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An in-depth examination of electric vehicle incentives: Consumer heterogeneity and changing response over time

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ABSTRACT

We investigate the impacts of a combination of incentives on the purchase decision of electric vehicle buyers in California from 2010 through 2017. We employ a comprehensive survey on over 14,000 purchasers of electric vehicles in the state of California. The survey covers a swath of purchase intentions, general demographics, and importance of various incentives. Our results indicate that the most important incentives for plug-in electric vehicle (PEV) owners are the federal tax credit, the California state rebate, and high occupancy vehicle (HOV) lane access. In addition, the importance of the incentives and their associated effect on purchase behavior has been changing over time: respondents are less likely to not change their decision and more likely to not buy a vehicle at all as time passes and the technology moves away from early adopters. Incentives are becoming more important for vehicle adopters as PEV market entry progresses.

1. Introduction

Over the last decade, plug-in electric vehicles (PEVs, which include both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs)) have been gradually increasing their market share across the world. This relatively new technology shifts energy usage in the light-duty transportation sector away from gasoline and towards electricity. Policy makers have been motivated to increase PEV sales due to their potential to reduce urban air pollution and decarbonize road transportation. As a result, a number of policy mechanisms (both regulatory in nature as well as market-based policies) have been applied in an attempt to spur the adoption of the new technology. In the United States, California remains a leader in the push for the technology. The state requires the sale of electric vehicles through the Zero Emission Vehicle (ZEV) mandate, which requires automakers to sell a portion of their vehicles as PEVs or fuel cell vehicles. Additionally, the state provides many incentives, such as the Clean Vehicle Rebate Program (CVRP) and high-occupancy vehicle lane access stickers (HOV access stickers) on top of the federal incentive for electric vehicle purchases.

This aim of this paper is to provide insights on the importance of incentives and how the importance of them may be changing over time. This is the first study to use multi-year post-purchase survey data to understand the influence of incentives on the decision to purchase a PEV. While other studies have examined the impact of incentives on adoption of electric vehicles, our work is the first to examine the heterogeneity of actual PEV owners and classify them with latent profile analyses. In addition, this study leverages the multi-year aspect of the survey to understand how the importance of incentives have been changing over time. These two focuses of our study directly address critical policy questions related to incentives: (1) how incentive policy can be structured to target specific populations and (2) when should incentives for PEVs expire while minimizing the effect on PEV adoption.

Incentives are being used to promote PEV sales in many regions. Incentives can be grouped into two categories, those that are

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Table 1
Details of the CVRP, federal tax credit, and HOV lane access for PEVs.

Incentive	Information
Clean Vehicle Rebate Project (CVRP)	• Rebates are provided to buyers of PEVs in the form of a check after they purchase the vehicles and after they apply for the rebate • Provides a $2,500 for buyers of BEVs • Provides a $1,500 for buyers of PHEVs • Includes a $1,500 additional rebate for low income households
Plug-In Electric Drive Vehicle Credit (Federal Tax Credit)	• Provides a tax credit to buyers of BEVs, FCVs, and PHEVs of $2,500 to $7,500. • The value of the credit depends on the kWh size of the PEVs batteries • The credit is claimed from the federal Internal Revenue Service when filling a tax return.
High occupancy vehicle (HOV) Lane Access	• Allows BEVs and Fuel Cell Vehicles with White Clean air Vehicle Decals to drive in HOV lanes until January 1st 2019. • Allows PHEVs with Green Clean Air Vehicle Decals to drive in HOV lanes until January 1st 2019.

applied to the purchase of the vehicle (purchase incentives) and those that are received during ownership of the vehicle (reoccurring incentives). This study focuses on purchase incentives and on one reoccurring incentive; high-occupancy vehicle (HOV) lane access (see Table 1).

Purchase incentives are intended to reduce the purchase price of a PEV. These incentives are applied in different ways. In all states of the USA buyers of PEVs receive a federal tax credit of up to $7,500 when they purchase an eligible vehicle. This incentive is received by consumers when they file their tax returns after the financial year in which they purchase their PEV. The maximum value of the incentive is dependent on the size of the battery in the PEV and whether the applicant has a tax liability of at least $7,500. In some states buyers receive state rebates. In California, car buyers typically receive $2,500 when they purchase a BEV (California Clean Vehicle Rebate Project, 2017). This incentive is received by BEV buyers when they apply for the rebate after purchasing their vehicle; they often receive this incentive via a bank check.

Reoccurring incentives differ from purchase incentives as they are often received throughout the entire period of PEV ownership. Incentives can include free or discounted parking, access to restricted lanes, free charging, road toll exemptions, or annual road fee exemptions. Of interest to this study are high occupancy vehicle (HOV) lanes, due to this incentive being available throughout the area of study. California, Maryland, Colorado, Arizona, Florida, New Jersey, New York, Tennessee, Utah, and Virginia are among states that have HOV lanes with exemptions that allow PHEVs or BEVs to drive in the lanes with a single occupant in the vehicle. This can be beneficial to PEV drivers who reside in regions with HOV lanes, as they may be able to avoid some traffic congestion by using the lanes.

2. Literature review

There is a wide body of literature on the impact of incentives of the adoption of new technology vehicles (such as PEVs). The earliest studies examining these policies were either qualitative in nature (Bakker and Trip, 2013) or were part of part of larger choice models that looked at adoption as a whole (Hackbarth and Madlener, 2013). Sierzchula et al. is the first study focused specifically on understanding the effect of financial incentives. The authors measure this econometrically and find a fairly low elasticity with a $1000 incentive corresponding to just 0.06% increase in market share. The use of more sophisticated data, methodologies, and longer time frames of study has led to a confluence of research that find relative agreement in price elasticities: Vergis's econometric approach treating incentives holistically showed a 22% increase in market share attributed to the purchase incentive (Vergis and Chen, 2015), DeShazo's focus on the California CVRP revealed an average $1,838 in incentives led to approximately a 7% increase in PEV market share (DeShazo et al., 2017), Tal's survey-based study of federal incentives found a 32.5% increase corresponding to the $7,500 incentive (Tal and Nicholas, Exploring the Impact of the Federal Tax Credit on the Plug-In Vehicle Market, 2016), and Jenn's panel study of incentives coupled with knowledge of the technology and incentives revealed a 2.6% increase in sales corresponding to $1,000 in incentives (Jenn et al., 2018). While these studies have some variation in their results, these can likely be attributed to differences in modeling approaches as well as discrepancies in region and the time period of examination. Hardman et al. provides a more comprehensive review of the purchase incentive literature identifying 35 studies of which 32 find incentives to be effective in promoting BEV sales (Hardman et al., 2017), but we find general agreement in the magnitude of the incentive effects. It should be noted that there has been some work to understand the differences in how a purchase incentive is structured and, for example, how a point-of-sale incentive can be more effective than a rebate credit (Matthews et al., 2017; DeShazo, 2016).

Researchers has also investigated the impact of reoccurring incentives on the decision to adopt a PEV. Studies that investigate the impact of HOV lane access are of interest to this study. Early studies investigated the impact of HOV lane access on hybrid electric vehicles (Ajanovic and Haas, 2016). These studies found that HOV lane access for hybrid vehicles was an effective policy measure in promoting the vehicles. More recent studies have begun to investigate the impact of HOV lane access for PEVs. These studies have used qualitative methods (Hardman and Tal, 2016), questionnaire surveys (Krause et al., 2013; Tal and Xing, 2017), and quantitative analysis (Ajanovic and Haas, 2016). Consensus amongst these studies is less clear than the in the body of literature for financial incentives. Broadly it appears that HOV lane access may have an impact on PEV adoption, however this is contingent on adopters residing near HOV lanes, the level of congestion on the roads in that area, and PEV buyers being aware of this incentive.

In addition to the previously mentioned studies which focus primarily on PEV sales in the United States, a number of studies have also been published on other strong electric vehicle markets such as Norway and China. Both Aaness et al. and Figenbaum et al. provide qualitative but comprehensive overviews on the importance of incentives in Norway and Europe (Aasness and Odeck, 2015; Figenbaum, et al., 2015). Others have attempted to measure elasticities comparable to the US studies: Langbroek finds a range of elasticities from −0.03 to −0.044 (Langbroek et al., 2016) while Zhang et al. identifies heterogeneity in elasticities with higher income buyers being less sensitive but lower income buyers to have elasticities as high as −0.07 (Zhang et al., 2016). In China, the largest incentives are resulting from restriction policies with exemptions for PEVs that lead to higher sales of those technologies. A number of studies have found that these policies are strong contributors to adoption: a 1% suppressed demand leads to a 1.2% increase in PEV market share (Ma et al., 2017), Beijing restriction policy has led to a 38.7% increase in PEVs while Shanghai's license cap has led to a 51.9% increase in PEVs (Wang et al., 2017a,b), lastly a corresponding willingness to pay for getting around the restriction (which is construed to be equivalent to adopting a PEV) of 100,000–120,000 CNY (Renminbi, Chinese currency). While these incentives are not strictly analogous to the purchase incentives commonly seen in the United States, they provide important points of comparison in understanding the relative effectiveness of different types of policy levers.

Studies in other regions have also investigated reoccurring incentives. HOV lanes are not as common in regions outside of the US, however some nations have introduced similar incentives that give PEV buyers access to special lanes. For example, in Norway zero-emission vehicles (ZEVs) can drive in bus lanes. This gives the vehicles a similar ability to avoid congestion as HOV lane access does. There are six studies currently published that consider bus lane access for ZEVs in Norway. Three of these studies didn't find bus lane access to be effective in promoting ZEV sales (Figenbaum and Kolbenstvedt, 2016; Mersky et al., 2016; Zhang et al., 2016). Three studies however found that this incentive was important in promoting ZEV sales (Aasness and Odeck, 2015; Bjerkan et al., 2016; Figenbaum, 2017). It therefore is also not clear whether these special lane access rules for ZEVs are effective in other regions which highlights the need for further analysis.

Our study seeks to contribute to the rich set of literature in the incentive impact domain. In particular we provide two new sets of conclusions not previously seen in the literature: firstly, we provide a more detailed approach in characterizing the heterogeneity in the adoption of PEVs across different groups of consumers in California and secondly, we provide analysis on the importance of incentives over time in order to understand whether these effects have been changing over the last decade. We have organized the remaining paper as follows: a description of the data used and methodological approaches in Section 3, a discussion of the results in Section 4, and close with the conclusion in Section 5.

3. Data and methods

3.1. Survey description

The Plug-in Hybrid & Electric Vehicle (PH&EV) center, part of the Institute of Transportation Studies at the University of California, Davis has been conducting a cohort survey of electric vehicle owners in California every year over the last four years (2015–2018). For the purposes of this study, we include phases 1–3 of the survey effort:

- Phase 1–1.5: Purchasers of electric vehicles from 2010 to 2015
- Phase 2–2.5: Purchasers of electric vehicles from 2015 to 2016
- Phase 3: Purchasers of electric vehicles from 2016 to 2017

The respondents of the survey are selected from the California Clean Vehicle Rebate Project (CVRP), a rebate program for purchasers and leasers of electric vehicles within California. The CVRP is administered by the Center for Sustainable Energy, which has an agreement with the University to provide contacts (e-mail) for solicitation for the purposes of disseminating and gathering respondents for the survey. Altogether, phases 1–3 include 15,275 respondents, all of whom have applied for the CVRP rebate following the purchase or lease of a plug-in electric vehicle (PEV). The number of survey respondents in comparison to the number of applicants for the CVRP as well as a comparison to the total PEV sales that occurred during each of the survey phases is shown in Table 2.

At the end of 2017, there were a total of 278,287 applicants that received the CVRP rebate out of a total 353,666 PEVs sold in California. In other words, our survey was taken by about 5.5% of the CVRP recipients and about 4.3% of the total PEV owners in California. However, there are several sources of selection bias in attempting to represent the population of PEV purchasers in California. The first source of selection bias is based on who responded to the survey out of population of CVRP recipients. The respondents to the survey may not accurately represent the true population of CVRP applicants. In order to address this potential bias, we weight our survey based on PEV model level data, scaling the observed models in the survey to the number of each model that

Table 2
A comparison of survey sample to incentive applicants and total sales.

	CVRP Survey	CVRP Applicants	CA PEV Sales
Phase 1, 1.5	6,864	135,272	184,540
Phase 2, 2.5	5,927	44,455	73,854
Phase 3	2,484	47,758	95,272

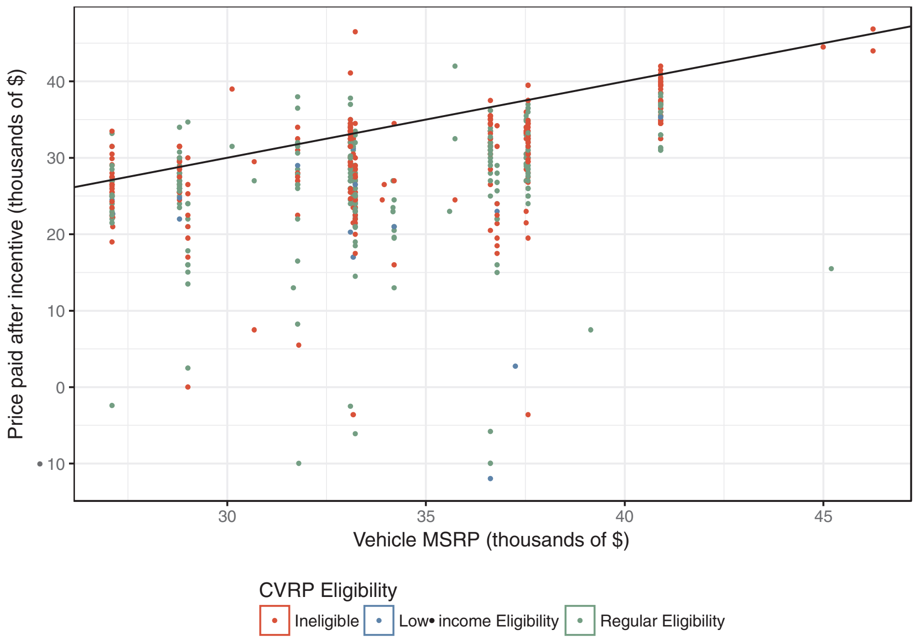

Fig. 1. The electric vehicle manufacturer's suggested retail price (MSRP) of vehicles (by trim) owned by survey respondents in the 2017 survey versus what they paid for them after factoring both the federal tax credit and the CVRP rebate. The eligibility of respondents who applied for a rebate is denoted by the color of each respective points with red points indicating ineligibility due to household income while green and blue points indicate regular eligibility and low-income eligibility (higher rebate amounts) respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

claimed the CVRP. There may also be a difference in the spatial representation of the respondents compared to the distribution of CVRP recipients. Unfortunately, we are unable to weight our survey based on regions—our weighting matrix is too sparse to conduct spatial and PEV model weighting, even for larger county regions.

Secondly, there is a source of bias in that our sample is derived from CVRP applications which itself is derived from the overall population of PEV buyers. However, there are several sources of bias in this second selection layer. First, the qualification requirements for the CVRP is based on an income cap (which has changed over time). Therefore, it is likely that our results may be skewed towards a "relatively" lower income proportion of the PEV purchasing population. It should be noted that the overall income levels of PEV owners in the survey is still significantly higher than the average population in California. It is also possible that our survey missed any PEV purchasers who were unaware of the availability of the incentive, though we are unable to determine how this segment of the purchasers differ in the attributes we are interested in. Unfortunately, we are unable to weight our sample directly to the population of PEV buyers in California as the data are not readily available.

One unique contribution of our survey analysis is the ability to provide a greater level of insight into claims for PEV incentives. In Fig. 1, we reveal that the actual price paid for the vehicle (post-CVRP incentive) varies quite dramatically. There are several reasons for this: different trim configurations for identical models are offered at varying prices, different optional extras selected by buyers, local dealership offers, negotiations on sticker price, and various fees that differ by region. Interestingly, a relatively large number of respondents attempted to claim CVRP but were denied due to eligibility reasons (their income was too high). Importantly, since the CVRP is a post-purchase rebate, lack of knowledge on eligibility may lead to increased PEV sales in the case that a respondent would have chosen not to buy the vehicle if they didn't receive the incentive. Even in the absence of the incentive, we find that the majority of consumers are paying less than sticker price for their vehicle.

Another observation we found among the survey respondents was an inconsistency in the federal credit received. Since the federal credit can be entered manually, we find that several respondents are able to claim a higher amount than should be awarded. In Fig. 2 below, the straight line indicates the federal credit received matches the credit that should have been awarded. While the clear majority are correct, some receive more credit (illegitimate) and some receive less credit (likely due to maxing out their tax liability). This points to some inconsistencies in the worth of the credit as some observations indicate a mismatch between what they should receive and what they receive.

Figs. 1 and 2 provide important considerations for incentive analysis: not all PEV users are able to claim the incentives and the incentive amounts claimed and received (particularly federal) do not always correspond to the correct amount that should be provided for their vehicle. Misconceptions on the value of the incentive (which can vary between incentives such as federal and state) can lead to biases on the true effect of the incentive if not considered within the analysis.

We also observe the stated importance of the incentives from our survey respondents. A matrix of the top two incentives for our respondents is shown in Fig. 3. Respondents were asked: "Plug-in cars are eligible for different local, state, and federal incentives.

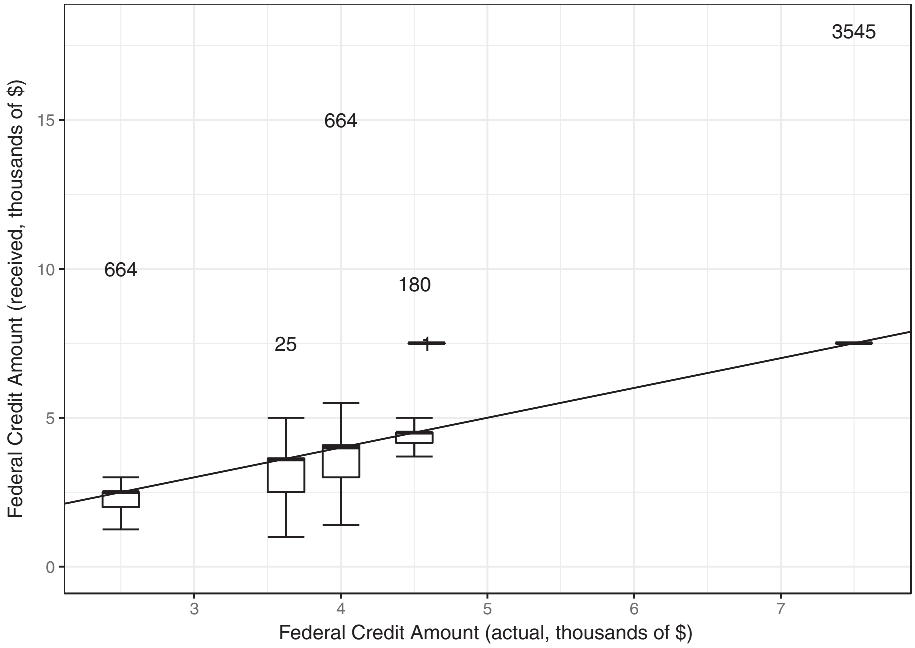

Fig. 2. Comparison of the federal tax credit requested versus what should have been received based on each respondents' corresponding electric vehicle. For the majority of credit requests, the respondents filed for the correct amount but there is significant variation both above and below the correct amount.

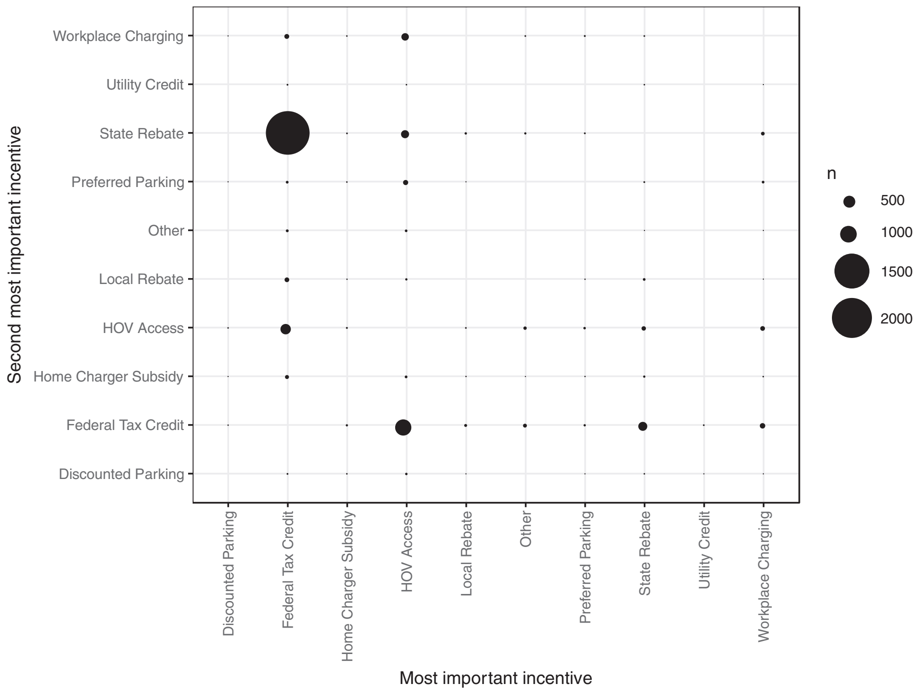

Fig. 3. A matrix indicating the top two important incentives among the survey respondents with the size of each dot indicating the number of responses. Across the ten listed incentives, the most important for respondents were the federal tax credit, the state rebate, and HOV lane access.

How important were those incentives in your decision to buy the [*respondent's vehicle*]?". This question was asked for each of the incentives seen in Fig. 3. By far the most prevalent combination is the federal tax credit (most important) and the state rebate (second most important) followed by the combination of federal tax credit (most important) and HOV lane access (second most important). The remaining combinations almost always include the federal tax credit, the state rebate, or the HOV lane access as one of the top two incentives across the full set of respondents. From an analytical standpoint, the inclusion of the monetary incentives and the HOV lane access (in California) is critical to understanding consumer adoption of electric vehicles. While other incentives are available, respondents have consistently shown that other incentives such as workplace charging or preferred/discounted parking are not as important as the direct monetary benefits of the federal and state credits or the value of reducing driving time via HOV lane access.

3.2. Latent class analysis of incentive importance

Latent class cluster analysis was used to classify PEV consumers based on their responses to a question regarding the importance of a number of different incentives: federal rebate, state rebate, local rebate, home charger installation support, discounted parking rate, workplace charging support, and high occupancy vehicle (HOV) lane access. Responses are based on a bounded continuous scale from −3 to 3 with the option to choose "not applicable". In total, 14 additional dummy variables are included in this analysis. Once these dummy variables are included, Euclidean distance based clustering methods are not applicable, as they do not fully capture the meaning of the dummy variables. To account for this, we use a model based cluster analysis: latent class cluster analysis.

Equation illustrates a latent class analysis model without covariates (Vermunt and Magidson, 2014): x is a single nominal latent variable, y_{it} denotes the response variable, and T is the number of individuals. In this paper, class membership is a function of individuals' perceived importance of a variety of PEV incentives in California. Therefore, y_{it} is individuals' perceived importance of the incentives, x is the class membership of the perceived incentive importance patterns. $f(y_{it}|x)$ is the conditional probability density for response variable i of individual t given condition of the membership x.

$$f(y_i) = \sum_{k=1}^{K} P(x) \prod_{t=1}^{T} (y_{it}|x) \tag{1}$$

To estimate the model, we employ the Expectation–Maximization (EM) algorithm along with Newton–Raphson Maximum Likelihood Estimation (Vermunt and Magidson, 2002). We note that although the estimation results from the two algorithms are quite stable, this model is very sensitive to local maxima of the likelihood function. Testing multiple models with different sets of parameter start values can help to resolve this issue (Goulias, 1999). Another operational issue for estimation is that the degrees of freedom are rapidly exhausted as the number of parameters is increased (usually by increasing the number of classes). In this regard, model identification (ability to estimate parameters) and convergence (subsequent estimation step parameters are not close enough) can be difficult to achieve. Therefore, we employ a hierarchical approach to address this issue:

(a) A model with only one class assumption is estimated.
(b) Increasing the number of latent classes until the model is impossible to identify and the resulting classes become too small.
(c) Selecting a suitable number of classes is based on multiple goodness of fit criteria, including Bayesian Information Criterion (BIC), Akaike Information Criterion (AIC) and the Consistent Akaike Information Criterion (CAIC). Although AIC, BIC, CAIC do not measure the goodness of fit directly, they can be used to compare models to determine whether the model uses more or less parameters, indicating they can be used as relative model fit indices for latent class analysis (McCutcheon, 2002; Nylund et al., 2007).

The latent class model provides probabilistic cluster membership for each respondent. This is one of most important advantages of using latent class cluster analysis as this can be used to relate latent class clusters to external variables (Vermunt and Magidson, 2014). To do this we assign respondents to the cluster in which they have the highest probablity of being assigned to, this cluster memebership is then used as the dependnat vairble in a multinomial logistic regression model. In order to understand the relationship between the perceived imporance of PEV incentives and individuals' socio-demographic characteristics, a multinomial logistic regression model (also called a step-three model in latent class analysis) was used to understand who they are. The socio-demographic variables we tested are as follows: income, education, age, gender, house ownership, number of vehicles in household, household size, number of drivers in household, Tesla dummy indicator, and PEV purchase year.

3.3. Multinomial analysis of purchase decisions

One of the key points of interest is how different factors (both regarding the respondent and to the vehicle) are related to how incentives would have changed a PEV adopters' decision to purchase the vehicle. Though our study may suffer from response bias, it examines a question that would be difficult to approach econometrically. We specifically focus on a question within the survey: "If the federal tax credit were not available when buying my PEV or any other PEV, I would have chosen" with answer choices:

- A conventional vehicle
- Another plug-in vehicle
- A hybrid non-plug-in vehicle
- Not to buy/lease a vehicle at all
- No change
- Don't know

Traditional econometric approaches have estimated elasticities of the federal tax credit with respect to vehicle sales. One of the primary sources of variation that these studies take advantage of is variation in MSRP. However, the dollar value of a tax credit likely differs from the dollar "off-the-hood" of the vehicle's MSRP because the car-buyer must wait to file his/her taxes to receive the incentive (rather than receiving it immediately). This also means that if the car buyer is financing the vehicle, he/she must loan the full price of the vehicle with a tax credit incentive while an incentive that directly decreases the MSRP would allow for a loan of the discounted price. Our approach, while susceptible to response bias, attempts to bypass this issue by relying on their stated preference change in behavior as the incentive is removed.

We employ a multinomial logistic regression (MNL) to calculate the probability corresponding to the vehicle purchasing decisions for existing PEV owners responding to the survey. This approach allows us to consider not only the effect of the incentive, but also a number of controls such as vehicle attributes (manufacturer's suggested retail price [MSRP]—a proxy for the transaction price of the vehicle, technology type) and demographic information. The probability that a respondent considers the absence of the federal tax credit to have a specific outcome on their purchase decision can be modeled as follows:

$$p(y_j) = \frac{\exp(\beta_{ij}\mathbf{x}_j)}{\sum_k \exp(\beta_{ik}\mathbf{x}_k)} \tag{2}$$

where the federal incentive effect on the PEV purchase, y_j, consists of the following decisions: no change in purchase behavior, would have bought another PEV, would have bought a non-PEV, would not have bought/leased a vehicle, and don't know (note that these categories are grouped slightly differently than above). The vector $\mathbf{x}_j$ describes the control variables: education, income, age, household size, PEV type, the percentage incentive discount of vehicle purchase price, and the year in which the PEV was bought. Using the MNL model we are able to estimate the relative probability that a respondent (given their input factors) would make each decision. More importantly, we are able to characterize differences in demographics and vehicle attributes and their relationship to the final PEV purchase decision when removing the federal tax credit. In this way, we are able to capture the consumer heterogeneity corresponding to the causal effect of the federal incentive.

4. Results

The results of our study are presented in two main sections. We dedicate Section 4.1 to describing the clustering of PEV adopters based on their purchase intentions, and the relationship between this and their demographic profile. Section 4.2 describes the MNL results measuring the impact of incentives on purchase decisions for PEV owners.

4.1. Classifying PEV purchaser heterogeneity

We cluster the survey respondents based on the relative importance of all incentives available to them as PEV purchasers. Fig. 4 illustrates the average importance of PEV incentives in each cluster. The second and third cluster show the most distinctive patterns: respondents in the second cluster (marked in dark blue color) perceived PEV purchase incentives as more important than any other clusters except for the discounted parking rate for PEVs. Among the different types of incentives, federal and state rebates were the most significant incentives to this group of respondents. HOV lane access and workplace charging were also perceived as important factors, but their differences across clusters were smaller than the financial incentives. The third cluster (marked in yellow) perceived the importance of incentives to be much smaller than other clusters asides from HOV lane access. The respondents in this cluster percieved the importance of federal and state rebates as being neither important or unimportant; and local rebates, home charging, and discounted parking as unimportant. The other two clusters perceived the importance of federal and state rebates in a slightly positive way (between 1.5 and 1.7), but the local rebate, home charging, and discounted parking incentives were percieved as unimportantin their decisions to adopt electric vehicles. The respondents in these two clusters either did not answer these questions or expressed that the incentives were not applicable to them. Although the first cluster perceived workplace charging and HOV lane access as slightly important incentives (0.3 and 1.1 respectively), HOV lane access was a slightly more relevant incentive for the fourth cluster (0.4).

In order to understand the characteristics of the respondents in each cluster, we used a multinomial logit model with socio-demographic variables and vehicle charateristic variables (Table 3). Overall, we find that income, age, gender, house ownership, number of vehicles, Tesla ownership, and the year in which a PEV was bought are significant variables to classify respondents into different groups based on Wald statistics. The respondents in the second cluster, who perceived most incentives as important, consists of relatively lower income, younger, homeowning males. They are not likely to be Tesla owners and were more likely to has purchased other PEVs recently. On the other hand, the third cluster perceived most incentives in a neutral or negative ways except for the federal and state rebate, were characteized by older, higher income owners who are more likely to have purchased a Tesla. The first and largest cluster perceive federal, state rebates, workplace charging, and HOV lane access as relatively more important incentives, and consist of relatively younger males with fewer vehicles in their households, and their PEVs are actually more likely to be a Tesla than other cluster. Lastly, the respondents in the fourth cluster were more likely to be older females with vehicles per household than the other clusters.

We calculated the year-to-year proportions of each of the clusters to understand s changes in the proportion of the latent classes amoung PEV buyers over time (Fig. 5). The proportion of people requiring incentives (cluster 2) were stable between 2012 and 2015 (between 17.6% and 22.2%), but grew in the last two years (23.6% and 27.2%). However, the proportion of people that do not consider the PEV purchase incentives to be an important factor (cluster 3) has gradually decreased over time from 38.5% to 16%. This

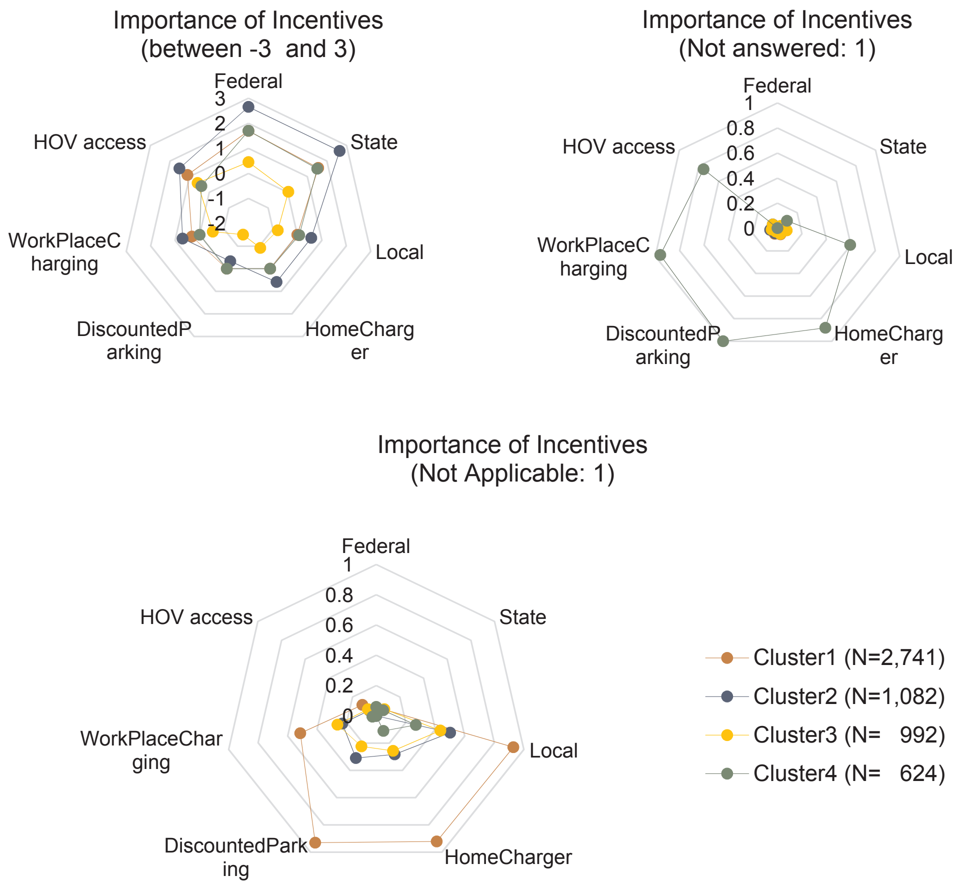

Fig. 4. Separate cluster results from the latent class analysis for regular respondents (*top left*), respondents who did not answer the importance of the federal incentive (*top right*), and respondents for which the federal incentive was not applicable (*bottom*).

Table 3
Estimated parameters for the STEP-3 (MNL) model (z-score in parentheses).

	Cluster1	Cluster2	Cluster3	Cluster4	Wald	p-value
Intercept	−20.862	−145.835	162.258	4.439	19.331	0.000
	(−0.706)	(−3.531)	(3.802)	(0.099)		
Income	0.000	−0.001*	0.001**	0.000	13.854	0.003**
	(0.652)	(−2.391)	(3.387)	(−1.183)		
Education	−0.014	0.017	0.020	−0.022	0.407	0.940
	(−0.355)	(0.319)	(0.371)	(−0.359)		
Age	−0.006**	−0.018**	0.007**	0.017**	74.007	0.000**
	(−3.334)	(−7.668)	(2.710)	(5.806)		
Female (1)	−0.021	−0.261**	0.021	0.261**	19.612	0.000**
	(−0.425)	(−3.947)	(0.321)	(3.532)		
House Owner (1)	−0.246**	0.416**	0.045	−0.215	26.152	0.000**
	(−3.371)	(3.941)	(0.420)	(−1.773)		
N of Vehicles	−0.089**	−0.026	−0.026	0.141**	15.403	0.002**
	(−3.201)	(−0.699)	(−0.708)	(3.297)		
HH size	−0.006	−0.009	−0.002	0.017	0.213	0.980
	(−0.243)	(−0.274)	(−0.068)	(0.435)		
Tesla (1)	0.145**	−0.321**	0.203**	−0.027	28.982	0.000**
	(2.829)	(−4.568)	(3.026)	(−0.333)		
N of Drivers	0.037	0.018	0.009	−0.064	1.224	0.750
	(0.889)	(0.331)	(0.151)	(−0.950)		
Buy Year	0.011	0.073**	−0.081**	−0.003	19.577	0.000**
	(0.755)	(3.549)	(3.821)	(−0.127)		

z-score in parentheses. $* = p < 0.1$, $** = p < 0.05$ $*** = p < 0.01$.

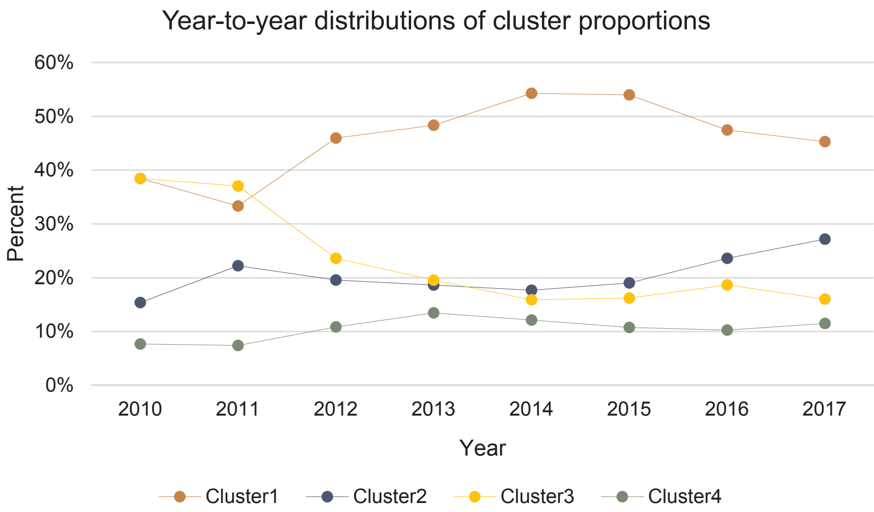

Fig. 5. Year-to-year distributions of cluster proportions.

may indicate incentives are increasing in importance over time, though further analysis is needed. Additionally, we provide a breakdown of cluster by vehicle model ownership in order to identify whether there are any differences among specific PEV technology types (Fig. 6). Despite the heterogeneity in consumers which we characterize by the clusters in the latent class analysis, these groups are present across all of the vehicle models in our data. While there is slight variation in the proportion of each cluster size when broken down by vehicle model (notably more Tesla owning households who do not perceive any incentives as important), these differences are relatively small compared to the shifts in cluster proportions over time. In other words, the heterogeneity in incentive preferences are not strongly correlated with the vehicle model of the survey respondents.

4.2. *Understanding purchase behavior in response to incentives*

We investigate the influence of the federal tax credit on each consumers' purchase decision. Using a multinomial logistic regression model, we reveal how demographic factors, the PEV technology type, year of purchase, and amount of discount from using the federal tax credit incentive influence a purchasers' decision to have "No change in decision", buy "Another plug-in vehicle", buy "A non plug-in vehicle", "Not to buy/lease a vehicle at all", or respond "Don't know". The full results of the regression can be found in Table 4. Our results show some immediate qualitative relationships between the purchase decision and the explanatory variables in our model. For example, higher income and older respondents were less likely to switch away from their purchase decision to another vehicle while those with higher education were on average more likely to switch to either another plug-in vehicle or a non plug-in

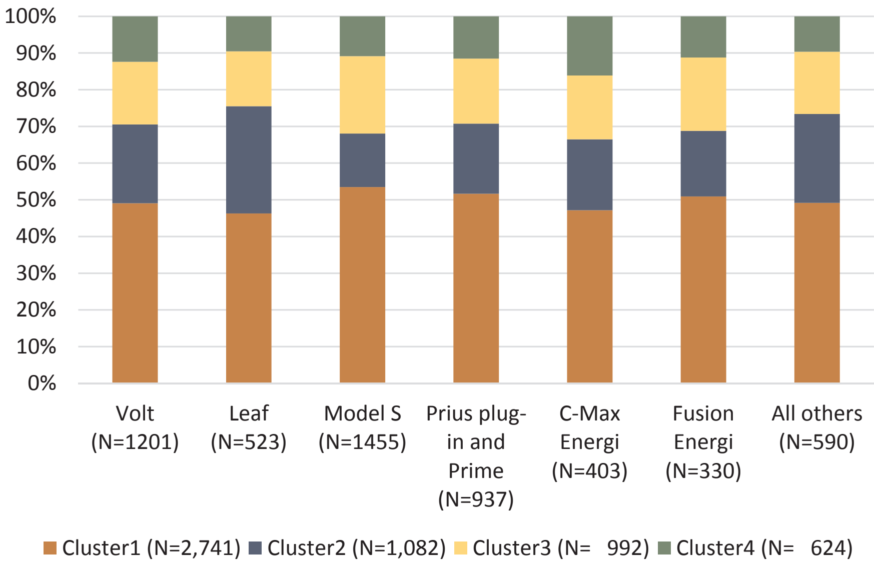

Fig. 6. Composition of PEV models by cluster.

Table 4
Multinomial logistic regression results (standard error in parentheses) for change in purchase decision in the absence of the federal tax credit. The base scenario is no change in decision.

	Another plug-in vehicle (1)	A non plug-in vehicle (2)	Not to buy/lease a vehicle at all (3)	Don't know (4)
Constant	−4.38***	−2.55***	−2.89***	−2.99**
	(1.13)	(0.571)	(0.717)	(1.22)
Years of education	0.0841*	0.0419*	0.0225	0.03
	(0.0454)	(0.0225)	(0.0284)	(0.0483)
Income ($)	−0.143*	−0.152***	−0.208***	−0.242**
	(0.0855)	(0.0447)	(0.0574)	(0.0991)
Age (Years)	−0.0199**	−0.0131***	−0.0127**	−0.00298
	(0.00408)	(0.00408)	(0.00514)	(0.00886)
Household Size	0.0883	0.0591	0.0656	0.081
	(0.0859)	(0.0453)	(0.0566)	(0.0969)
PEV Type (PHEV)	0.194	0.627***	−0.0359	−0.0826
	(0.212)	(0.111)	(0.136)	(0.232)
Incentive Discount	3.19***	3.14***	4.16***	3.78***
	(1.18)	(0.658)	(0.725)	(1.21)
Model Year	0.076	0.075**	0.128***	−0.0928
	(0.0684)	(0.0347)	(0.0443)	(0.0738)
Akaike Inf. Crit.	5659.97			

Standard error in parentheses. $* = p < 0.1$, $** = p < 0.05$ $*** = p < 0.01$.

vehicle. We also observe that the type of electric vehicle was an important factor in determining whether the driver would switch to a non plug-in vehicle: battery electric vehicle owners were less likely to make this switch than plug-in hybrid owners.

We translate the results of the MNL model to display the corresponding probability outcomes in Fig. 7, specifically focusing on the role of PEV technology type. We find that on average, over 60% of respondents state they would not have changed their decision if the federal tax credit were removed. While BEV purchasers were statistically significantly different from PHEV purchasers in this regard, the difference is marginal with BEV purchasers being a few percentage points higher (for no change). This particular result confirms previous studies that have derived elasticities of the purchase incentive (Tal and Nicholas, Exploring the Impact of the Federal Tax Credit on the Plug-In Vehicle Market, 2016; Jenn et al., 2018).

Additionally, one point of interest is that BEVs were statistically less likely to purchase a non-plug-in vehicle by nearly a 10% margin as compared to PHEVs. We hypothesize that PHEV buyers are less enthusiastic about PEVs in general, as is exhibited by their

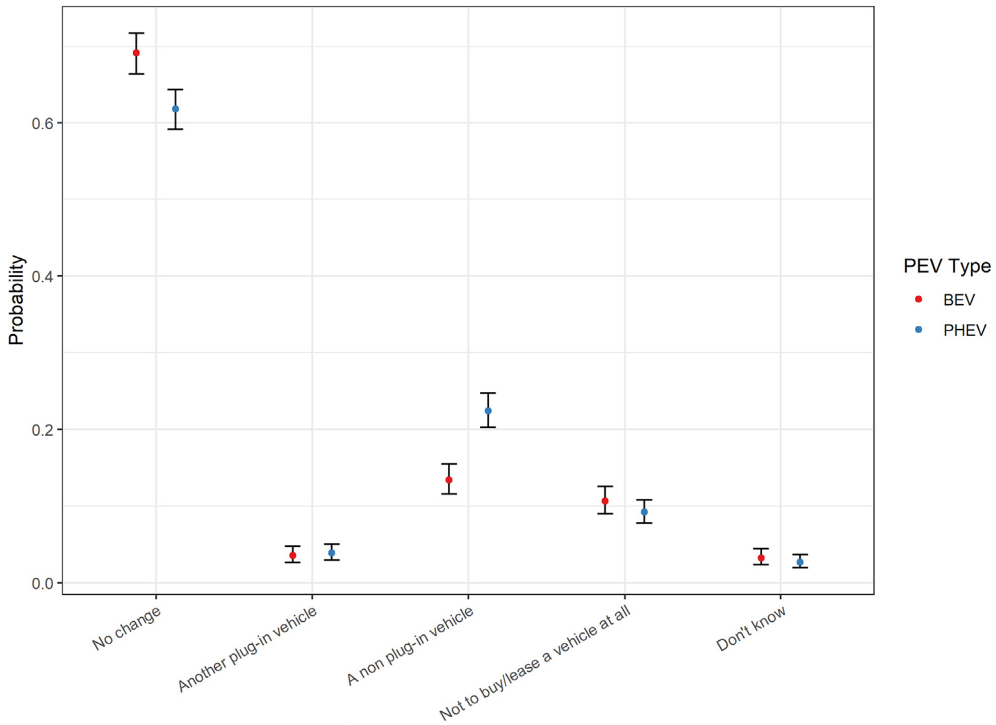

Fig. 7. Average probabilities associated with MNL model output for decision criteria relating the technology type of the PEV (BEV vs PHEV).

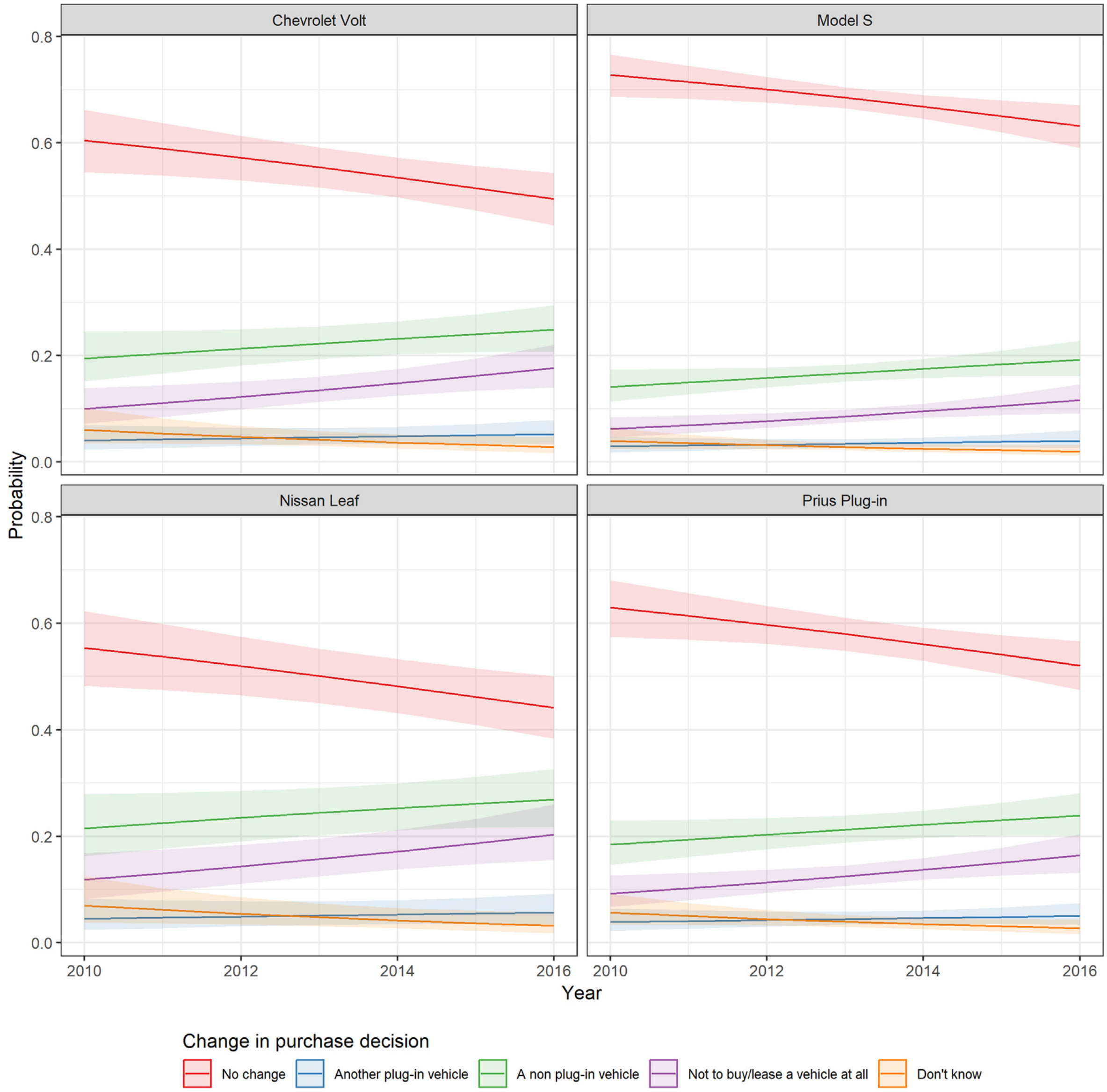

Fig. 8. Change in federal incentive importance over time from the MNL model. The "No change" category consistently decreases as time passes, indicating that removing the tax credit will cause a larger impact in later years.

adoption of a partially electrified vehicle. Their decision therefore may have been more greatly impacted by incentives rather than personal motivations to own a PEV. Therefore, these adopters would have a higher probability of purchasing either a conventional gas vehicle or a traditional hybrid vehicle compared to the BEV respondents in the survey. At approximately 15% to 23% for BEVs and PHEVs who would have purchased a non-plug-in vehicle respectively, this would indicate that the incentive would alter their decision on which vehicle to buy but not that the initial decision to purchase a vehicle. The shift to not purchase a vehicle at all is about a 10% outcome for both BEV and PHEV owners.

In Fig. 8, we observe for four of the most popular PEV models the different probabilities associated with a decision outcome when removing the federal tax credit incentive. One of our findings is that the Tesla Model S has a statistically significantly higher chance of not changing the decision when the incentive is removed relative to the Chevrolet Volt, Nissan Leaf, and Prius Plug-in. This may be due to the fact that the discounted amount relative to the price of the vehicle is much smaller for the Tesla compared to the other PEVs and therefore less valuable. It may also be related to Tesla buyers having exceptionally high household incomes. We also find a significant trend in the causal effect of the incentive over time. There is a decrease ranging from 10% to 20% over a period of 7 years for respondents who would have chosen "No change" if the federal incentive were removed. Meanwhile, there is a marked corresponding increase (statistically significant) in PEV adopters who would have chosen "a non plug-in vehicle" or "not to buy/lease a vehicle at all" over time. This means that fewer buyers would have purchased a PEV in 2017 than in any prior years if incentives were not inplace.

5. Discussion and conclusions

There is a broad array of literature addressing the efficacy of incentives, our work seeks to contribute to two particularly relevant policy questions regarding incentives for electric vehicles. Firstly, to whom are incentives most effective and for what demographics or vehicles can they be removed to improve their efficacy? Secondly, as the market segment for PEVs continues to improve, can we begin to phase out incentives and what would the corresponding impact be? Our work is not a seminal answer to these questions but we bring novel results to the discussion particularly due to the multiyear nature of the data.

Regarding the first question, our work indicates that there are clear clusters among the heterogeneous population of PEV adopters. There are segments of this unique population that find the importance/value of the federal and state tax credits to be relatively low: older and wealthier purchasers who were statistically significantly more likely to own a Tesla Model S or Model X. This has already been reflected in changes in numerous incentive policies: California now has an income-based cap on applicants of the CVRP and many other states have introduced restrictions based on the MSRP of the vehicle. Nevertheless, we find that the large majority of PEV owners still rate the federal and state tax credits as well as the HOV lane access to be important incentives to their purchasing decisions. This is reflected in both the latent class analysis as well as the MNL modeling approach.

The issue of incentive phase-out is critical to the sustainability of the electric vehicle market. The federal government has already provided \$2.5 billion in subsidies through their federal tax credit and the state of California has provided \$450 million in subsidies through the CVRP program. From a financing standpoint, it is unlikely that governments would be able to continue funding incentives indefinitely. As we begin to consider phasing out incentives, it is vital to consider the effect on the market to avoid a collapse of PEV adoption (as has been seen in empirical examples of Georgia and the Netherlands)[1]. Unfortunately, our findings indicate that the incentives have become increasingly important over time. The very first early adopters of the PEV technology were significantly less sensitive to the incentive availability and we have found about a 20% increase in PEV owners who would not have purchased a PEV in 2016 compared to 2010 if the federal incentive were removed. This trend is the opposite of what is necessary from a policy perspective and points to a necessity of a more sustainable funding mechanism for the incentive policy or a marked decrease in PEV prices to reliably phase out the incentives without drastically affecting the market, an example of such approach included the bonus malus systems in place in France and Sweden. These findings can serve as a lesson for policymakers in nations who have yet to promote PEVs heavily or to policymakers working on introduction other new environmentally beneficial technologies. These policymakers should consider that in the very early market introduction of PEVs, latent demand may exist amongst a group of innovative consumers who will adopt the technology with or without incentives. For California and potentially other nations with mature PEV market, a gradual phase out of incentives may not be possible. An alternative approach could be introducing more targeted eligibility requirements for PEV adopters, for example by household income and vehicle purchase price. This would ensure high income buyers and buyers of expensive luxury vehicles who are less sensitive to the incentives do not receive them. This could allow more funding to be available for lower income buyers for who the incentives are important, and could increase the cost effectiveness of policy measures.

As with any survey-based study, our results are likely influenced by sample bias; not only by how the respondents represent the population of CVRP recipients from whom they are sampled, but also how they represent the full population of PEV buyers in California, of whom CVRP recipients are just a subset. For the former selection bias, we attempt to calibrate our results by weighting to PEV model representation in CVRP recipients, but if there is systematic bias in how households decided to respond to the survey request that is independent of the PEV models, then our results would be slightly more limited in their applicability. Perhaps the larger source of bias is related to PEV buyers who did not apply to the CVRP. This likely represents a subset of the population who are either ineligible (higher income), not interested, or did not hear about the state-wide incentive. It is more likely that there is some systematic bias in this population, and therefore we are less confident about extending our results to the full population of PEV buyers. However, we are reasonably confident in the applicability of our results to the broader population of CVRP recipients—in fact without any weights, the results are nearly identical to the results presented in this study. Therefore, we conclude that of the subpopulation of PEV buyers that received the CVRP, the incentive has become increasingly important over time. This may not be true for the remaining PEV buyers who did not receive the CVRP, a proportion that may be changing over time.

Our study only investigates PEV adopters in California. This approach allows us to undertake the most detailed analysis of incentives in any region, however it does limit the scope of the analysis. Future studies should aim to investigate the changing importance of incentives over time in other regions to understand if this trend of incentives increasing in importance over time exists in Asia and Europe for example. This information will be important for policymakers in those regions who are grappling with increasing PEV sales and may have budgetary constraints. This may mean they are also considering how or if incentives can be phased out.

The increasing importance of incentives overtime may be related to a changing socio-demographic profile of PEV adopters. The PEV market is moving beyond innovators and early adopters towards more mass market consumers with moderate incomes who may need more of a nudge to purchase PEVs. At some point during PEV market introduction it is hoped that the market will reach 'critical mass' and be self-sustaining, after this point incentives may no longer be needed. The point at which this will occur is not yet clear

[1] Tal, Gil, Austin Brown. "Credits and Rebates Play a Key Role in Building Consumer Market for Cleaner Electric Vehicles." *GreenLight Blog*. https://its.ucdavis.edu/blog-post/credits-rebates-play-key-role-building-consumer-market-cleaner-electric-vehicles/

with no studies approaching on a concrete answer to this question. Understanding when the PEV market may become self-sustaining will help in planning incentives and could lead to a smoother market introduction of PEVs.

Author contributions

Alan Jenn was responsible for the bulk of the writing and conducted the MNL regression analysis. Jaehyun Lee contributed to writing the methods and results for the latent class analysis. Scott Hardman contributed to development of the literature review section as well as editing the manuscript and co-developed the initial idea for the paper. Gil Tal was responsible for the initial idea for the paper and contributed suggestions and edits throughout the project and writing.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tra.2019.11.004.

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