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Factors Affecting Demand for Plug-in Charging Infrastructure: An Analysis of Plug-in Electric Vehicle Commuters

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Factors Affecting Demand for Plug-in Charging Infrastructure: An Analysis of Plug-in Electric Vehicle Commuters

A Research Report from the University of California Institute of Transportation Studies

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16. Abstract

The public sector and the private sector, which includes automakers and charging network companies, are increasingly investing in building charging infrastructure to encourage the adoption and use of plug-in electric vehicles (PEVs) and to ensure that current facilities are not congested. However, building infrastructure is costly and, as with road congestion, when there is significant uptake of PEVs, we may not be able to "build out of congestion." We modelled the choice of charging location that more than 3000 PEV drivers make when given the options of home, work, and public locations. Our study focused on understanding the importance of factors driving demand such as: the cost of charging, driver characteristics, access to charging infrastructure, and vehicle characteristics. We found that differences in the cost of charging play an important role in the demand for charging location. PEV drivers tend to substitute workplace charging for home charging when they pay a higher electricity rate at home, more so when the former is free. Additionally, socio-demographic factors like dwelling type and gender, as well as vehicle technology factors like electric range, influence the choice of charging location.

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Factors Affecting Demand for Plug-in Charging Infrastructure: An Analysis of Plug-in Electric Vehicle Commuters

UNIVERSITY OF CALIFORNIA INSTITUTE OF TRANSPORTATION STUDIES

January 2020

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Executive Summary

The public sector and the private sector, which includes automakers and charging network companies, are increasingly investing in building charging infrastructure to encourage the adoption and use of plug-in electric vehicles (PEVs) and to ensure that current facilities are not congested. However, building infrastructure is costly and, as with road congestion, when there is significant uptake of PEVs, we may not be able to "build out of congestion." We modelled the choice of charging location that more than 3000 PEV drivers make when given the options of home, work, and public locations. Our study focused on understanding the importance of factors driving demand such as: the cost of charging, driver characteristics, access to charging infrastructure, and vehicle characteristics. We found that differences in the cost of charging play an important role in the demand for charging location. PEV drivers tend to substitute workplace charging for home charging when they pay a higher electricity rate at home, more so when the former is free. Additionally, socio-demographic factors like dwelling type and gender, as well as vehicle technology factors like electric range, influence the choice of charging location.

Introduction

Consumers are increasingly embracing battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) (collectively referred to as plug-in electric vehicles [PEVs]) as an alternative to internal combustion engine vehicles (ICEVs). In response, utilities, government agencies, automakers, and charging network companies are investing in building charging infrastructure to encourage further adoption of PEVs and to ensure that current facilities are not congested. Public infrastructure is undoubtedly required to encourage adoption and address issues like cost of home infrastructure and range limitation. However, intelligent deployment of charging infrastructure during the anticipated increased uptake of BEVs and PHEVs is one of the most pressing challenges for any local government. It is difficult to quantify the optimal amount and location of charging infrastructure required, including its impact on BEV adoption and usage. Moreover, it is very expensive to build public infrastructure. While the at-home installation cost of a Level 2 charger can be as low as $400, in a public location like a shopping mall or parking garage the cost can be as high as $6000.[1]

As the market for PEVs evolves, the optimal extent of charging infrastructure will increasingly depend on factors driving demand, including: the electric range of the newer vehicles, the number of consumers with access to charging facilities at home (often dictated by dwelling type), and the pricing schemes adopted for home, workplace, and public charging. Electricity price at home can be expected to play a major role in determining home versus non-home charging demand, particularly for routine trips. If electricity rates are too high, PEV owners may substitute home charging with workplace or public charging. Understanding the impact of these behavioral and economic factors on the demand-side of the vehicle charging market is not only important for planning future infrastructure investment but also for evaluating the impact of EV charging demands and electricity consumption on the power grid.

This study models the choice of charging location of existing BEV and PHEV drivers in California as a function of the factors mentioned above and considers the policy implications of the driving factors. While most studies on this topic have modeled the demand for infrastructure using simulation methods, stated preference data, or a small number of instrumented PEVs, our study leverages the revealed behavior data of 3,200 PEV owners to determine which behavioral and economic factors drive charging behavior. The goal is to provide insights for policymakers that can be used when developing charging infrastructure plans, so that they might yield improved benefits.

[1] A Level 1 charger is the usual 120-volt power plug, which can be used for home charging at a rate of 1.4-1.9 kW (4-6 mi/hour). A Level 2 charger can be installed at home but also in public locations, and is the most common type of charger. It usually provides power at the rate of 6.6 kW (20 mi/hour). DC Fast chargers (DCFCs) are only installed in non-home locations. DCFC is the fastest and also the costliest option, offering power at the rate of 50 kW (50 mi/hour). The installation cost of DCFC ranges between $10,000 and $40,000 (source: https://afdc.energy.gov/files/u/publication/evse_cost_report_2015.pdf).

Literature Review

Travel patterns and vehicle driving range primarily impact PEV owners' overall need for charging. Multiple studies on electric vehicle charging behavior have shown that PEV drivers prefer to fulfill these charging needs at home or work rather than at public charging stations [1–4]. Overall, 50% to 80% of charging events for PEVs occur at home [5,6]. Workplace or commute location charging is the next most used option [1,7,8], with approximately 15-20% of charging events occurring at the workplace for BEV owners. Only about 5% of charging events occur at publicly accessible locations.

PEV drivers usually consider the various pros and cons of charging at each of the locations available to them. Overnight home charging is favored mainly because of easy access and flexibility in terms of charging schedule [9–11]. On the other hand, charging at work can be preferred when it is free, even if the number of spots is limited or they are congested [7]. Public charging stations, when paid, can be more expensive than home or work, and using them usually requires careful planning. However, they offer other advantages, such as the privilege of a reserved parking spot at locations associated with usual activity patterns (shopping centers, hotels, transport hubs, and highway corridors).

In general, depending on the vehicle charging needs of an individual, there is a tradeoff between monetary cost and convenience when choosing a charging location. The cost of charging at home can be affected by the offerings of local utilities, such as time-of-use (TOU) electricity tariffs or special EV rate plans. A 2016 study in California found that these tariffs, which provide cheaper electricity during the nighttime, encourage consumers to charge their vehicles at home overnight [11]. Photovoltaic rooftop solar systems are a complementary technology that can be adopted by households to reduce the overall cost of charging their PEVs [9,12,13]. Although special rate plans and/or solar systems allow households to lower the monetary cost of home charging, they are not free. In cases where PEV owners have access to free workplace charging, they frequently trade off the convenience of home charging for the zero cost of refueling at work. This substitution behavior could make this workplace infrastructure offering financially unsustainable in the long run, as well as cause negative consequences like charge point congestion [1,7,14].

According to Nicholas and Tal, a significant motivator for charging at work was employers offering free charging [7]. They also found that, while PEV drivers who use the free infrastructure are mostly those who could complete their daily drive without recharging, BEV drivers who would actually need to charge at work to complete their daily trip might not risk using their BEV for the work commute if they perceive charge point congestion to be an issue [7,10]. Prior research on public and workplace charging behavior suggests that dynamic pricing policies that properly incorporate the cost of vehicle parking could be used to ensure more efficient use of charging infrastructure. Charging spots could be freed up for PEV users who are more dependent on non-home charging infrastructure (e.g., apartment dwellers and renters) as well as allow providers to run a sustainable business model [15–18]. Therefore, policymakers need to develop and implement pricing strategies and incentives that can use the tradeoff between monetary cost and convenience in an individual's decision process to limit shifting of home charging to workplace or public charging.

In the last 5–6 years, the number of PEVs in the US has grown from approximately 120,000 to more than 1 million. Nonetheless, PEVs still face several significant barriers to wider adoption, including high purchase costs, limited charging infrastructure, and long charging times. The positive effect of charging infrastructure availability on PEV adoption is well-documented in the literature [3,19–21]. However, determining the optimal amount of charging infrastructure required to support PEV market growth is still a challenge. Most of the literature so far has focused on identifying the location of charging events and predicting the optimal supply of public infrastructure based on observed travel patterns of ICEV drivers, or by simulating possible driving scenarios for PEV owners [22,23]. Though there has been some focus on how the strategic provision of public charging can improve BEV feasibility [10,24–27], the majority of these studies do not account for the behavioral and economic factors that might drive charging behavior. It is important to understand the determinants of individual-level behavior when developing models to assess the vehicle charging needs of PEV drivers and their response to varied charging service propositions [28]. Due to limited data on revealed preferences for PEV use and charging behavior, many studies that do consider the socio-economic factors affecting PEV owners' choices of charging location are based on stated preference data or on data from a small number of instrumented PEVs [6,9,29–31]. In contrast, in this study we analyzed revealed preference data on choice of charging location from more than 3000 PEV drivers to understand how economic, socio-economic, and demographic factors might influence the choice of charging location. Using the same survey data as in this study, Lee et al. [8] grouped PEV drivers by their use of charging locations and analyzed the characteristics of PEV owners in each group. Here, we extend that study to provide a more detailed analysis of the drivers of demand for charging locations by estimating discrete choice models and examining their marginal effects.

Data and Methods

Descriptive Analysis of Charging Behavior Data

The data in this study were drawn from a cohort survey of PEV owners in California, conducted in 2015, 2016, and 2017 by the Plug-in Hybrid & Electric Vehicle (PH&EV) Research Center, part of the Institute of Transportation Studies at the University of California, Davis. Participants who owned at least one PEV were recruited using a random sampling procedure from a list of Clean Vehicle Rebate Program (CVRP) recipients and Department of Motor Vehicles (DMV) registration data. The response rate for the completed survey was about 15%. For this study, we used a subsample of 7,979 households who owned or leased a PEV and had charged it at least once during the period when we collected charging history. There were six categories of questions in the survey: travel behavior, commute characteristics, vehicle type, vehicle characteristics, response to PEV incentives, and charging behavior.

For charging behavior, respondents were asked to provide 7 consecutive days of charging choices that focused on location decisions. For each day, each respondent recorded whether he/she charged the PEV at each of the following eight combinations of types and locations of chargers: Level 1 home, Level 2 home, Level 1 work, Level 2 work, DC Fast charger work, Level 1 non-work, Level 2 non-work, DC Fast charger non-work. For each day, a respondent indicated usage of each of the eight options with a “Yes” or “No.” If the respondent did not charge on a particular day, we observed a “No” for all the options in the data. In a separate set of questions, the survey established which of the options were available to the respondent, regardless of whether or not they were ever used.

The primary objective of the study was to identify and quantify the importance of factors that influence the charging location choices of BEV and PHEV owners. To capture all the possible location options, we focused on the charging behavior of a sub-group of 3,201 PEV drivers who used their vehicle for commuting and had access to charging infrastructure at the commute destination (henceforth referred to as “work”). We considered three types of locations: home, work, and public. (Although the chargers used for charging while at work might actually be public chargers, the charging location is denoted as “work”. The “public” location indicates that charging occurred at a non-work time and location.) We excluded from our analysis data on the non-chargers, non-commuters, and commuters with no access to workplace charging. Finally, we considered observations only from the five weekdays—i.e., when charging was available at all locations.

Error! Reference source not found. gives the distribution of charging locations on weekdays for BEV and PHEV commuters. Figure 1 shows the distribution of charging patterns among noncommuters and commuters without charging available at the workplace. We aggregate the choices over all types of chargers (i.e., Level 1, Level 2 and DC Fast Charger) during a charging event and only consider the choice of location. Among BEV and PHEV commuters, home is the most frequent charging location. Among non-home locations, BEV commuters tend to use workplace charging and public chargers more than PHEV commuters. While the latter can use the internal combustion engine in their vehicles to complete their commute, BEV drivers do not have this flexibility. This could cause BEV drivers to use workplace chargers more frequently. In the case of public chargers, the inability of PHEV drivers to use DC Fast charging points may be a factor in their lower use of these charging locations. Though BEV drivers are plugging in more at work and public locations, the number of non-charging days is lower among PHEV drivers, and conversely their use of multiple locations is higher. This indicates that PHEV drivers in this specific sample are generally making charging decisions that are consistent with a preference for using electric miles rather than gasoline miles. One possible reason is to minimize the driving cost of their commute.

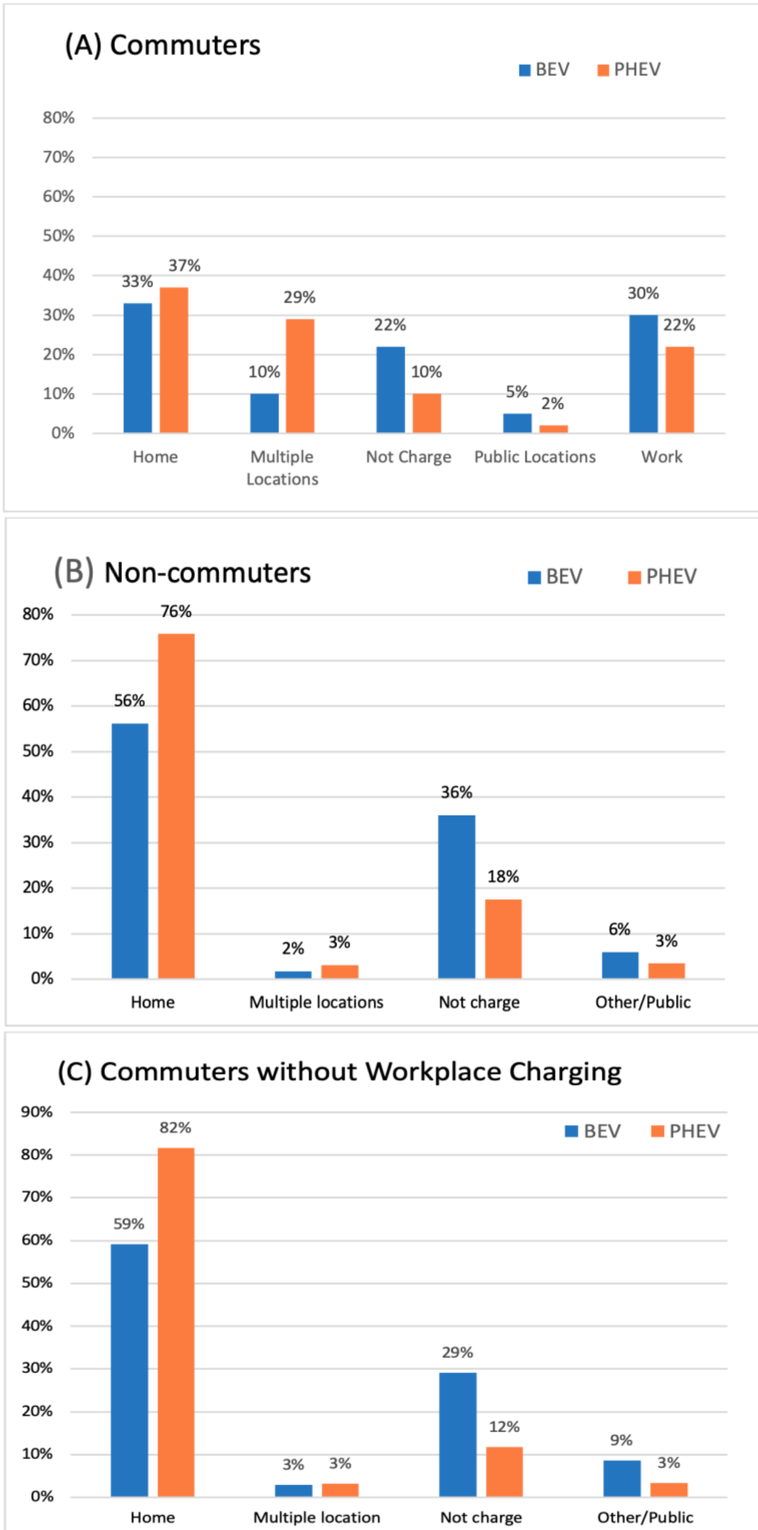

Figure 1. Distribution of weekday charging location choice of BEV and PHEV (A) commuters, (B) noncommuters, and (C) commuters without workplace charging available.

In comparison to the PEV commuters (Figure 1), both the non-commuters and those with no workplace charging display a significantly higher proportion of home charging events. However, the number of non-charging days is higher among these two groups than PEV commuters with non-commuters having the highest percentage of non-charging days. The percentage of public charging events is also slightly higher in comparison to PEV commuters.

Model Description

Demand drivers for charging infrastructure

To estimate the importance of factors that affect a PEV owner's charging-related decisions, we developed a discrete choice model to explain the weekday charging events reported by the survey respondents. Responses have been simplified so that, for each weekday, respondents are viewed as making a choice from among the following five options: charge at home, charge at work, charge at a public location, charge at multiple locations, or, do not charge at all. Weekday charging behavior is defined based on the day the respondent reported that a charging event was initiated. For example, when the respondent said the car was plugged-in at home on Friday, we consider that as Friday's charging behavior, even if the charging might have started at midnight.

Utility specifications for the discrete choice model are based on what theory and the previous literature suggests would affect PEV owners' preferences for the charging options defined above—see the conceptual framework in Figure 2. To illustrate, we first consider aspects of two major factors that would affect the choice of where to charge (home, work, or public/other), given that plugging-in has been deemed necessary: monetary costs of charging, and convenience/access to charging. Because PEV commuters in our sample have access to both home and workplace charging, the primary issue is the tradeoff between cost and convenience. For home charging, both factors can be affected by housing type, with major differences among detached homes, condominiums, and apartments [32]. For example, homes with garages or other dedicated parking are more convenient, and installing L2 chargers is more feasible. Costs can vary for home versus workplace charging: alternative electricity rate plans and rooftop solar can lower the cost of home charging for many respondents, but many respondents might also be able to charge for free while at work.

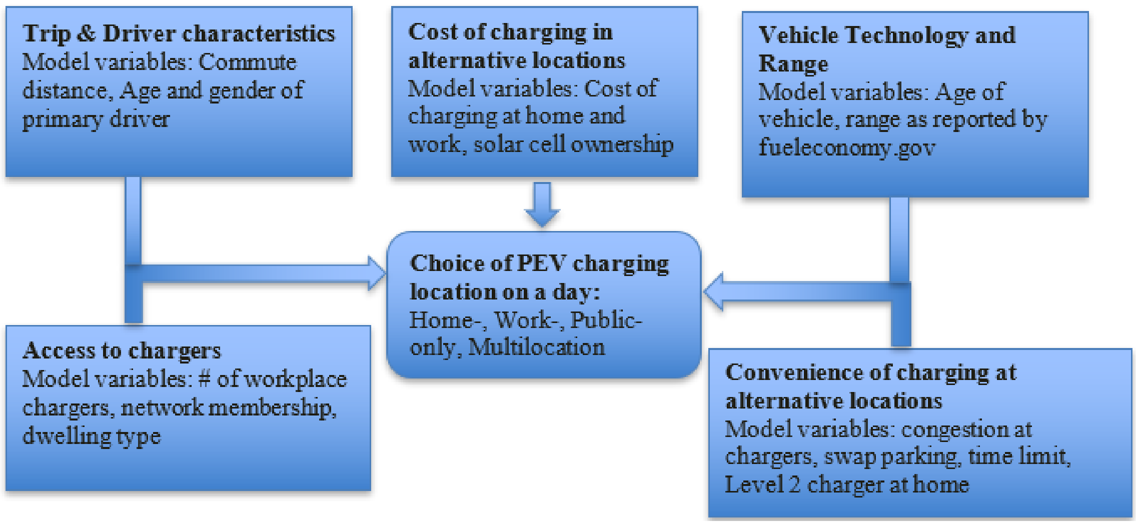

Figure 2. Conceptual framework

These effects were evident in our exploratory data analysis of aggregate responses, where charging events for BEV owners in detached homes occur at home on 37% of the weekdays, versus only 12% for apartment dwellers. This is consistent with the hypothesis related to convenience and control over parking, including the feasibility of installing Level 2 chargers. BEV owners living in condominiums and apartments rely more on workplace and public charging infrastructure. The pattern is similar for PHEV owners. The percentage of workplace charging events on weekdays is 45% for apartment dwellers and 18% for those residing in detached homes.

As noted, access to alternative electricity rates at home can be expected to play a role in the location choice decision. Among the survey respondents, BEV owners who have enrolled in special rate plans (EV rates) are twice as likely to charge at home than those with a flat rate plan. Though we observe a similar pattern among PHEV owners, the difference in the percentage of charging events under flat rate versus EV rate is higher for BEV owners than PHEV owners. Sensitivity to cost is also observed for workplace charging. The percentage of workplace charging events is approximately 44% for BEV owners when charging is free but only 15% when paid. In an experimental set up with different pricing scenarios, Shampanier et al. (2007) showed that when people have a choice between two products, one being free, they favor the free product because “zero price” not only conveys the literal fact of “no cost,” but there is additional utility (added value) due to the free versus non-free distinction [33]. They explain their result by demonstrating empirically that a higher positive feeling arises when people face free offers, and this positive feeling affects their choices. This zero-price effect is not just confined to the choice of products with similar attributes but also applies in multi-component contexts [34]. In our data on charging location choices, even though home charging may be more convenient, the demand for workplace charging increases dramatically when it is free. With this as background, we provide a framework for estimating how these and other factors affect the observed choices for charging options.

Choice model of charging behavior

PEV owners are assumed to make choices consistent with Random Utility Maximization (RUM) [35]. It is assumed that individual *i'*s utility for choice alternative *j* (U_{ij}) can be modeled as:

$$U_{ij} = \alpha_j + \beta' x_{ij} + \varepsilon_{ij}^*, \tag{1}$$

where x_{ij} is a vector of explanatory variables for alternative *j* that can be different for each individual (*i*), β is a vector of parameters that represent average preferences in the population, ε_{ij}^* is a random disturbance term that includes a variety of unobserved effects, and α_j is a parameter for the mean of such effects for alternative j. The respondent chooses the alternative for which U_{ij} is largest.

More general versions of this model assume that each individual has a different β (unobserved taste variation for *x*'s), and a unique, idiosyncratic unobserved preference difference for each alternative. These heterogeneous preferences are assumed to follow some distribution, leading to, e.g., random coefficient models. In equation (1) above, these effects are absorbed into the disturbance term. In the case of repeated choices from the same individual, these unobserved effects cause responses to be correlated, violating the independence assumptions typically made in model estimation.

For the choice models used here, we adopted highly parsimonious versions of equation (1) that capture potentially important correlations across choices, while also maintaining most of the other simplifying assumptions associated with the standard conditional logit model. Specifically, we assume no taste variation for the *x*'s (i.e., β is a vector of fixed coefficients), but allow for systematic, unobserved, idiosyncratic preference differences for the specific "labeled" alternatives (e.g., home, work, etc.) to be represented as individual-specific error components. In this error component logit (ECL) model, the utility derived from alternative *j* on a particular day *d* (equation (1)) takes the form:

$$U_{ij}^d = \alpha_j + \beta' x_{ij} + \theta_j' E_{ij} + \varepsilon_{ij}^d, \text{ for } j = \{\text{not charge, home, work, public, multi-location}\}, \tag{2}$$

where the vector of unobserved error components E_{ij} is assumed to follow a standard normal distribution, and ε_{ij}^d are IID Gumbel. Let y_{id} be the observed choice of individual *i* on day *d*. The conditional probability that y_{id} = *j* is given by:

$$P(y_{id} = j | E_{i1}, E_{i2}, \dots E_{in}) = \frac{\exp(\alpha_j + \beta' x_{ij} + \theta'_j E_{ij})}{\sum_{q=1}^{J} \exp(\alpha_q + \beta' x_{iq} + \theta'_q E_{iq})} \tag{3}$$

Computing the unconditional probability requires integration over the error components. The final model specifications require additional restrictions on equation (2) based on behavioral considerations and to ensure identification of parameters. The base category is the decision to not charge the vehicle on a weekday *d,* so that *j* = 0 denotes "not charge." Explanatory variables for "not charge" are those that capture the "charge versus don't charge" aspect of decision making. Explanatory variables for the other options are location specific, capturing the relative preference for competing locations given that charging occurs. (Details on these are provided next.) Finally, based on theoretical considerations combined with testing, the final model specifications use three error components placed on: (i) the option to charge (versus not charge) that includes charging at home, work, public, or in multiple locations (E_{i1}), (ii) the option to charge in a single location (conditional on the decision to charge), which includes home, work, or public (E_{i2}), and (iii) the option to charge in a non-home location (work or public) (E_{i3}), conditional on the decision to charge in a single location. Analogous to a nested logit model, this structure captures the effect of unobserved common factors (e.g., individual-level heterogeneity) shared by alternatives in a particular nest as defined by the error components [36], which yields correlation across alternatives. Below, Figure 3 offers a graphical representation of the model structure estimated here.

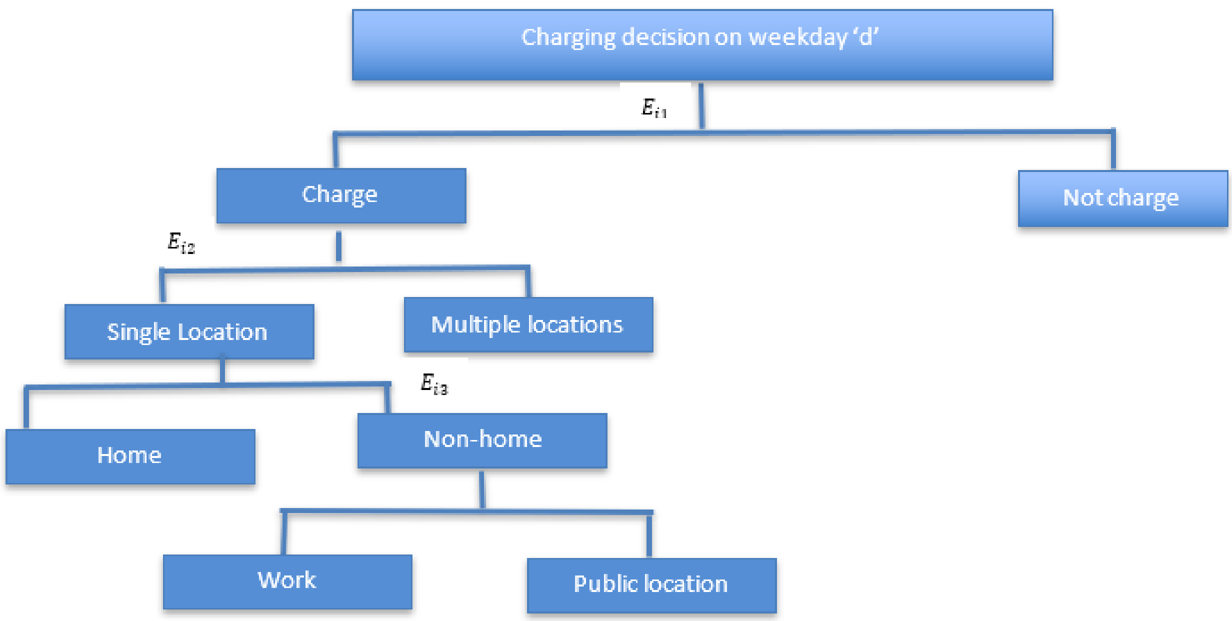

Figure 3. Error component logit model structure

For BEVs, E_{i1} can represent a (unobserved) systematic need for charging or other idiosyncratic effects that result in the decision to plug-in the vehicle on a particular day, and which vary from individual to individual. Similarly, E_{i2} can represent an unobserved preference for habitually plugging-in at the same location as a matter of routine, in contrast to being more "flexible" and opportunistic with regard to plugging-in. Finally, E_{i3} may represent any unobserved, systematic factors that might cause an individual to prefer plugging in their vehicle at non-home locations (like workplace and public locations) versus at home (e.g., inconvenience from moving vehicles around in multivehicle families). This allows the model to capture possible correlation between the non-home location options versus the at-home option. Similar effects would also occur for PHEVs (but probably for different reasons). We conclude with additional details about the data and explanatory variables.

The explanatory variables for the vector x_{ij} are summarized in Table 1. In the ideal case, a specific electricity cost (in cents/kWh) would be available for each location, so that a single (generic) preference parameter for electricity cost could be estimated. However, this type of detailed data is not available, so most effects rely on dummy variables to capture location-specific factors. The model has essentially no generic attributes, i.e., all effects are alternative specific. For example, access to a Level 2 charger at home along with factors like solar cell ownership are included in the utility of the "home" option. In addition, demographic characteristics like dwelling type and the gender and age of the primary driver are used to define the utility from "home charging." Workplace charging characteristics are used to define the utility derived from the choice of "work" as a charging location. Network membership along with a dummy indicating if the vehicle is a Tesla are included in the utility function of the "public location" alternative for BEV owners. For PHEV drivers, we consider network membership and the electric range of the vehicle. As the electric range of PHEVs increase, drivers may be incentivized to use the electric mode for longer commutes and use public chargers for the ability to do so.

Table 1. Explanatory Variable for the Choice Model

Category of Explanatory Variable	**Explanatory Variables**
Characteristics of household charging infrastructure	• Electricity rate at home (cents/kWh) • Availability of Level 2 chargers at home
Other household characteristics	• Solar cell ownership (dummy) • Dwelling type (categorical): single detached unit, condominiums, multi-unit dwellings • Membership of charging station networks (dummy)
Characteristics of workplace charging infrastructure	• If the respondent faces congestion at workplace charge points (dummy) • If they must swap parking spots once charging is done (dummy) • If there is any time limit for charging (dummy) • Number of chargers at the respondent's workplace or commute location • If charging at the workplace is free (dummy)
PEV characteristics	• Age of the vehicle • Range of the PEV (electric range if it is a PHEV) • Tesla or not (for the choice model of BEV owners)
Trip and primary driver characteristics	• Commute distance • Gender • Age

As noted previously, variables for the "no charge" alternative are associated with the overall need for charging. For BEV owners, utility from the "not-charge" alternative is primarily a function of commute distance and range. We consider the ratio of commute distance to range ("share of range utilized") to capture the need to charge the vehicle to complete commute trips. Because of the relatively short electric range of PHEVs, this measure would not serve the same purpose, so the corresponding utility for the "not-charge" option is instead a function of commute distance. In both models, dummy variables for the types of rate plans used at home (TOU and EV rates) are used as proxies for effects related to overall PEV usage. Adoption of a generic TOU rate could indicate a response to overall higher than average standard electricity rates in the respondent's region, and therefore less overall charging on average. Adoption of a special EV rate could be a sign of engagement with the process of PEV use, awareness of the potential cost savings from the operation of the vehicle, and a higher than average charging rate.

The multi-location option represents a more complex behavioral pattern that is difficult to associate with specific explanatory variables. Its utility could be affected by a variety of unobservable effects like the need to charge or the behavioral pattern of a PEV owner, captured by the error component E_{i1} in the model for BEV and PHEV commuters. In addition to the error component, the BEV model includes only an alternative-specific constant (and no other explanatory variables) for the multi-location option. However, the PHEV model includes electric range as an explanatory variable for the multi-location option. It serves as an indicator of the reduced requirement for charging at, e.g., both home and work on any given day to ensure that the entire trip is performed using electric miles.

One important caveat for these models is the potential for endogeneity issues with some of the explanatory variables. For example, the electricity price at home is specifically affected by the choice of electricity rate plan, and for respondents who own detached homes, the presence of a Level 2 charger and rooftop solar may not be exogenous factors. They are actually choices that could depend on unobservable factors that are correlated with the respondent's choice to own a PEV, but these factors could also be correlated with charger behavior choices. Although these effects could possibly be addressed with a much more complex modeling approach, we have adopted the ECL approach here as a practical alternative. Nevertheless, parameter estimates for some of these factors should be interpreted with some caution.

For completeness, we provide additional details on how the home electricity rate variable was constructed. In the survey, we asked respondents to report the perceived cost of charging at home, and the perceived electric range of the vehicle. However, these could not be used as explanatory variables (for reasons to be discussed). For the cost of charging at home, instead of using the perceived cost data, we used information about the local utility provider, and the reported rate structure and usage of timers, to impute electricity rates households were likely to pay for charging their vehicle at home. This was required because 55% of the respondents did not state a perceived cost per kWh. Moreover, some PEV owners perceived an inflated cost of charging their vehicle at home, skewing the distribution of perceived cost to the right, including many levels that simply do not occur in reality. In the survey, 40% of the respondents said that they changed to a special EV rate, while an equal proportion of households were still on a flat-rate structure. Since more than 80% of the latter respondents resided in detached homes, in the imputation process, we assumed that households face tier 2 rates (higher tier rates) under a flat-rate structure. For the 44% who said they did not know the rate type, we assumed a flat-rate structure and tier 2 prices. We also estimated the choice models under an alternative scenario using tier 1 prices for the flat-rate option, and for those who did not know their rate type. There were no sign changes for the estimated effects, nor any noticeable differences in the marginal effects of the other factors, so the results are not included here.

Results

Logistic Regression Model Estimates

Table 2 gives estimation results for the ECL choice models. The coefficient estimates are grouped according to the alternative they are associated with.

Table 2. Coefficient Estimates from the Choice Model

		BEV Owners	PHEV Owners
Choice Alternative	**Variables**	**Model 1: with Commute Distance/Range (Standard Error)**	**Model 2: Main effects only (Standard Error)**
Not Charge	Commute distance (miles)	-	-0.073*** (0.002)
	Share of range utilized	-15.02*** (0.888)	-
	TOU rate (Base: Tiered rate) 1: if true	0.162 (0.268)	1.279*** (0.298)
	EV rate (Base: flat/Tiered rate)1: if true	-0.369* (0.193)	-0.897(0.288)
	Age of the PEV (in months) [a]	-6.176*** (1.549)	-4.025*** (1.240)
Home	Rate paid @ home (cents/kWh) [a]	-4.294*** (0.840)	-4.150 *** (1.482)
	Level 2 Charger @ home (1: if true)	2.326*** (0.142)	0.642*** (0.249)
	Solar at home (1: if true)	0.097 (0.143)	0.327 (0.270)
	Detached home (base: apartment)	1.013*** (0.263)	2.342*** (0.352)
	Condominium (base: apartment)	0.964*** (0.306)	2.420*** (0.426)
	Gender of primary driver (1: female)	0.515*** (0.153)	0.718***(0.243)
	Age of primary driver	0.006 (0.005)	0.019** (0.009)
Work	Charger congestion @ work (1: if true)	-0.049 (0.072)	-0.387*** (0.107)
	Swap parking @ work (1: if true)	1.336*** (0.071)	1.304*** (0.112)
	Time limit @ work (1: if true)	-0. 317*** (0.074)	-0.264** (0.106)
	Number of chargers @ work [a]	1.138*** (0.143)	5.303*** (0.498)
	Free workplace charging (1: if true)	1.693*** (0.070)	1.625*** (0.043)
Other	Network membership (1: if true)	0.902*** (0.087)	-0.669*** (0.200)
	Tesla owner (1: if true)	1.199*** (0.089)	-
	Electric range	-	0.017*** (0.003)
Multi-location	Electric range	-	-0.047*** (0.005)

		BEV Owners	PHEV Owners
Choice Alternative	**Variables**	**Model 1: with Commute Distance/Range (Standard Error)**	**Model 2: Main effects only (Standard Error)**
Error components	Decision to charge	2.553***(0.154)	3.958*** (0.210)
	Single location charging (Home, Work, or Other)	3.020***(0.112)	4.597*** (0.196)
	Non-home charging (Work and Other)	2.751***(0.126)	4.950*** (0.243)
Constants	Home	-3.342*** (0.464)	-0.786 (0.716)
	Work	-3.593*** (0. 273)	-2.358*** (0.422)
	Public location	-4.342*** (0.271)	-3.572*** (0.412)
	Multi-location charging	-3.893*** (0.274)	2.585 (0.353)
	Log-likelihood	-8399.814	-5601.125
	No. of observations	8,380	6,590

[a] the variables have been scaled by a factor of 100
*** 1%, ** 5%, * 10% level of significance

The estimated coefficients for the error components represent standard deviations of the normally distributed unobserved random effects. They are statistically significant, indicating that there are unobserved individual-level factors that affect the decision to charge, the choice of multiple locations versus other alternatives on any given day, and the choice of non-home locations over home. For the model with BEV owners, the coefficients of the other explanatory variables have the expected signs, although the coefficients for the TOU rate are subject to a variety of alternative interpretations. In terms of commute distance and need to charge, we observe that as the commute distance increases relative to the vehicle range, the probability of not charging on a given day decreases. This would be expected, since BEV owners are dependent solely on their battery for completing trips (unlike PHEV owners).

In the PHEV owner model, all coefficients have expected signs except the effect of network membership on choice of public location. We also observe that the effects of the PHEV's electric range on choice of charging in public locations versus multi-location charging have opposite signs. Unlike other PHEVs, BMW i3s (here with the range extender) have the capability of using the fast chargers in public locations and their owners may have access to free charging sessions at EVgo stations. This could be a reason for the positive effect of electric range on the choice of public locations. On the other hand, the negative effect of electric range on multi-location charging is consistent with the idea that higher electric range allows the PHEV owners to complete their daily commute in the electric mode with a single charge (as discussed earlier).

Considering the effect of sociodemographic characteristics, in both the models we observe that residents of detached homes and condominiums are more likely to charge at home than apartment dwellers. However, solar cell ownership does not have a significant effect on the choice of home charging. The results can be affected by the fact that we are analyzing weekday charging behavior of commuters and home charging induced by solar cell ownership may not be possible if the car is in the commute location for most of the day. Also, if the primary driver of the PEV is female, she is more likely to charge at home than at any other location. This gender-based behavioral difference could be due to security concerns. The potential difference in use of PEV charging infrastructure by male and female drivers needs to be investigated further. Nevertheless, these results have important policy implications in terms of planning the location of charging infrastructure and developing charging etiquettes.

Marginal Effects of Key Demand Drivers

Here, we use the results from the models to display marginal effects and probability outcomes focusing on the effect of some of the major demand drivers—infrastructure availability at home, workplace charging infrastructure characteristics, cost of charging at home, and vehicle range. The marginal effect of a continuous explanatory variable x_k is estimated as

$$\frac{\partial P_{ij}}{\partial x_{ik}} = P_{ij}(\beta_{jk} - \sum_{m=1}^{J-1} P_{im}\beta_{mk}). \quad (4)$$

For the discrete explanatory variables (e.g., dummy variables), the marginal effect is calculated by computing the average predicted probability when the discrete variable is set to 1 and then when set to 0. Table 3 gives the marginal effects of some key workplace, home, and public infrastructure characteristics and factors affecting access to these locations on the choice of charging location.

Table 3. Marginal Effects of Key Drivers of Choice of Charging Infrastructure

BEV Owners					
Variables	**Not Charge**	**Home**	**Work**	**Public**	**Multi-location**
Level 2 @ home	-0.044	0.147	-0.059	-0.020	-0.024
Electricity rate @ home	0.023	-0.084	0.036	0.010	0.014
Free workplace charging	-0.023	-0.046	0.099	-0.018	-0.012
Number of chargers @ work	-0.003	-0.006	0.013	-0.003	-0.001
Swap parking @ work	-0.016	-0.031	0.068	-0.013	-0.008
Time limit for charging @ work	0.002	0.005	-0.012	0.003	0.001
Network membership	-0.001	-0.003	-0.007	0.012	-0.001
Share of range utilized	-0.135	0.051	0.035	0.007	0.042
PHEV Owners					
Variables	**Not Charge**	**Home**	**Work**	**Public**	**Multi-location**
Level 2 @ home	-0.003	0.016	-0.006	-0.001	-0.007
Electricity rate @ home	0.011	-0.070	0.024	0.004	0.030
Free workplace charging	-0.006	-0.029	0.057	-0.009	-0.013
Number of chargers @ work	-0.003	-0.014	0.030	-0.005	-0.007
Swap parking @ work	-0.004	-0.020	0.040	-0.007	-0.009
Time limit for charging @ work	0.001	0.003	-0.007	0.002	0.001
Charge point congestion @ work	0.001	0.004	-0.009	0.002	0.002
Commute distance (miles)	-0.055	0.017	0.006	0.001	0.030

Note: Marginal effects are significant at 1% level.

Characteristics of workplace charging infrastructure like cost of charging and charging etiquette have strong marginal effects on the choice of charging location. Free workplace charging has a significant positive effect on a commuter's probability of choosing the workplace as the charging location. As we observe in Table 3, when workplace charging is free, on average the probability of choosing "workplace" goes up by 9.9 (5.7) percentage points for BEV (PHEV) drivers. On the other hand, the probability of home charging falls by 4.6 and 2.9 percentage points and public charging falls by 1.8 and 0.9 percentage points for BEV and PHEV drivers, respectively. This result conforms with the finding of Nicholas and Tal that free workplace charging may incentivize PEV owners to shift to workplace charging from other alternatives, primarily from home [7]. Along with free workplace charging, the number of chargers at the workplace has a positive impact and increases the probability of charging at work by 1.3 (3) percentage points for BEV (PHEV) drivers. Good parking etiquette, represented by swapping parking spaces at work, allows one charger to support more than one PEV throughout the day, thus increasing the availability of workplace chargers to PEV owners. This is consistent with the observed strong positive marginal effect of swapping parking places on the choice of workplace charging: the probability of workplace choice increases by 6.8 (4) percentage points for BEV

(PHEV) drivers. On the other hand, time limits on charging duration have a negative effect on the probability of workplace charging for both BEV and PHEV commuters, with the effect being stronger for the former. As we observe in Table 2, though charge point congestion does not have a significant effect on the probability of workplace charging for BEV drivers, it has a significant negative effect on the choice of PHEV commuters. This may be driven by the fact that unlike PHEV owners, BEV drivers are solely dependent on their battery to complete the commute trip. Therefore, even if BEV owners face congestion, it may not affect their choice of charging location on a particular day. In the case of PHEV drivers, congestion reduces the probability of choosing workplace charging on a particular day by 0.9 percentage points.

Among the household characteristics, access to Level 2 chargers at home affects the probability of home charging among both BEV and PHEV owners. The probability of charging at home increases and workplace or public charging probabilities decrease with the increased availability of Level 2 charging at home. We can hypothesize that the convenience of home charging and the higher charging needs of BEV drivers is driving the 14.7 percentage point rise in the probability of home charging, with a corresponding decrease in usage of other location options.

To have routine access to the widest possible variety of public charging stations, PEV owners must obtain memberships of charging networks like ChargePoint or EVgo. Table 3 shows that, all other factors held constant, if a BEV commuter has a membership with one of the charging networks, the probability of choosing a public charger increases by 1.2 percentage points. (However, recall our earlier caveat that some explanatory variables like this one are vulnerable to endogeneity effects.) We do not observe a significant effect of network membership on public location charging for PHEV owners.

Figure 4 and Figure 5 give a graphical representation of the effect of electricity price on the choice for BEV and PHEV owners, respectively. All else constant, on average, the probability of home charging is 8 percentage points lower if BEV owners face electricity costs of 40 cents/kWh compared to 20 cents/kWh. On the other hand, the probability of workplace charging is higher by 4 percentage points. However, the probability of no charging also increases by 4 percentage points as the electricity rate goes up. We can hypothesize that as the cost of vehicle charging at home goes up, people substitute home with workplace charging or use other vehicles in their household.

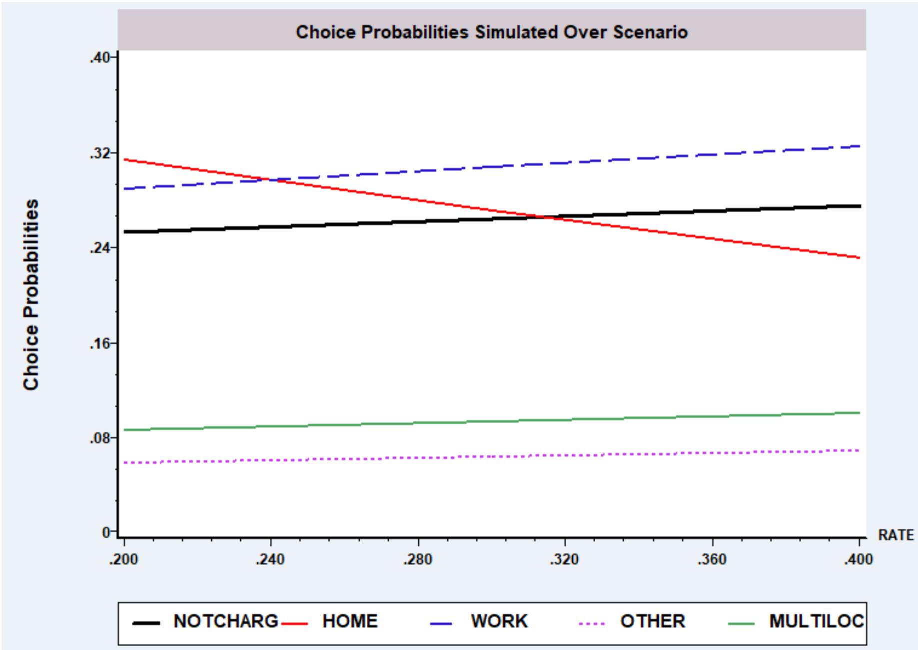

Figure 4. Predicted probability of choice of charging location by electricity rate ($/kWh) at home (BEV)

Among PHEV owners, the probability of home charging is on average lower by 7-8 percentage points when the electricity rate is 40 cents/kWh compared to when it is 20 cents/kWh. The share of workplace charging goes up by 2 percentage points and days when the vehicle is not charged rises by 1-2 percentage points.

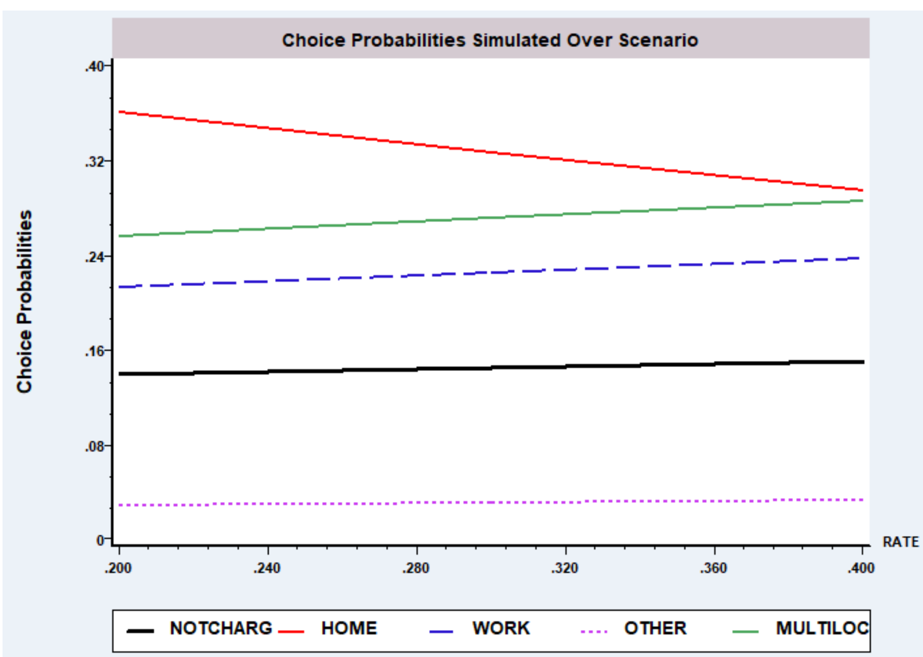

Figure 5. Predicted probability of choice of charging location by electricity rate ($/kWh) at home (PHEV)

Price elasticity of demand is an alternative way of measuring the impact of electricity price on charging decisions. Calculating the elasticity of choice of each alternative with respect to the cost of charging at home, we observe that a 10-percentage point increase in the cost of charging at home yields a 3.6 (2.2) percentage point decrease in probability of home charging for BEV (PHEV) owners and a 1.5 (1.2) increase in the probability of workplace charging.

Finally, vehicle range plays an important role in driving charging needs and therefore the choice of charging location. For BEV owners the model uses the “share of range utilized” as a factor determining the need for charging on any particular day. As the ratio of commute distance to range goes up, the need for charging increases. Therefore, as we observe in Figure 6, when the ratio increases from 0.10 to 0.90, the probability of both home and workplace charging on a particular day goes up by 5 and 3 percentage points, respectively. Also, as expected, the probability of no-charging falls. For PHEV owners (Figure 7), with all else constant, as the electric range of the vehicles goes up, the predicted shares of the location choices of home, work, and public increase by 11%, 2%, and 5%, respectively, while the share of multi-location choices drops dramatically. This is consistent with PHEV owners being increasingly able to meet their need for electric miles by plugging in at home, work, or a public location a single time, without the need to charge additional times at alternative locations during the day to complete their trip using electric miles.

This decrease in the demand for multi-location charging will have an impact on the total number of charging events that accumulate at home, work, and public chargers. Multi-location charging on a given day includes the following combinations: home-work, home-public, work-public, and all (home, work, and public). In the sample of PHEV commuters, the proportion of these combinations was 52.4%, 38.1%, 6.4%, and 3.1% respectively. Using these proportions, and the predicted probability (share) estimates from Figure 7, we calculated for every 100 PHEVs the total number of non-charging and charging events at home, work, and public locations for different values of vehicle electric range—see Figure 8. This shows that, as the electric range of PHEVs increase, the total number of charging events at home, work, and public locations, respectively, decreases, even though the “location shares” of these options increase (as seen in Figure 7). For example, if 100 PHEVs with 5-mile electric range are replaced by 100 PHEVs with 85-mile range, there may be 43% fewer charging events at public locations, even though its location share increases. This reduction in the overall number of charging events is driven by the reduction of multi-location charging events like home-other, work-other, and plugging-in at all the locations on a given day.

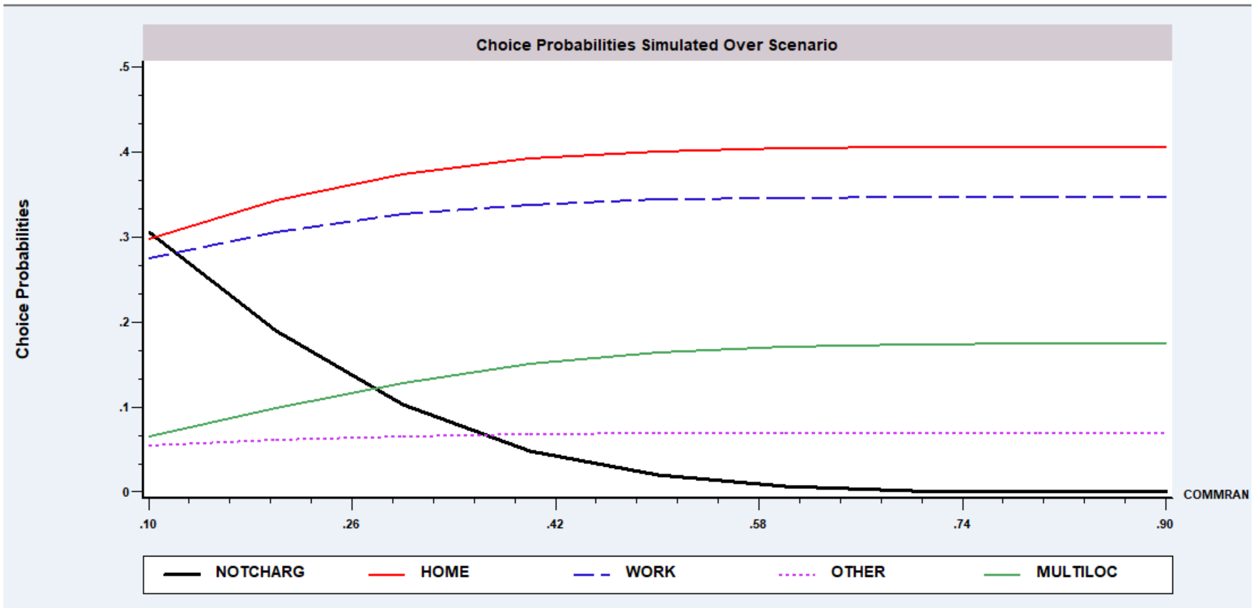

Figure 6. Predicted probability of choice of charging location by share of range used to commute

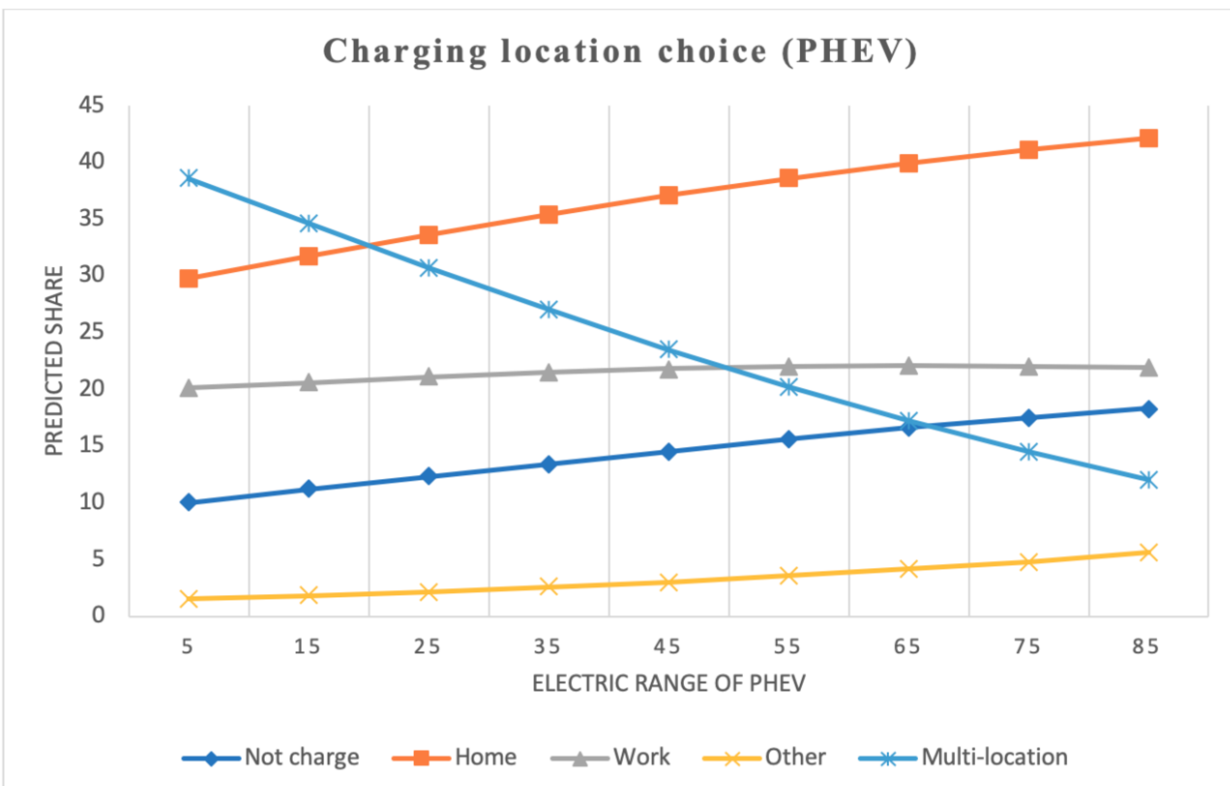

Figure 7. Predicted probability (share) of charging events by electric range

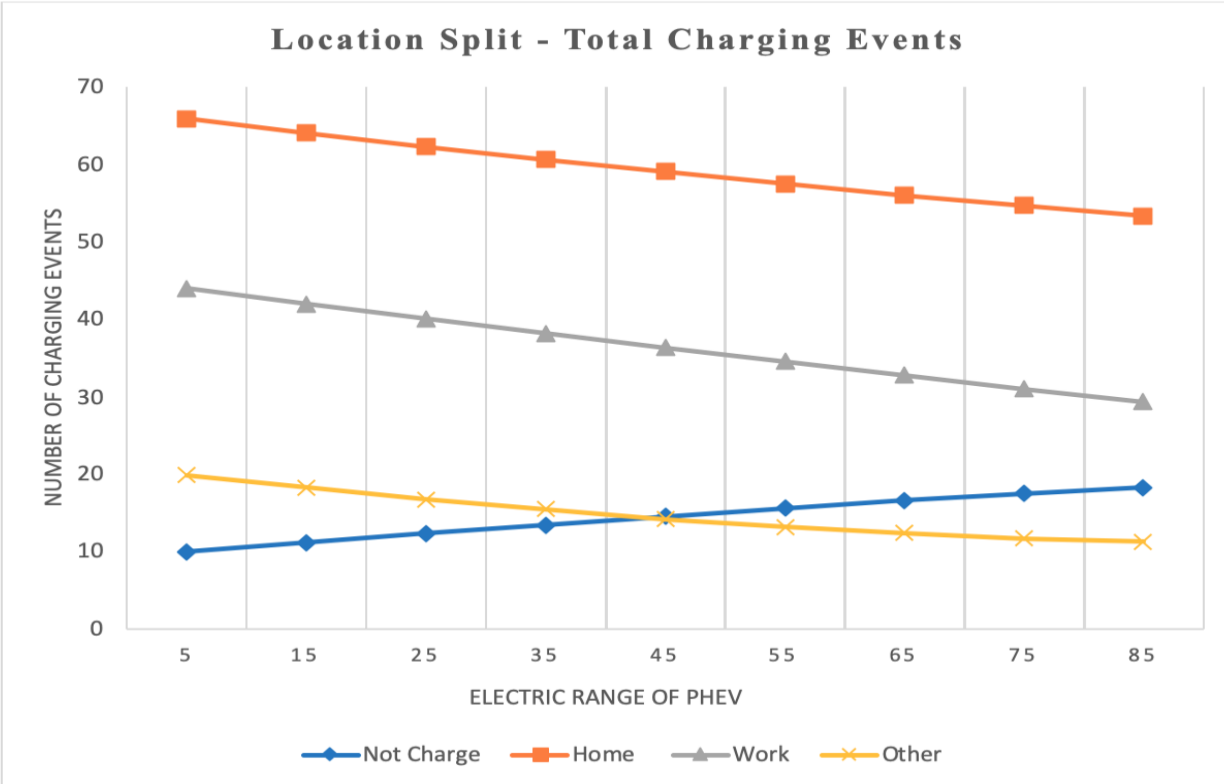

Figure 8. Number of charging events per 100 PHEVs (given day) by electric range

Discussion

Even though there is a broad array of literature addressing the need for charging infrastructure to support adoption of PEVs, our work using revealed preference choice data seeks to contribute to three important policy questions regarding the demand for vehicle charging infrastructure. First, what are the socio-economic and infrastructure specific factors that drive the choice of charging location? Secondly, what is the role of the monetary cost of charging in the PEV owner's choice decision? Finally, how would improvements in vehicle technology (electric range) impact charging needs?

Understanding the economic and behavioral factors driving demand for charging infrastructure is important for effective planning of charging infrastructure investments. The second question pertaining to substitution between home and workplace charging in response to monetary costs of charging in the two locations is important not just in relation to demand for infrastructure but also for PEV usage and energy demand management at the grid level. Finally, considering there will be more long-range PEVs in the market in the future, analysis of charging behavior of short- and long-range PEVs would help in the evaluation of future infrastructure needs.

Regarding the first and second questions, our results indicate that characteristics of workplace charging infrastructure like charging etiquette (swap parking) and number of chargers have a significant effect on the charging decision. Also, access to Level 2 charging at home has a strong positive effect on the probability of home charging while reducing the likelihood of workplace and public location charging. Using the predicted probability and share estimates from the ECL model we estimate that, with everything else held constant, for every 10 BEV drivers with access to Level 2 charging at home, there will be almost one less workplace charging event. In the case of PHEV drivers, on the other hand, 10 Level 2 home chargers will result in approximately 0.2 fewer work charging events on a particular day. In an equivalent way, considering the cost of charging at the workplace, we find that if it is free then the demand for workplace charging infrastructure will be 19.6% and 10% higher for BEV and PHEV commuters, respectively, versus the scenario where workplace charging is paid. Electricity rates at home also play a key role in the location choice. Households with lower electricity rates are more likely to charge at home than elsewhere.

As for the third question, the results initially suggest that as the range of PHEVs go up, the importance of public chargers as a “choice” would increase as they start using their vehicle for longer commutes. However, with longer electric range, PHEV commuters may not need to charge their vehicle at multiple locations during a day and can rely on a single charging event to maximize their electric miles. Overall, this can lead to fewer charging events in public locations or even at the workplace, particularly if there is higher availability of Level 2 chargers at home. Among BEV owners, as the ratio of commute distance to range goes up, the share of non-charging days goes down, while the proportions of home and workplace charging go up on average by 5 and 3 percentage points, respectively. From a policy perspective however, we can expect that a higher number of future BEVs will have longer range than present vehicles, and if commute distance does not change dramatically, we can expect to observe lower shares of range utilized and more non-charging days, as well as a lower proportion of home and workplace charging events. However, higher range BEVs will also make longer commutes possible. In this scenario, as the share of range utilized goes up, there will be more charging events. Considering the share of long-range BEVs will go up among future BEV owners, the charging pattern will be similar to the ones we see among current commuters with a high share of range utilization. Table 4 below summarizes the key results from the choice model and their policy relevance.

The results and policy discussions here are based on the charging behavior of PEV commuters with access to all possible charging locations. While the drivers of demand for non-commuters can be completely different, we can hypothesize that if commuters who at present do not have access to workplace chargers are given such access, their response will be similar to the group of PEV owners analyzed here.

Table 4. Policy Implications of the Choice Model Results

Result	Policy Implication
Access to Charging Infrastructure & Vehicle Characteristic	
Access to a Level 2 charger at home encourages home charging.	Incentives for Level 2 installation in BEV households can help reduce the need for expensive investment in building public infrastructure as well as reduce congestion at charge points in the future.
Higher electric range reduces the probability of multi-location charging by approximately 25 percentage points for PHEV drivers. For BEV drivers, a higher range incentivizes regular charging at home or work.	Future infrastructure investment plans need to account for changes in charging needs of long-range PEV drivers. The need for public/workplace infrastructure can be lower than currently anticipated
Role of Electricity and Infrastructure Pricing	
High electricity prices at home disincentivize home charging and increases the probability of not charging. It also encourages shifting demand to workplace especially, if the latter is free.	Programs encouraging households to sign up for special rate plans can encourage PEV usage and help optimal usage of public infrastructure.
Free workplace charging reduces the probability of home charging by 4.6 percentage points and increases the probability of workplace charging by 9.9 percentage points among BEV drivers	Free charging is not sustainable. With significant PEV uptake, it can lead to congestion of current infrastructure. Also, financial unviability of workplace infrastructure can discourage future investment. It is necessary to price workplace charging events.

Conclusion

The initiatives by policymakers, utilities, and OEMs in building large-scale charging infrastructure will create a dependable charging network, important to the success of large scale PEV adoption. Major utilities in California have launched programs to partner with businesses and charging network companies to install Level 2 chargers near multi-unit apartment buildings and at the workplace. While these investments are necessary, they are expensive. The budget for some of the programs is approximately $130 million. Trying to maximize coverage with limited information on charging behavior and demand drivers can prevent maximization of the investment benefits. Moreover, the infrastructure goals are usually set considering the current PEV technology. As our results indicate, long-range BEVs and PHEVs may have different charging needs than short-range PEVs currently sold in the market. Commuters may use long-range PEVs for different travel needs than the short-range ones. Moreover, as the access to Level 2 chargers at home improves over time, it may be possible to complete a days' travel needs in a long-range PEV with only overnight charging. Policymakers should account for the fact that there will be more long-range PEVs in the market when setting the investment needs for public infrastructure.

The location of the infrastructure must be strategic as well. Compared to PEV owners in detached homes or condominiums, apartment dwellers are more dependent on workplace and public infrastructure than home. Promoting installation of chargers at a workplace and near multi-family units can encourage PEV adoption and usage among apartment dwellers.

Pricing policies will play a key role in determining the demand for charging infrastructure. In 2017, only 6% of the residential utility customers in California had adopted time-of-use rates [EIA-861]. In comparison to the standard tiered pricing structure, time-of-use rates or PEV special rates allow households to reduce the cost of charging their vehicle at home and encourage home charging. Along with residential electricity prices, pricing policies for workplace charging is also a critical issue. At present, a majority of the workplace charging infrastructure is free. This practice encourages households to shift charging behavior from home to work or to plug-in unnecessarily. In the future, when there is significant PEV uptake, as in the case of road traffic, it might not be possible to "build out of congestion." Moreover, free charging is not financially sustainable. Policymakers need to develop pricing schemes that will prevent an unnecessary shift of charging behavior from home to non-home locations and allow optimal use of the public infrastructure.

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