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Understanding discontinuance among California's electric vehicle owners

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For the market share of plug-in electric vehicles (PEVs) to continue to grow and reach 100% of new vehicle sales, adopters of the technology, who initially buy PEVs, will need to continue choosing them in subsequent purchases. Although much research has focused on the reasons for, and barriers to, initial PEV purchase, less has been devoted to the reasons for discontinuance—abandoning a new technology after first purchasing it. Here, on the basis of results from five questionnaire surveys, we find that PEV discontinuance in California occurs at a rate of 20% for plug-in hybrid electric vehicle owners and 18% for battery electric vehicle owners. We show that discontinuance is related to dissatisfaction with the convenience of charging, having other vehicles in the household that are less efficient, not having level 2 (240-volt) charging at home, having fewer household vehicles and not being male.

For any new product to achieve a 100% market share, owners must make initial purchases, continue to purchase the technology and not revert back to purchasing the incumbent product whenever they replace their initial purchase or buy additional products. Plug-in electric vehicles (PEVs), which include battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), have a growing market share in many nations. In California, the region of analysis in this study, PEVs reached 10% market share in 2019, whereas in Norway, the country with the largest PEV market share, the vehicles reached over 50% market share in 2019. California, Norway and several other nations have goals of reaching 100% of new vehicles sales being electric by 2025 (Norway), 2030 (Denmark, Ireland, India, UK), 2035 (California) and 2040 (France)[1]. These goals will be more difficult to achieve if PEV owners are discontinuing PEV ownership.

Most published research on PEV market penetration and consumer choice focuses on initial adoption and characteristics of early buyers. Discontinuance occurs when a BEV or PHEV owner no longer owns any PEV and now owns an internal combustion engine vehicle or hybrid electric vehicle. To our knowledge, there are no published reports on PEV discontinuance—that is, when an adopter no longer owns or uses the technology that they originally adopted[2]. IHS Markit has published data on electric vehicle loyalty, showing that 55% of households who owned a new PEV purchased another PEV in the last three months of 2018[3]. This does not reveal anything about discontinuance as those that did not purchase a PEV may or may not own their original PEV.

Although the literature does not include studies on PEV discontinuance, insights on who is buying PEVs, the barriers to adoption and purchase motivations are still useful for this study. The factors related to PEV adoption or non-adoption could be related to the decision to continue or discontinue PEV ownership. We therefore use insights from the literature to inform our study. Early studies used stated preference methods with surveys of general population to identify PEV adopters[4–13]. These studies typically found that those most likely to purchase a PEV tended to be male and have a high household income, a high level of education and multiple vehicles in the household. More recent research gathered data from consumers who had purchased a PEV. Studies in Sweden, Norway, the United States and Canada are consistent in finding that PEV owners are mostly male, middle aged with mid-to-high household income and high education[14–18]. Several studies[7,18–23] identified a relationship between pro-environmental attitudes and positive perceptions of PEVs. Having pro-technology attitudes is also related to PEV adoption or adoption intent[19,23], as is having preferences for vehicles with higher efficiencies[24].

Reasons for PEV purchase include environmental motivations[25–31] and low running and ownership costs—especially related to refuelling, but also to maintenance[7,25,31,32]. The high performance and rapid acceleration of PEVs can be a purchase motivator[30,33]. Reasons for adoption also include wanting to be the first to adopt a new technology or novelty seeking[26,30,31], which is related to having pro-technology attitudes. PEV buyers are also encouraged to buy the vehicles through direct incentives such as grants, rebates and tax credits[34], and indirect incentives such as free or discounted parking, access to bus or carpool lanes and toll fee waivers[35].

Studies on barriers to PEV adoption find some combination of purchase price, driving range, model availability and lack of infrastructure is the most substantial barrier to adoption[5,29,36–42]. Some suggest limited driving range is the largest barrier[5,40], whereas others suggest is it purchase price[37,39] or the availability of charging[43].

The aim of this study is to understand why PEV owners in California are discontinuing PEV ownership. We use results from five questionnaire surveys to achieve this, conducted between 2015 and 2019. The first four surveys are cohort surveys of PEV owners; in the final survey respondents are recruited from the first four surveys. We construct logistic regression models to assess the correlation of various factors with the decision to discontinue ownership of a BEV or PHEV (see Methods). In this study we find that discontinuance occurs at a rate of 18.1% for BEV owners and 20.1% for PHEV owners. Discontinuance is correlated with having fewer vehicles in the household and dissatisfaction with the convenience of charging for both BEV and PHEV owners. BEV discontinuance is correlated with owning other household vehicles with lower energy efficiencies and not having level-2 charging at home. PHEV discontinuance is also correlated with not being male, not living in a detached house, being dissatisfied with the purchase price of the PHEV but being satisfied with running costs, shorter commute distances and undertaking more long-distance trips.

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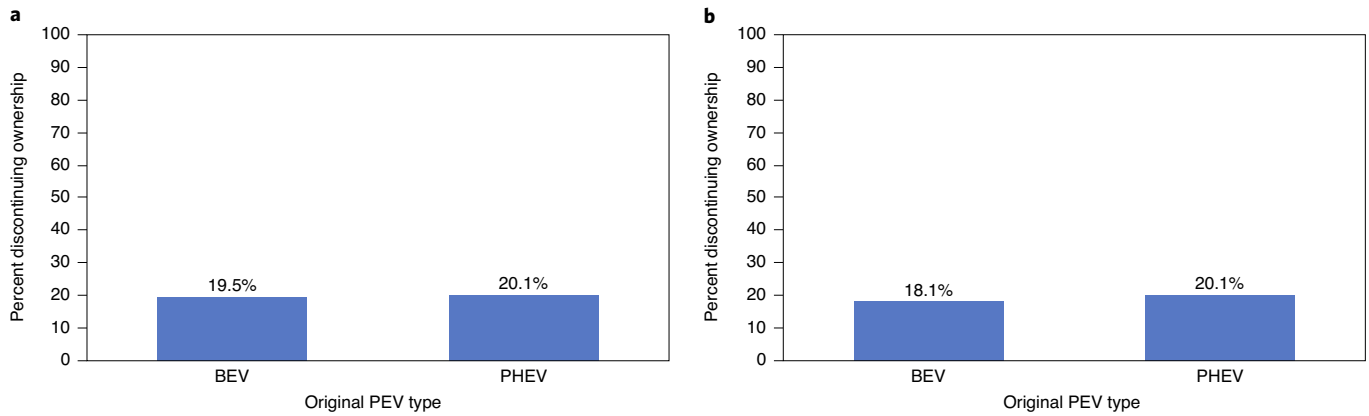

Fig. 1 | Percent of PHEV and BEV owners who discontinued ownership. a,**b**, Percentages are given for the sample (**a**) and the weighted percent (**b**). See Supplementary Table 1 for weights of PHEV and BEV owners in the sample (n=1,727).

Discontinuance among California electric vehicle owners

Figure 1 shows the percent of PHEV and BEV owners who discontinued PEV ownership in the survey sample and the weighted percent (see Supplementary Table 1 for weights); PHEV discontinuance is slightly higher than BEV discontinuance. Figure 2 shows discontinuance among common PEV makes in the sample. The highest rate of discontinuance is among those who adopted a Fiat PEV, whereas the lowest is among those who adopted a Tesla PEV.

Supplementary Table 3 shows the number of people in the household, number of vehicles in the household, age, gender, household income, highest level of education, home type and home ownership for those that discontinued or continued PEV adoption. We also include data for California PEV buyers who purchased a vehicle between 2011–2020 for comparison. Supplementary Table 4 shows t-test comparisons for continuous variables and Supplementary Table 5 shows X^2 tests for nominal variables. Of the eight socio-demographic variables tested, seven are significantly different: households that discontinued PEV ownership have fewer people in the household ($P<0.001$), fewer vehicles in the household ($P<0.001$), are younger ($P=0.0156$), have lower household incomes ($P<0.001$), fewer are male ($P=0.0024$), more of them rent rather than own their home ($P<0.001$) and more live in a house that is not a single-family home/detached house ($P<0.001$). Supplementary Table 6 shows t-test results for respondents's travel behaviour. Two significant differences exist: those who discontinued PEV ownership have lower annual vehicle miles travelled ($P=0.0354$) and shorter one-way commute distances ($P<0.001$).

Survey respondents were asked to rate how satisfied they were with their previous PEV for ten vehicle attributes. Figure 3 shows the distribution of responses for those who continued PEV ownership (top row) and those who discontinued PEV ownership (bottom row) for the five attributes that have significantly different distributions (Supplementary Fig. 1 includes a graph with all ten attributes). Table 1 shows X^2 test results for these distributions for all ten attributes. Respondents are mostly satisfied with their PEVs; the electric driving range is the only attribute where more respondents are dissatisfied than satisfied. The distributions are significantly different for safety ($P=0.0345$), refuelling/recharging costs ($P=0.0177$), reliability ($P=0.0241$), electric driving range ($P=0.0246$) and convenience of charging ($P < 0.001$). For all of these attributes, those who discontinued PEV ownership are less satisfied than those that continued ownership. The most significant difference is with satisfaction with charging convenience. The distribution for those that continued ownership is towards more satisfied than for those that discontinued PEV ownership.

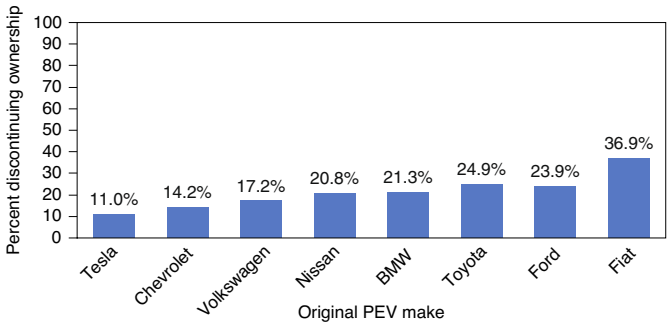

Fig. 2 | Percent of PEV owners who discontinued ownership by make of original PEV owned. We exclude less common vehicles within the sample for this graph. See Supplementary Table 2 for a table of all vehicles in the sample, and the percentage of each that discontinued PEV ownership (n=1,727).

Figure 4 shows access to charging for those who continue versus discontinue PEV ownership. Having no charging access at home is more common among respondents who discontinue rather than continue PEV ownership (28.4% versus 13.5%, Fig. 4). These charging variables are measured during the early phase of adopters PEV ownership using results from survey 1, not their access to charging when we surveyed them a second time. Of those who continued ownership, 49.8% have access to level-2 (240 V) charging at home, compared with only 29% of those who discontinued PEV ownership. There are no significant differences in access to workplace charging for households that continued or discontinued ownership. Of those that continued PEV ownership, 58.4% report no public charging, compared with 62.7% of those that discontinued ownership. More households that continued PEV ownership report using only level-2 charging, although fewer report using level 2 in combination with direct current (DC) fast charging. X^2 tests (Table 2) comparing these distributions show that workplace charging access and public charging use are not significantly different. The distributions for access to home charging are significantly different: fewer households that no longer own a PEV have home charging, and of those that do, fewer have level-2 charging.

Factors related to discontinuance

Table 3 shows the results for the BEV and PHEV binary logistic regression models (see Methods for details). The table shows odds ratios for each variable. A value higher than one indicates higher

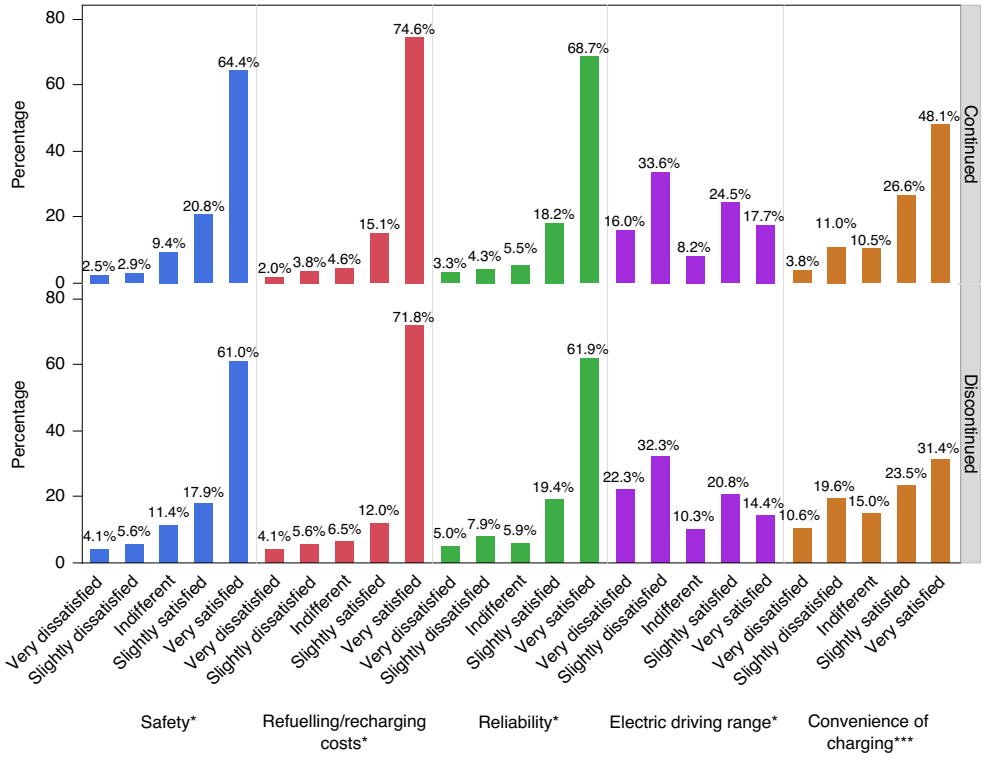

Fig. 3 | Satisfaction with previous PEV. The figure shows satisfaction with previous PEV for those who continued PEV ownership and those who discontinued PEV ownership for five attributes that have significantly different distributions. The figure represents answers to the question "Thinking about your {make and model of previous PEV}, how satisfied were you with the vehicle for each of the below?" (n = 1,672). Significance stars indicate whether distributions are significantly different (* = <0.05, ** = <0.01, *** = <0.001) using the X^2 test (see Table 1).

Table 1 | X^2 test results for satisfaction with previous PEV for those who continued PEV ownership and those who discontinued PEV ownership

	n	DF	Pearson X^2	*P*-value
Safety	1,672	4	10.378	0.0345*
Comfort	1,672	4	4.96	0.2914
Refuelling/recharging costs	1,672	4	11.954	0.0177*
Performance	1,672	4	5.461	0.2432
Environmental impacts	1,672	4	9.104	0.0586
Vehicle purchase price (including rebates, discounts and so on)	1,672	4	6.857	0.1436
Reliability	1,672	4	11.228	0.0241*
Electric driving range	1,672	4	11.181	0.0246*
Convenience of charging	1,672	4	63.701	<0.001***
Driving assistance features	1,672	4	4.477	0.3452

Results compare distributions in satisfaction on a Likert scale from very dissatisfied, slightly dissatisfied, indifferent, slightly satisfied, to very satisfied, for those who continued PEV ownership and those who discontinued PEV ownership (* = <0.05, ** = <0.01, *** = <0.001). DF, degrees of freedom.

odds of discontinuing BEV or PHEV ownership, whereas a value less than one indicates lower odds of discontinuing BEV ownership for a one-unit increase in the given independent variable.

In the BEV model, the number of vehicles in the household has an odds ratio of 0.563, that is, for a one-unit increase in the number of vehicles in the household there are 43.7% lower odds of discontinuing BEV ownership. This could be explained by households being less willing to own a BEV when they have fewer vehicles due to reduced flexibility from a limited range BEV compared with a conventional vehicle.

For a one-point increase in satisfaction with the convenience of charging a BEV, there are 19.5% lower odds of discontinuing BEV adoption. Those that no longer own a BEV have less favourable attitudes towards the convenience of charging compared with those that continued ownership.

For a one-unit increase in the MPG of the second vehicle in the household there are 2.6% lower odds of discontinuing BEV ownership. This could indicate that those who discontinue BEV ownership are less interested in energy efficient vehicles in general or have preferences for larger vehicles.

For access to level-2 charging from home compared to level-1, there are 52.8% lower odds of discontinuing ownership. Having level-1 charging over no charging does not have any significant relationship with discontinuance. This shows the importance of having higher speed level-2 charging at home over low speed level-1 charging. Of the two, level-2 charging gives drivers faster charging times and maximizes the amount of travel they can do in a BEV. Furthermore, the installation of a level-2 charger at home is an investment that will not be used if BEV ownership were discontinued. Access to charging at work or the use of public chargers has no relationship with discontinuance.

In the PHEV model the dummy variable for gender (1 = male, 0 = other) has an odds ratio of less than one, showing the odds of discontinuing PHEV adoption is 54.2% lower for males. For a one-unit increase in the dummy variable for home type (1 = detached house, 0 = other) there are 60.4% lower odds of

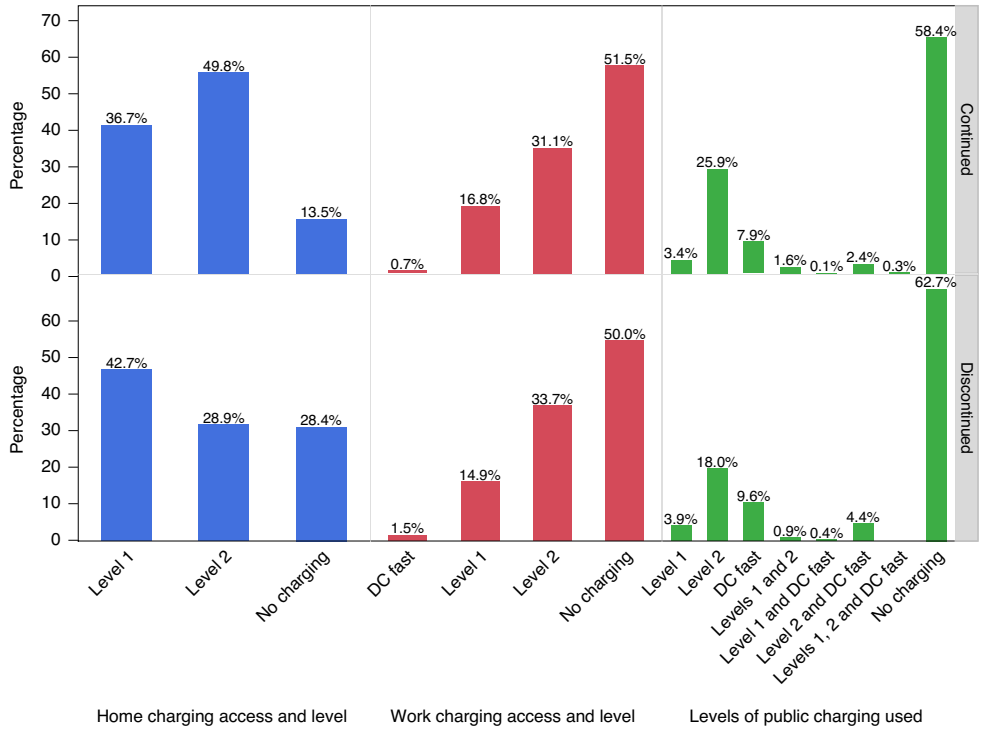

Fig. 4 | Usage of different charging types. The figure shows access to charging at home (blue) and work (red), including charging level and whether respondents report having used public charging, and the levels of charging they report using (green) for those who continued and discontinued PEV ownership.

discontinuing PHEV adoption. For one-unit increase in number of vehicles in the household there are 41.2% lower odds of discontinuing PEV ownership.

Similar to the BEV model, with a one-unit increase in the variable that measures satisfaction with the convenience of charging there are 24.3% lower odds of discontinuing PHEV adoption. For a one-point increase in satisfaction with vehicle purchase price there are 0.815 odds of discontinuing PHEV ownership. Those that discontinued owning a PHEV may be dissatisfied with the price they paid for their PHEV. Satisfaction with refuelling/recharging costs is positively correlated, showing 54.5% higher odds of discontinuing PHEV adoption for a one-unit increase in satisfaction. This is counterintuitive but is explained by those that continued PEV ownership moving from a less efficient PHEV that they were unsatisfied with to a more efficient PEV. For those that continued PHEV ownership the mean fuel economy of their original PEV is 68 MPGe, while the mean fuel economy of their newest PEV is 78 MPGe (miles per gallon equivalent). Although those that discontinued PHEV adoption were satisfied with this attribute, this was not influential enough for them to continue PHEV ownership.

Commute distance has an odds ratio of 0.978, indicating for a one-mile increase in commute distance there are 2.2% lower odds of discontinuing PHEV ownership. Households that continue PEV ownership may be doing so due to longer commutes, which can give them a greater financial benefit of owning a PHEV in comparison to an conventional gasoline vehicle. For a one-unit increase in the number of 200-mile trips taken in the past twelve months there are 2.6% higher odds of discontinuing PHEV ownership. This could be a result of buyers perceiving PHEVs to be less suited to long-distance travel, perhaps as the electric range of a PHEV is only useable in the first 10–40 miles on a long-distance trip.

No variables related to charging access (at home, work or in public) are significant in the PHEV model, although perceptions around convenience of charging are. This could be a result of drivers being able to use PHEVs regardless of whether they charge them or not.

Table 2 | X^2 test results for charging

	N	DF	Pearson X^2	*P*-value
Home charging access and level	1,795	2	69.774	<0.001***
Work charging access and level	1,049	4	1.784	0.586
Levels of public charging used	1,270	7	11.732	0.109

Results compare distributions in access to charging at home and work, including charging level, and whether respondents report having used public charging, and the levels of charging they report using for those who continued PEV ownership and those who discontinued PEV ownership. (* = <0.05, ** = <0.01, *** = <0.001).

The results of the BEV and PHEV models differ in a few areas. Only two variables are significant in both. Discontinuance of PHEVs and BEVs is correlated with having fewer vehicles in the household and dissatisfaction with the convenience of charging. BEV discontinuance is also correlated with owning household vehicles with lower efficiencies and not having level-2 charging at home. PHEV discontinuance is correlated with not being male, not living in a detached house, being dissatisfied with the purchase price of the PHEV, being satisfied with running costs, shorter commute distances and undertaking more long-distance trips.

Conclusion

It should not be assumed that once a consumer purchases a PEV they will continue owning one. In California, 18.1% of BEV and 20.1% of PHEV owners who purchased their PEV between

Table 3 | Binary logistic regression model results for BEV and PHEV discontinuance

	BEV model			PHEV model		
Term	**Odds ratio**	**Std error**	**Prob. > X^2**	**Odds ratio**	**Std error**	**Prob. > X^2**
Intercept			0.1101			0.5941
Age	1.0124	0.0101	0.2148	0.9934	0.0117	0.5713
Gender	0.6840	0.1583	0.1009	0.4585	0.1398	0.0105**
Education	0.8867	0.1365	0.4347	0.9193	0.1738	0.6564
Lease (1 lease, 0 other)	0.7769	0.2629	0.4557	1.5882	0.5195	0.1573
Number of people in the household	0.9552	0.1033	0.6721	0.9918	0.1325	0.9507
Number of vehicles in the household	0.5635	0.0834	<0.001***	0.5884	0.1112	0.0050***
Home type (detached 1, other 0)	0.8372	0.2378	0.5316	0.3959	0.1434	0.0105**
Miles per gallon of second vehicle in household	0.9737	0.0076	0.0007*	0.9914	0.0059	0.1447
Year of PEV purchase	1.1451	0.0958	0.1053	0.9479	0.0974	0.6030
Electric driving range	0.9976	0.0022	0.2745	0.9966	0.0061	0.5761
Satisfaction with vehicle attributes:						
Safety	0.9148	0.1188	0.4930	1.0184	0.1716	0.9137
Vehicle purchase price (including rebates, discounts and so on)	0.9273	0.0984	0.4767	0.8150	0.0997	0.0945*
Reliability	0.9221	0.1075	0.4864	0.8245	0.1282	0.2144
Convenience of charging	0.8053	0.0754	0.0208**	0.7569	0.0879	0.0165**
Refuelling/recharging costs	0.9282	0.1215	0.5694	1.5446	0.3139	0.0324**
Commute distance	0.9882	0.0080	0.1461	0.9783	0.0097	0.0271**
Long-distance trips	0.9952	0.0140	0.7302	1.0263	0.0138	0.0535*
Home charging categories:						
Level 2/level 1	0.4718	0.0752	0.0014**	0.6419	0.1163	0.1474
No charging/level 1	0.7595	0.1283	0.4423	1.0479	0.2259	0.9035
No charging/level 2	1.6098	0.2719	0.1991	1.6326	0.3519	0.2608
Work charging dummy (1 = L1, L2, DC, 0 = none)	0.9696	0.2122	0.8880	1.1127	0.3147	0.7059
Public charging dummy (1 = L1, L2, DC, 0 = none)	0.9276	0.2072	0.7364	0.5739	0.1983	0.1080
Log likelihood	311.076			201.054		
R-squared (U)	0.132			0.1334		
Observations (or sum of weights)	759			489		

Binary logistic regression model where the dependant variable is 1 = discontinued PEV ownership, 0 = continued PEV ownership (* = <0.1, ** = <0.05, *** = <0.01).

2012 and 2018 discontinued PEV ownership. This discontinuance occurred between the years 2015 and 2019. Without data from other sources to compare with, it is not clear whether this is a high or low rate of discontinuance. What is clear is that this could slow PEV market growth and make reaching 100% PEV sales more difficult.

Even after initially overcoming the barrier of the different refuelling style, some BEV and PHEV owners decided not to continue with PEV ownership for the same reasons many do not purchase one in the first place. The fact that discontinuance is not correlated with vehicle range but is correlated with access to charging and the convenience of charging intuitively makes sense. The way in which a PEV is charged has not changed, whereas vehicle range has been increasing since PHEVs and BEVs were introduced. PEV owners have the option to purchase longer-range vehicles, whereas they cannot yet purchase a vehicle that is charged differently (for example, though inductive charging).

Both PHEV and BEV discontinuance is negatively correlated with number of household vehicles. Those that continued ownership have on average more vehicles in their household than average California households, whereas those that discontinued ownership have a similar number of vehicles on average. This may mean households with fewer vehicles struggle to incorporate PEVs into their household fleet, something which could be problematic as the PEV market moves towards mainstream consumers.

The reasons why women are more likely to discontinue ownership of PEVs is not clear; similarly, the reason why so few PEV owners are women remains unclear[44]. More research is needed on this topic to understand how to encourage women to adopt and continue to own PEVs.

Finally, discontinuance of PEV adoption is occurring concurrently with more PEV owners reporting they would not purchase their PEV without incentives year on year[45] and with buyers's socio-demographics changing each year, with more moderate income buyers adopting a PEV[46]. This will mean that the introduction of BEVs and PHEVs will face more challenges over time, will not get easier as some hope and will still require policy support.

Initial purchase of a PEV by a consumer does not ensure that they will continue ownership. Most existing research investigates how to increase rates of first-time PEV adoption through incentives, infrastructure and other policies. We hope to encourage more research into understanding how to ensure PEV owners become

permanent adopters and do not abandon a PEV for vehicles that are less energy efficient.

Methods

Overview. Using results from five questionnaire surveys, this study investigated rates of discontinuance and factors correlated with discontinuance. We investigated discontinuance among those who had made a subsequent purchase decision regarding their original PEV. These households now own a newer vehicle or chose to purchase their original PEV at the end of the lease period. We excluded those who have not made any decisions on the ownership of their original PEV as these households may or may not be planning to continue with PEV ownership. Leaving these out of the analysis was important, as we do not know whether their attitudes, satisfaction with their vehicle or any other factors are representative of someone who is planning to abandon or continue PEV ownership. If a BEV adopter purchased a PHEV after owning a BEV initially (or vice versa) this qualifies as continuing PEV ownership. Respondents originally purchased their PEVs in the years 2012–2018 and the decision to continue or discontinue PEV ownership occurred between 2015–2019.

Questionnaire surveys. The five questionnaire surveys conducted between 2015 and 2019 included four cohort surveys and a final survey where respondents were recruited from the first four surveys. The initial questionnaire surveys were conducted in 2015, 2016, 2017 and 2018. These surveys recruited households in California that purchased a PEV between 2012 and 2018. The California Air Resources Board helped in recruitment by sending survey invites to households that applied for a California Clean Vehicle Rebate. The final fifth survey was conducted in December 2019. Households that indicated willingness to participate in future studies at the end of the first survey were sent an email inviting them to take the final survey.

The sample is potentially biased. First, the initial recruitment using rebate recipients omits PEV owners who did not apply for a rebate due to being unaware of it or because they are ineligible. Second, the resurvey asked respondents of the initial surveys to participate in additional data collection. This could bias the sample towards households that are interested in sharing their experiences with electric vehicles. This sample bias could mean we over sampled those who continued PEV ownership, and under sampled those who discontinued ownership. The latter may be less inclined to take a survey on a technology they no longer own. This could mean the results on the number of PEV owners who discontinued ownership are not representative of the entire California market. Nevertheless, the results highlight the issue and reveal what factors are correlated with discontinuance.

The first four surveys were mostly concerned with understanding PEV adopters in California[46], their charging behaviour[47] and the impact of incentives on the decision to purchase a PEV[45]. The surveys contained the following sections:

- Household information including number of vehicles in the household, number of people in the household, age and gender of household members, household income, home type (for example, single-family home or multi-unit dwelling), home ownership.
- Information on household vehicles including make, model, year of purchase and odometer readings.
- Electric vehicle charging behaviour, including location of charging (for example, home, work or public charging).
- Travel behaviour questions, including home and work locations, which are used to determine commute distance and information on long-distance trips.
- The importance of incentives in the decision to purchase a PEV, including the US federal tax credit, California clean vehicle rebate, high occupancy vehicle lane access and other local incentives (for example, from utilities).

The final survey contained the same sections as previous surveys but added the following sections that were designed to help understand subsequent purchase behaviour of PEV owners. These included:

- Questions on satisfaction with vehicle attributes for their previously owned PEV in the following areas: safety, comfort, refuelling/recharging costs, performance, environmental impacts, vehicle purchase price (including rebates, discounts and so on), reliability, electric driving range, convenience of charging and driving assistance features.

The final survey was sent to 14,128 households that had previously participated in one of the four original surveys. Of these, 4,925 started the survey, and 4,167 completed it. Households that have not made an ownership decision on their original PEV are not included in the study. This leaves 1,842 respondents who have made a decision regarding their original PEV and therefore a decision to continue or discontinue PEV ownership. Discontinuance in this sample is 20.6% (356 households), whereas 79.4% (1,371 households) continue to own a PEV. Of those that continued with PEV ownership, 245 purchased their PEV at the end of the lease period and 1,213 now own a different PEV. The 384 households that discontinued PEV ownership own no plug-in vehicles in their household and own only conventionally fuelled vehicles.

Statistical analysis. To explore descriptive data, we compared responses to questions based on whether respondents continued or discontinued PEV ownership using X^2 for discrete data and t-tests for continuous data. Pearson's X^2 compares the distributions of frequencies in categorical data, it tests a null hypothesis of there being no difference in the distributions. We used a two-sample student's t-test to compare continuous data. The t-test is used to test the null hypothesis of there being no difference in the means of the two populations (those that continued and discontinued PEV ownership). We used a 5% (<0.05) level to reject the null hypothesis for both X^2 and student's t-test. We used binary logistic regression to model factors related to discontinuance. We used this to draw our conclusions, rather than X^2 and student's t-tests, as it allowed us to control for additional explanatory variables rather than investigating them in isolation.

As the decision to continue or discontinue PEV ownership is a binary outcome we used a binary logit model to investigate which variables are correlated with discontinuance and use odds ratios to measure the effect of these variables on discontinuance. We do not seek to predict discontinuance in the entire population of California PEV owners, rather we seek understand why discontinuance has occurred using responses to the questionnaire survey. We estimated two models to understand discontinuance: one for BEVs only and one for PHEVs only. We estimated separate models for BEVs and PHEVs because the vehicles are different in key areas, most notably their driving range and refuelling/recharging requirements. This allows us to see if reasons for discontinuance of a BEV or a PHEV diverge.

The models included socio-demographic variables that are commonly correlated with PEV adoption or adoption intention[29,46]. We originally intended to include lifestyle variables in the model, as studies show attitudes and lifestyles (for example, pro-technology attitudes), not just socio-demographic variables, are correlated with interest in PEVs. However, as these questions were recorded post decision to continue or discontinue PEV ownership it is plausible that this variable could be endogenous; for example, deciding to continue with PEV ownership could lead to respondents indicating they have more positive attitudes to technology. For charging we included respondents's access to charging at home, including the level they have access to as a categorical variable (no charging, levels 1 or 2). For workplace charging we included a dummy variable for whether they have access to any charging at work (level 1, level 2, DCFC). For public charging we included a dummy variable for whether respondents have used level 1, level 2 or DCFC charging. We included variables on how satisfied consumers were with their PEV across various attributes. Vehicle attributes are common barriers to adoption (for example, range)[5,25–29,36–41]. The year of PEV adoption is included as past studies have identified differences in PEV buyers's response to incentives and differences in their socio-demographic profile by year of PEV purchase[45,46]. Early buyers of PEVs are more likely to be innovators compared with later buyers, which may have a relationship with interest in continuing PEV adoption. The models contained the following variables:

- Socio-demographic variables: age of survey taker, gender (1 male, 0 other) of survey taker, highest level of education of survey taker, vehicle ownership (1 lease, 0 other), number of people in the household, home type (1 detached, 0 other).
- Charging variables: a categorical variable for whether respondents had charging at home (no charging, level 1, level 2), whether respondents have charging at work (1 yes, 0 no), whether respondents use public level 1, level 2 or DCFC (1 yes, 0 no), recorded during the early phase of their PEV ownership. This variable is taken from responses to the first survey respondents took, in which PEV owners had owned their vehicle for a median of 10 months and mean of 13 months (compared with 36 and 41 months in the second survey that they took).
- Travel variables: commute distance, number of trips over 200 miles in the past 12 months.
- Household vehicle variables: efficiency of the second vehicle in the household (in Environmental Protection Agency (EPA) MPG), BEV (or PHEV) EPA electric driving range, number of vehicles in the household.
- Respondent satisfaction with the following attributes of their PEV: safety, vehicle purchase price, reliability, convenience of charging, refuelling/recharging costs and electric driving range.
- Year that the PEV was purchased.

We originally ran two models for PHEVs and two for BEVs. The separate models included a measure of EV driving range and a measure of respondents' satisfaction with EV driving range. Separate models were used as these variables were closely related. In these models neither EV range nor satisfaction with EV range were correlated with discontinuance. We therefore only present the models with EV range in the paper. We had hypothesised that a change in home type or access to charging at home could be a reason for discontinuance. We found that of those that discontinued ownership 82% experienced no change in their home type, 13% moved from an apartment or condo to a house, and 5% moved from a house to an apartment or condo. Of those who changed house type more moved to a home type associated with having charging at home, than those who moved to a house type associated with less charging access. We also asked respondents whether they discontinued ownership due to a change in charging access at home. Only 2% of those who discontinued ownership indicated this. For these reasons we use home type and access to charging at home in the models.

We checked for multicollinearity using the variance inflation factor, we excluded variables with a variance inflation factor of greater than three; note this is lower than in linear models since logistic regression results are more sensitive to multicollinearity. We exclude the following: annual vehicle miles travelled, as it is correlated with commute distance; five of the ten vehicle-satisfaction measures (satisfaction with comfort, performance, environmental impacts and driving assistance features are excluded); and home ownership, as it is correlated with home type. We exclude satisfaction with electric driving range and use a measure of actual driving range in the models (using EPA ranges) to account for potential endogeneity issues. Finally, to detect observations that may have a large influence on the model and identify outliers we checked deviance residuals and studentized residual. This resulted in removing five observations from the PHEV model and three from the BEV model.

Ethics and consent. The University of California, Davis Institutional Review Board (IRB) Administration granted approval of this study. The study followed all relevant ethical regulations in the study of human subjects for social research. All participants consented to participating in the questionnaire survey.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The questionnaire survey data used in this study can be obtained from The Dryad Digital Repository: https://doi.org/10.25338/B8WS6R. More information on the data, the variables included, and a description of each variable are available in DRYAD.

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Author contributions

S.H. and G.T. were responsible for study design and conception, performed data collection, drafted and revised the manuscript, and approved the final version of the manuscript. S.H. performed the analysis.

Competing interests

The authors declare no competing interests.

Additional information

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Software and code

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Data collection	Data collection was via Lime Survey
Data analysis	JMP Pro 15

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Study description	The data in this study is questionnaire survey data. The data comes from five questionnaire surveys conducted between 2015 and 2019. The first four are cohort surveys and a final survey where respondents are recruited form the first four surveys. The final survey was sent to 14,128 household who had previously participated in one of the four original surveys. Of these, 4925 started the survey, and 4167 completed it. This study uses data from 1727 respondents who have made a purchase decision regarding their original electric vehicle.
Research sample	Plug-in electric vehicle buyers in California recruited from the California Clean Vehicle Rebate Project for the cohort surveys. Respondents for this study are recruited from cohort survey respondents who indicated they are willing to participate in future studies and provided an email address. The sample is weighted to be representative of the electric vehicle market in California. This sample was chosen since California is the largest PEV market in the US.
Sampling strategy	The sample was a convenience sample using a database of electric vehicle buyers we had previously surveyed (in the 4 cohort surveys). The aim of sampling was to achieve a margin or error of less than 5% at a 95% confidence level. Given 695,582 electric vehicle buyers in California our sample gives us close to a 2% margin of error at a 95% confidence level.
Data collection	Lime Survey online questionnaire survey
Timing	1st cohort survey April-June 2015, 2nd cohort survey June-September 2016, 3rd cohort survey May-September 2017, 4th cohort survey July-November 2018. Final resurvey of respondents in all cohorts: November and December 2019
Data exclusions	Households who still own their original PEV are not included in the study since their attitudes, preferences, demographics, etc. may or may not be representative of a household who will continue or discontinue electric vehicle ownership. This is explicitly mentioned in the manuscript. This leaves 1842 responses for our study.
Non-participation	No survey respondents declined to participate in the survey post participation. The survey response rate was 29.5%.
Randomization	n/a

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Methods

n/a	Involved in the study
☒	☐ ChIP-seq
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☒	☐ MRI-based neuroimaging

Human research participants

Policy information about studies involving human research participants

Population characteristics	See above
Recruitment	Cohort survey respondents were recruited from the California Air Resources Board database of Clean Vehicle Rebate Project participants, they were contacted via email address. Resurvey respondents were contacted by UC Davis using email addresses reported in their originla survey response.

Ethics oversight	UC Davis IRB Administration (study was given exempt status)

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