to market shares of the representative national sample. Table 5 shows the model predictions for BEV, PHEV, and HEV market shares are identical to the actual market shares in the sample.

4.1 Model Assumptions

There are two major assumptions underlying our counterfactual analysis. Our vehicle choice model models consumer choice conditional upon having decided to purchase a new vehicle. Due to the mesh structure of the model, we cannot include an outside option to not purchase a new vehicle.[3] Thus, our counterfactual analysis assumes that the total number of new vehicle purchases is the same- i.e., when PEVs and/or HEVs are not available, the same population still decides to purchase a new vehicle. We find this to be a reasonable assumption because although a household might delay purchasing a new vehicle as they anticipate the arrival of a particular model (e.g., the Tesla Model 3), in a counterfactual world devoid of PEVs or HEVs, a household would not have these models to anticipate.

The second assumption is that in the counterfactual scenarios, prices of available vehicles are unchanged- i.e., we only model the demand side, not the supply side. Langford and Gillingham (2015) model both the supply and demand sides of the new vehicle market for their counterfactual analysis. They find that if hybrids were not available from 2001-2008, equilibrium prices of close substitutes would be lower. However, Table 3 of their paper shows a maximum price decrease of $18. Such small price changes are unlikely to significantly change our counterfactual analysis results.

5 Counterfactual Analysis

We predict consumer vehicle choice under three different scenarios: 0) the actual set of available vehicles is available, 1) PEVs are not available, and 2) neither PEVs nor HEVs are available. Table 6 shows market share estimates for various vehicle types under each scenario. In Scenario 1 when PEVs are not available, less than 5 percent of the would-be PEV purchasers (who make up 0.81 percent of the total market) purchase HEVs instead. More would-be PEV purchasers purchase SUVs (11 percent) and pickups (11 percent) instead. Overall, more than a quarter of the would-be PEV purchasers switch to a light truck, leading to an increase in overall light truck market share (from 48.24 percent to 48.45 percent)

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[3] This would require knowing how many people did not purchase a new vehicle are in each mesh category.

and decrease in passenger car share (from 51.76 percent to 51.55 percent). These trends are exacerbated in Scenario 2 when HEVs are also unavailable, with light truck share increasing to 49.36 percent and passenger car share decreasing to 50.64 percent.

Table 6: Market Shares, Fuel Economy, and Gasoline Consumption of Counterfactual Scenarios

	Scenario 0	Scenario 1	Scenario 2
	Predicted	No PEVs	No PEVs or HEVs
HEV	2.57%	2.61%	
SUV	32.7%	32.8%	33.2%
Convertible	0.8%	0.8%	0.8%
Coupe	3.4%	3.4%	3.5%
Full Size Car	0.2%	0.2%	0.2%
Hatchback	5.3%	5.1%	5.0%
Minivan	3.0%	3.0%	3.1%
Pickup	12.6%	12.7%	13.0%
Sedan	33.6%	33.6%	32.6%
Wagon	8.5%	8.5%	8.6%
Passenger Car Share	51.76%	51.55%	50.64%
Light Truck Share	48.24%	48.45%	49.36%
MPG Passenger Cars	28.81	28.55	28.09
MPG Light Trucks	19.58	19.53	19.51
MPG Fleet	23.47	23.33	23.08
Annual Billion Gal of Gas	7.14	7.18	7.26

Table 7 shows market shares of different makes in each of the three scenarios. From Scenario 0 to Scenario 1, where PEVs are no longer available, market shares of makes with popular PEV models such as Chevrolet (maker of the Volt), Ford (maker of the C-MAX Energi, Fusion Energi, and Focus Electric), and Toyota (maker of the Prius Plug-in) decline. Nissan's predicted market share actually increases from Scenario 0 to Scenario 1, despite the popularity of the Nissan Leaf, which is no longer available in Scenario 1. This suggests that some would-be PEV buyers switch to other non-PEV Nissan models. Similarly, Cadillac and Mercedes-Benz market shares increase slightly and BMW's remains the same despite several PEVs of these makes no longer being available in Scenario 1. This is consistent with larger increases in market share of several premium brands, including Audi and Lexus. Jeep and Subaru, whose popular models are SUVs, also have larger increases in market share.

Table 7: Brand Market Shares (percent) of Counterfactual Scenarios

	Scenario 0	Scenario 1	Scenario 2
	Predicted	No PEVs	No PEVs or HEVs
Acura	0.83	0.84	0.85
Audi	1.30	1.32	1.35
BMW	2.11	2.11	2.16
Buick	1.36	1.37	1.40
Cadillac	0.99	1.00	1.02
Chevrolet	9.00	8.98	9.20
Chrysler	1.56	1.57	1.62
Dodge	2.73	2.74	2.80
FIAT	0.27	0.26	0.27
Ford	10.96	10.91	10.96
GMC	3.07	3.10	3.17
Honda	10.66	10.60	10.06
Hyundai	4.46	4.49	4.51
INFINITI	0.85	0.86	0.85
Jeep	5.31	5.34	5.44
Kia	3.92	3.93	3.98
Land Rover	0.04	0.04	0.04
Lexus	2.38	2.41	2.34
Lincoln	0.65	0.65	0.66
MINI	0.41	0.41	0.43
Mazda	2.20	2.23	2.29
Mercedes-Benz	2.20	2.21	2.26
Mitsubishi	0.50	0.50	0.51
Nissan	7.93	7.96	8.15
Porsche	0.74	0.73	0.75
Ram	2.64	2.65	2.72
Scion	0.39	0.39	0.40
Smart	0.04	0.03	0.04
Subaru	4.19	4.23	4.34
Toyota	13.67	13.62	12.86
Volkswagen	2.17	2.17	2.20
Volvo	0.34	0.35	0.36

Together, the top panel of Table 6 and Table 7 suggest that while some would-be PEV buyers switch to HEVs and other small cars, many instead switch to larger vehicles including SUVs and light trucks, as well as premium makes, which tend to have lower fuel economy.

Similar patterns emerge for Scenario 2 in Table 7. When HEVs are also unavailable, Toyota and Honda, makers of popular HEVs, have significant market share declines. Market shares of makers of larger vehicles increase (e.g., GMC, Jeep, and Subaru). However, unlike Scenario 1, market shares of non-premium brands like Chevrolet and Nissan increase more than those of premium brands. This suggests that while many both would-be PEV and HEV buyers substitute toward larger vehicles, substitution towards premium brands is driven by would-be PEV buyers.

For each scenario we use the predicted fleet to calculate the vehicle-weighted fleet fuel economy, as shown in the bottom panel of Table 6. In Scenario 0, predicted fleet fuel economy is 23.47mpg. In Scenario 1, when PEVs are removed from the choice set, predicted fleet fuel economy declines 0.60 percent to 23.33mpg. In Scenario 2, when both PEVs and HEVs are removed from the choice set, predicted fleet fuel economy declines 1.68 percent from Scenario 0 to 23.08mpg. To put these changes in perspective, recall that in 2015, PEVs accounted for 0.81percent of the market and HEVs for 2.57 percent.

For Scenarios 1 and 2 we also calculate a “conventional” counterfactual generated similarly to counterfactuals currently used in the literature and policy analysis to show how our results differ when we use a more sophisticated choice model to generate the counterfactuals. The conventional fuel economy counterfactuals assume that if BEVs, PHEVs, or HEVs are unavailable, they are replaced by a vehicle with the average fuel economy of that BEV/PHEV/HEV’s size (e.g., compact, mid-size, or full-size) and class (e.g., car, pickup, or SUV). In Scenario 1, the conventional counterfactual predicts a 0.48 percent decrease in fleet fuel economy relative to our 0.60 percent estimate. In Scenario 2, the conventional counterfactual predicts a 1.12 percent decrease in fleet fuel economy relative to our 1.68 percent estimate.

Our model predicts larger decrease in fleet fuel economy mainly because the conventional counterfactuals do not allow would-be PEV drivers to switch vehicle class. Most PEVs are compact or midsize cars. The conventional counterfactuals assume that if the PEVs or HEVs are not available, these consumers all choose compact or midsize ICEs. However, our vehicle choice model suggests that absent their preferred PEV or HEV, many consumers would instead purchase a larger vehicle (or a premium vehicle), which typically have lower gas mileage than compact or midsize ICEs. This difference suggests that conventional counterfactuals such as those used in the existing literature underestimate the fuel economy improvements from PEVs and HEVs.

Using the predicted fleet and reported monthly miles driven[4] we also calculate total annual gasoline consumption of the new vehicle fleet for each scenario, as shown in the bottom panel of Table 6. Annual gasoline consumption in Scenario 1 is 0.61 percent greater than Scenario 0 (7.18 versus 7.14 billion gallons). Annual gasoline consumption in Scenario 2 is 1.71 percent greater than Scenario 0 (7.26 versus 7.14 billion gallons). In other words, we predict that if PEVs were unavailable, the fleet would consumer 0.61 percent more gasoline, and if HEVs also were unavailable, the fleet would consumer 1.71 percent more gasoline.

Annual gas consumption values for Scenarios 1 and 2 are calculated using the conventional fuel economy counterfactuals and the sample-weighted mean VMT of 1,116 miles per month (as existing studies, lacking individual data, typically rely on population averages). In Scenario 1, the conventional counterfactual predicts a 0.49 percent increase in annual gasoline consumption relative to our 0.61 percent estimate. In Scenario 2, the conventional counterfactual predicts a 1.14 percent increase in annual gasoline consumption relative to our 1.71 percent estimate.

Table 8: Miles Driven Per Month by Fuel Type

	Mean	StDev
All	1,116	843
ICE	1,114	832
HEV	1,160	984
BEV	1,181	1437
PHEV	1,167	1340

Thus, when accounting for heterogeneous vehicle preferences and substitution patterns, predicted gasoline savings from PEV and HEV adoption are 25 percent and 50 percent greater than the conventional counterfactuals suggest. This difference is due to the larger decrease in fleet fuel economy

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[4] When aggregating individual data to meshes, we take a weighted sum of monthly vehicle miles traveled for all individuals in that mesh.

in the predicted scenarios relative to the conventional counterfactuals. If more PEV drivers switch to light trucks instead of midsize cars, for example, then gasoline consumption would be greater.

We predict that gasoline consumption increases by slightly more than fleet fuel economy decreases (0.61 percent relative to 0.60 percent and 1.71 percent relative to 1.68 percent). This is due to the fact that PEV and HEV drivers tend to drive more miles. Table 8 shows the number of miles households intend to drive their newly purchased vehicle, broken down by vehicle type. The average BEV and PHEV drivers' average monthly VMT are 5-6 percent greater than the average ICE driver, and the average HEV driver's VMT is more than 4 percent greater than the average ICE driver. Thus, when a would-be PEV or HEV driver instead purchases an ICE, this vehicle not only gets lower gas mileage, but is also driven more than the average ICE.

5.1 Fuel Savings from PEV Adoption Incentives

Many states offer financial incentives for PEV adoption in addition to the Federal tax credit of up to $7,500. Using the estimates from our vehicle choice model, we adjust prices by removing the state and federal incentives previously added (see Section 4) and predict PEV sales. Absent these incentives, PEV market share decreases from 0.81 to 0.59 percent. This suggests that (0.81-0.59)/0.81=27 percent of PEV sales, and therefore 27 percent of the gasoline savings from Scenario 1, are a result of PEV incentives. We define the total policy cost as the sum of all state and federal incentives, assuming all PEVs received incentives for which they were eligible. Dividing the total policy cost by gasoline savings resulting from the policy (27 percent of gasoline savings from Scenario 1) equals $69 per gallon of annual gasoline savings. Assuming a vehicle lifetime of 10 years, this cost decreases to $6.90 per gallon. This is nearly $2 per gallon less expensive than the $8.75 per gallon we calculate using the conventional counterfactual. Nevertheless, despite the significant environmental benefits from PEV adoption, demand-side policy costs appear to be relatively expensive.

5.2 Caveat: CAFE/GHG Standards

As shown in Table 6, we predict that if PEVs and HEVs were not available in 2015, average fuel economy for the fleet of new vehicles would be lower and gasoline consumption higher. One caveat is that these may only represent short run effects because, without PEVs to sell, some vehicle manufacturers may adjust supply (e.g., putting fuel savings technology on more models or lowering the price of more fuel efficient models) in order to comply with CAFE/GHG standards. Such supply responses would increase the fleet fuel economy in the long run.

We calculate 2015 CAFE standards and compliance of our nationally representative sample based on the official methodology (Federal Register, 2012). The fuel economy values in our data are adjusted, unlike the laboratory performance test results used to evaluate regulatory compliance. Gillis, Brobeck, and Cooper (2016) estimate that a CAFE test score of 54.5mpg would correspond to an EPA consumer label of 40mpg. Accordingly, we use a conversion factor of 54.5/40 = 1.3625 to convert our fuel economy values for use in the CAFE compliance calculations. We find that while several automakers are non-compliant in 2015, none of the automakers would change to noncompliant in either of our counterfactual scenarios. Therefore we can interpret the fuel savings from PEVs and HEVs as additional to those from CAFE standards.

Even if some manufacturers became non-compliant in the counterfactual scenarios, fleet fuel economy would still lower because many would-be PEV buyers would purchase light trucks instead, as shown in Table 6. CAFE/GHG standards are size-based standards and are less stringent for larger vehicles. A shift in the vehicle mix towards light trucks would result in a larger share of vehicles being subject to less stringent, but difficult to meet, standards. Furthermore, CAFE/GHG standards only regulate fleet fuel economy, not gasoline consumption. If would-be PEV drivers with high VMT purchase less fuel efficient vehicles, their increase in gasoline consumption will not be offset by lower VMT drivers purchasing slightly more fuel efficient vehicles as a result of CAFE/GHG standards.

5.3 Caveat: The Rebound Effect

Our estimates of changes in gasoline consumption implicitly assume that drivers of PEVs drive the same number of miles, regardless if they drive the PEV or the alternative ICE vehicle. In other words, they assume zero rebound effect. If there is a rebound effect, these drivers may increase their vehicle miles travelled when adopting the PEV, suggesting that miles travelled on the ICE substitute could be lower, which would reduce the gasoline savings from PEVs. However, if there is a rebound effect, it is likely to be small.

Gillingham (2014) estimates a rebound effect of 9 percent for Californian households in the period 2000-2006. Small and Van Dender (2007) find that the rebound effect for motor vehicle travel in the US has been declining over time and is decreasing with income. With income at 1997-2001 levels they estimate a short- and long-run rebound effect of 3.1 percent and 15.3 percent, respectively. Literature on consumer residential energy demand also suggests the rebound effect is declining in income (Henly, Ruderman, and Levine (1998); Reiss and White (2005)). Since PEV drivers tend to be high income, any rebound effect is likely to be on the low end.

In an analysis of the 2009 federal Cash for Clunkers program, West et al. (2017) find that while households did purchase more fuel efficient vehicles as a result of the scrappage program, despite a lower cost per mile due to an increase in fuel economy, households did not respond by increasing miles driven. Gillingham, Jenn, and Azevedo (2015), who estimate a gasoline price elasticity of -0.1, find that this elasticity is driven by low fuel economy vehicle drivers. They find that higher fuel economy vehicles' miles traveled are highly inelastic to changes in the gasoline price and that newer vehicles are also less responsive. Since PEV consumers tend to have high incomes and since we analyze new vehicle sales, the consumers who are "switching" in the counterfactual case are likely to have inelastic price elasticities of demand for vehicle miles traveled. As such, any potential rebound effect is likely to be very small.

6 Conclusion

We find that if PEVs and HEVs were not available, fleet fuel economy would decrease. Many clean vehicle purchasers would instead purchase larger vehicles, leading to a shift in the vehicle class mix. Would-be PEV buyers would also substitute towards premium brands, which tend to have lower fuel economy. Also, since PEV and HEV consumers also tend to drive more miles, in the absence of clean vehicles, gasoline consumption increases by slightly more than fleet fuel economy decreases. Together, these results imply that clean vehicle technology has led to a significant reduction in gasoline consumption and will continue to do so in the near future despite potential leakage from CAFE and GHG regulations. Our estimates of fuel economy improvements and gasoline savings from PEVs are larger than conventional back of the envelope calculations imply, suggesting that recent estimates of environmental benefits of PEVs may be underestimates. Finally, our results imply that PEV adoption incentives cost $6.9 per gallon of gasoline saved, assuming a vehicle lifetime of 10 years, suggesting need for improvement in the cost-effectiveness of current demand-side measures to support PEV adoption.

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