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Consumer Choice of Electric Vehicle Infrastructure: What are the Drivers and their Importance?

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Summary

This paper presents a model of choice of charging infrastructure for commuters with Plug-in Electric vehicles (PEVs). Modeling the choice behavior of more than 3000 PEV, we focus on understanding the importance of factors driving demand for infrastructures like the cost of charging, driver characteristics, access to charging infrastructure, and vehicle characteristics. We find that differences in the cost of charging plays an important role in the demand for charging location. Additionally, socio-demographic factors like dwelling type and gender, as well as vehicle characteristics like range, has an influence on the choice of charging location.

Keywords: BEV (battery electric vehicle), PHEV (plug in hybrid electric vehicle), charging, demand, infrastructure

1 Introduction

Battery electric (BEV) and plug-in hybrid electric vehicles (PHEV), referred to as plug-in electric vehicles (PEVs) are being increasingly embraced by consumers as an alternative to the internal combustion engine (ICE) vehicles. In response, utilities, government agencies, as well as many OEMs are increasingly investing in building vehicle charging infrastructure to encourage further adoption of PEVs as well as to ensure the current facilities are not congested. Though public infrastructure is undoubtedly required to encourage adoption (*1-6*), early attempts to maximize the coverage of charging stations (e.g. under the federal EV project) with limited information regarding charging behavior have resulted in low or almost no utilization of publicly accessible charging points in some locations (*7, 8*). As the market for EVs evolves, the optimal size of charging infrastructure required will increasingly depend on factors driving demand for charging infrastructure including the range of the newer vehicles, number of consumers with access to charging facilities at home (often dictated by dwelling type), and the pricing models adopted for home and public charging. In this study, modeling the choice of charging location of 3,200 PEV drivers in California, we focus on analyzing the importance of these demand-drivers and their policy implications. Policymakers need to carefully consider these demand drivers in their charging infrastructure plans to maximize its benefits.

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 pattern of ICE drivers or by simulating possible driving scenarios of PEV owners (*9, 10*). There has been some focus on how the strategic provision of public charging can improve BEV feasibility (*2, 11-15*) but, most of these studies do not account for the behavioral and economic factors that may drive charging behavior, important for developing models that assess the vehicle charging needs of PEV drivers and their response to varied charging service propositions (*16*). Due to limited data on revealed PEV use and charging behavior, studies that do consider the effect of socio-economic factors are based on stated preference data or a small number of instrumented PEVs (*17-21*).

In this study, we analyze the revealed choice of charging infrastructure of PEV drivers to understand the importance of these socio-economic and demographic factors influencing their choice.

Multiple studies on electric vehicle charging behavior have indicated that PEV drivers prefer to fulfill their charging needs at home or work rather than at public charging stations (*22-28*). Though travel patterns and vehicle driving ranges primarily impact PEV owners' charging needs, they generally consider all the pros and cons of charging at each of the locations in their choice decision. In general, conditional on the vehicle charging needs, there is a trade-off between monetary cost and the convenience of charging in the choice of charging location. Overnight home charging is favored mainly because of easy access and flexibility in terms of charging schedule (*13, 19, 29*). Additionally, one of the factors that drive home location charging is the use of time-of-use electricity tariffs or special EV rate plans offered by utilities. A 2016 study in California found that these tariffs, which provide cheaper electricity during the night time, encourage consumers to charge their vehicles at home overnight (*29*). Ownership of photovoltaic cells that may allow households to reduce the cost of charging further encourages home charging (*19, 30, 31*) as well. Though special rate plans and solar cells allow households to lower monetary costs of home charging it is not free. In this scenario if workplace charging is free, PEV owners usually tradeoff the convenience of home charging for the zero cost of refueling at work, even when the number of spots is limited or congested. Public charging stations, when paid can be more expensive than home or work and using them usually requires careful planning but they offer additionally the privilege of a reserved parking spot in a wide variety of places (shopping centers, hotels, transport hubs, highway corridors).

Free workplace charging attempts to reduce the operating cost of PEVs and encourage adoption. Even though free workplace charging can induce PEV adoption and usage, it may not be sustainable and can have negative consequences like charge point congestion (*23, 28, 32*). According to Tal et al. (2014), a significant driver for charging at work was employers offering charging for free (28). The authors also find that, while PEV drivers who mostly use the free infrastructure are ones who can complete their days driving without recharging, BEV drivers who need to charge to complete their travel needs may not risk driving their PEV if they perceive charge point congestion to be an issue (*13, 28*). Prior research on public charging behavior have suggested that dynamic pricing policies accounting for the cost of vehicle parking can ensure more efficient utilization of the workplace charging infrastructure. It will free up charging spots for PEV users who are more dependent on non-home charging infrastructures like apartment dwellers and renters as well as allow providers to run a sustainable business model (*33-36*). Overall, policymakers need to develop and implement pricing strategies and incentive policies that can utilize the tradeoff between monetary cost and convenience in an individual's decision process to limit shifting of home charging to a workplace or public charging.

Investing in charging infrastructure is necessary for the success of large-scale PEV adoption. But, deploying charging infrastructures intelligently in the prospect of large-scale BEVs' and PHEVs' uptake, is one of the most pressing challenges for any local government (*17*). It is difficult to quantify the optimal amount of charging infrastructure required and its impact on BEV adoption and usage (*37*). Moreover, building charging infrastructure is expensive. Understanding the behavioral and economic factors affecting 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. The analysis in this study gives an estimate of how various economic, socio-demographic and vehicle technology factors affect the demand for charging infrastructure. The results indicate the importance of monetary costs, accessibility to infrastructure dictated by dwelling type, and vehicle technology as the main demand drivers.

2. Data & Model Description

2.1 Descriptive Analysis of Data

The data used in this study is drawn from a cohort survey of PEV owners in California conducted in the years 2016 and 2017 by the Plug-in Hybrid & Electric Vehicle (PH&EV) Center, part of the Institute of Transportation Studies at the University of California, Davis. Participants who owned at least one PEV were recruited based on the list of Clean Vehicle Rebate Program (CVRP) recipients and Department of Motor Vehicles (DMV) registration data using a random sampling procedure. The response rate for the completed survey was about 15%. For this study, we use a subsample of 7,979 households who own or lease a PEV and had charged at least once in the period for which we collect their charging history.

There were six categories of questions in the survey: travel behavior, commute characteristics, vehicle performance (MPG), vehicle characteristics, response to EV related incentives, and charging behavior. For charging behavior, respondents were asked to provide 7 days of charging history from the survey date and answer if his/her PEV was charged at the following locations with the given types 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 must answer the 8 above questions with a "Yes" or "No". If the respondent did not charge on a particular day, we observe a "No" for all the options. There were 500 respondents who did not charge at all in the 7-days out of which 394 are PHEV owners and 106 are BEV drivers. One potential reason for not charging a BEV for 7 days is very low usage. Also, if the commute distance is short, then some of the long-range BEVs like Tesla or Chevrolet Bolt may not need charging for a week. In the case of PHEVs, no-charging can be an indication of low usage of the vehicle or low electric miles.

The primary objective of the study is to identify and quantify the importance of the factors that influence the charging location choice of BEV and PHEV owners. To capture all the possible location options, we focus on the charging behavior of a sub-group of 3,201 PEV drivers who use their vehicle for commute and has access to charging infrastructure at that place. Moreover, we only consider their weekday charging behavior when all the location options are available. We consider three type of locations 1- home, 2- work, or while at work, including charging at work or public chargers while at work and 3- public including any location other than 1 and 2. We drop the group of non-chargers, non-commuters, and commuters with no access to workplace charging from our analysis.

Figure 1 gives the distribution of charging locations on weekdays for BEV and PHEV commuters. We aggregate the choice of type of charger i.e. Level 1, Level 2 and DC Fast Charger during a charging event and only consider the choice of location. We observe that for both BEV and PHEV owners, home is the most important charging location. Among non-home locations, BEV owners tend to use workplace charging and public chargers more than PHEV owners. While PHEV owners can use the ICE engine of their vehicle to complete their commute, BEV drivers do not have the flexibility. This can 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 explains 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 their use of multiple locations on a particular day is higher. This indicates that PHEV drivers in our sample try to maximize their electric miles to lower the overall cost of their commute.

Even with the PEV market globally hitting the 1 million mark, the technology is still in the early stages of the diffusion curve. Most of the PEV owners can be considered as early adopters of the technology. As early adopters, the PEV owners analyzed here may have some unique characteristics in terms of income, age, education, house ownership, or level of adoption of complementary technology that can impact their charging behavior. Table 1 gives the descriptive statistics of the 3,201 PEV commuters we analyze in this study. More than 88% of the commuters with PEVs in our sample have a household income higher than the median income in California ($67,739 according to the 2016 Census American Community Survey 1-year survey) and the percentage of people with graduate or professional degrees are 88.7% (California state-wide 12.3%). 70% of respondents owned their houses that are detached units higher than the state average of 58.1%. Also, in our sample, males tend to be the primary user of a PEV more than females. Our sample of PEV owners is also different in terms of adoption of dynamic pricing policies offered by the utilities in California. While the state average is around 5.6% (*38*), almost 55% of the sample here had either the time-of-use rate or the special EV rate that offers a different per kWh rate during peak and off-peak hours of demand for electricity. The survey slightly over-sampled BEV owners compared to PHEVs. Overall, about 50% of respondents have the Chevrolet Volt, Tesla, or the Nissan Leaf, and a considerable number of the rest used the Prius plug-in hybrid or the Bolt.

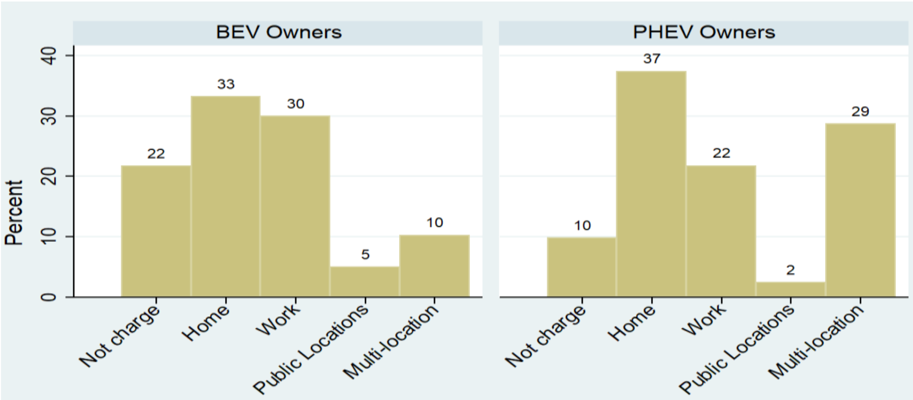

Figure 1: Distribution of weekday charging location choice of BEV and PHEV commuters

Table 1: Descriptive Statistics of PEV Commuters (n=3,201)

Household Characteristics				**PEV Characteristics**	
Income		Total Vehicles		Share of Fuel Type in Sample	
< $99,000	374	1 vehicle	344	Number of BEVs	1,769
$100,000-$149,999	608	2 vehicles	1,696	Number of PHEVs	1,432
$150,000 - $199,999	606	3 or more vehicles	1,161	Purchase or Lease	
$200,000 - $299,999	740	Household Size		# BEVs purchased	650
$300,000 - $399,999	276	1 person	293	# BEVs leased	1,119
$400,000 - $499,999	116	2 people	1,042	# PHEVs purchased	727
> $500,000	150	3 people	664	# PHEVs leased	705
Prefer not to answer	331	4 people	896	Vehicle Model in Sample	
Gender (Primary user)		> 5 people	306	Prius Plug-In	272
Male	2,499	Solar Cell Owners		Nissan Leaf	590
Female	702	Solar Cell	843	Bolt	261
Education Level (Primary User)		House Ownership		C-Max Energi	158
High school	346	Own	2,558	e-Golf	244
College	1,272	Dwell Type		Volt	580
Post-graduate	1,570	Detached Home	2,449	Tesla	439
Age (Primary User)		Condominium	456	BMW	291
20-29	203	Apartment	296	Ford Fusion	143
30-39	838	Rate Paid and Rate Perceived (cents/kWh)		Home L2 charger	
40-49	962	Avg. rate paid	20.45	L2 charger @ home	1,313
50-59	766	Avg rate perceived	16.28		
60-69	325	Rate Types of PEV Owners			
70-79	67	Flat Rate	1,411		
More than 80 years old	5	Time-of-Use Rate	635		
Missing	35	EV rate	1,155		

Note: The vehicle models reported here had the highest share in the sample. The column with the frequency of each vehicle model does not add up to 3,201.

2.2 Model Description

We analyze a location choice model here to estimate the importance of demand drivers that affect a PEV owner's decision to charge their vehicle on a given day at home, work, in a public location, use a combination of these options, or not charge at all. The factors that we consider here are monetary cost of charging at home and work, access to charging opportunity at home and work, ownership of complementary technology like solar cells, infrastructure characteristics at a workplace, vehicle technology (age and range of the vehicle), and demographic characteristics. In demographic characteristics, we include dwelling type of the PEV owner as it has a major influence on PEV adoption and usage *(39)*, solar cell ownership, the gender of the primary driver of the vehicle, and age.

In our exploratory data analysis, we observe that while BEV owners in single detached homes did home charging on 37% of the weekdays, it is only 12% for apartment dwellers (Figure 2). This difference is mostly driven by the fact that homeowners are more likely to invest in installing Level 2 chargers at home and has a greater guarantee of availability of charging opportunity at their residential location. BEV owners living in condominiums and apartments rely more on workplace and public charging infrastructure. We observe a similar pattern for PHEV owners.

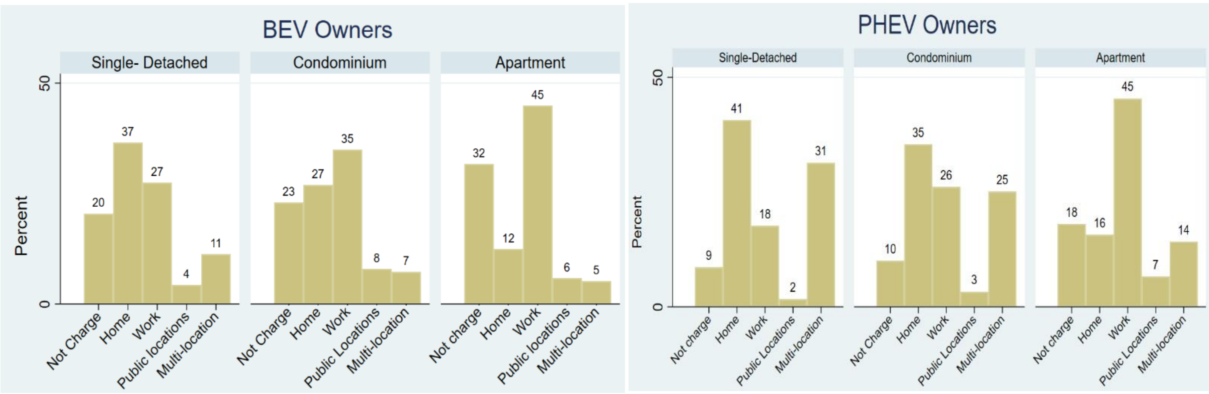

Figure 2: Distribution of Charging Locations by Dwelling Type

Given the trade-off between the convenience of home charging and cost that drives substitution between charging location, electricity rate at home is expected to play a vital role in the location choice decision. As we observe in Figure 3, BEV owners who have enrolled in special rate plans (EV rates) are twice more likely to charge at home than those under flat rate structure. Though we observe a similar pattern among PHEV owners, the difference in the percentage of charging events under flat rate type and EV rate is higher for BEVs than PHEV owners. Sensitivity to cost is observed in case of workplace charging as well. Figure 4 shows that the percentage of workplace charging events is approximately 44% for BEV owners when it is free while it is only 15% when paid.

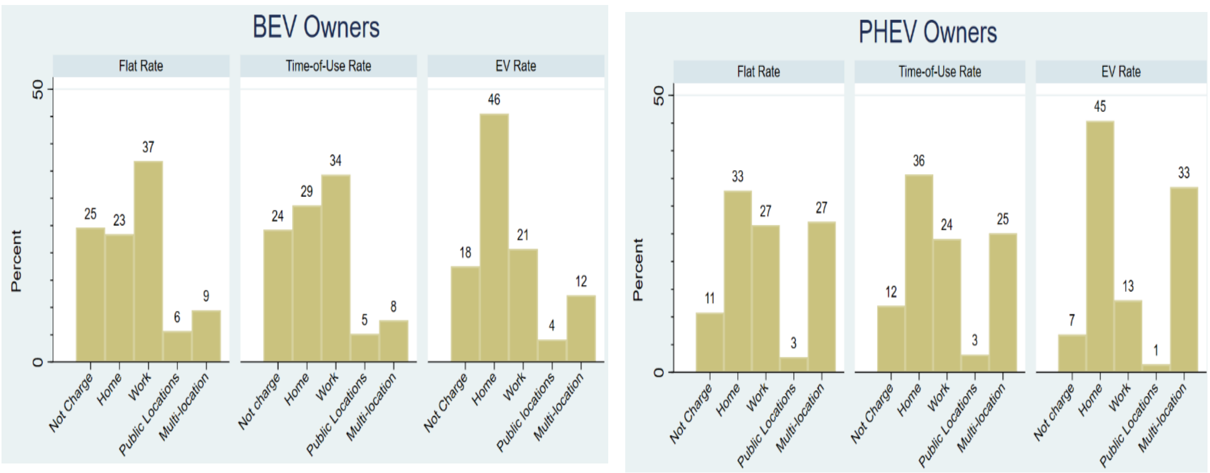

Figure 3: Distribution of charging locations by cost of charging at home

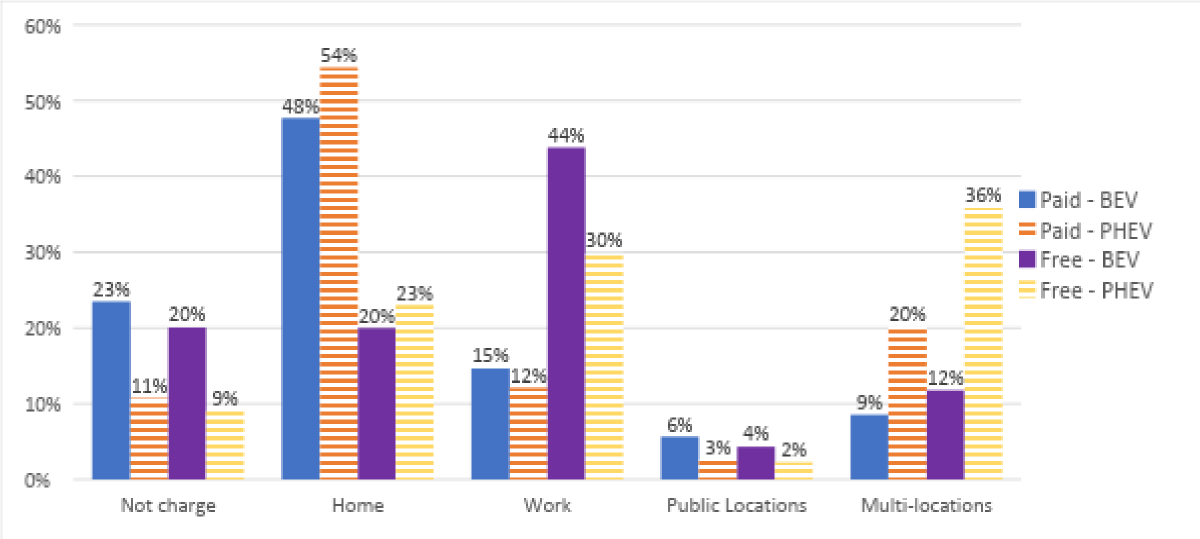

Figure 4: Distribution of charging locations by cost of charging at work

We use a multinomial logistic regression (MNL) to estimate the probability corresponding to the location choice. A major drawback of the MNL model is the assumption of Independence of Irrelevant Alternatives (IIA). The IIA assumption is problematic if the model estimates are used to make predictions or explain substitution behavior. Since the objective of this study is to only understand the average effects of sociodemographic characteristics, vehicle characteristics, cost of charging, and workplace charging facilities on the choice of charging location, the IIA assumption is less concerning (40).

We estimate separate choice models for BEV and PHEV owners since only the former has access to DC Fast chargers available in public locations. The probability that a respondent 'n' chooses location 'i' to charge their vehicle on a weekday 'd' can be modelled as follows:

$$P(y_{ni}^{d}) = \frac{exp\ (\beta' x_{ni})}{\sum_{k} \ \ exp\ (\beta' x_{nk})} \qquad (1)$$

Where, y_{ni}^{d} consists of the following decisions: charge vehicle at home, at work, use public chargers (chargers in shopping malls, movie theatres etc.), use any combination of the former locations (multi-location charging), or not charge at all. The base category is the decision to not charge the vehicle on a weekday 'd'. Here weekday charging behavior is defined based on the day the respondent reports his/her charging history. For example, when the respondent says the car was plugged in at home on Friday, we consider that as Friday's charging behavior even if the charging may start at midnight. The vector x_i describes the explanatory variables included in the choice model - socio demographic characteristics of the primary driver of the vehicle like age and gender, household characteristics like type of housing and solar cell ownership, and vehicle characteristics like range and age of the PEV. We also control for cost of charging at home and work, characteristics of workplace charging infrastructure, membership of charging networks, and commute distance.

3. Results from the choice model

In this section, we use the results of the MNL model to display marginal effects of factors driving the choice of charging location and probability outcomes focusing on some of the major demand drivers- the cost of charging at home, role of infrastructure availability at home, workplace charging infrastructure characteristics, and vehicle range. The marginal effect of a continuous explanatory variable x_k is estimated as $\frac{\partial P_{ij}}{\partial x_{ik}} = P_{ij}(\beta_{jk} - \sum_{m=1}^{J-1} P_{im}\beta_{mk})$, noting again that the coefficient is zero for the baseline outcome. For the discrete explanatory variables, marginal effect is calculated by computing average predicted probabilities when the discrete variable is set to 1 (e.g. dummy variables) and then when set to 0.

Figure 5 focuses on the role of electricity price in the choice decision for BEV and PHEV owners. All else constant, the probability of home charging is on average 10 percentage points lower for BEV owners facing electricity costs of 45 cents/kWh than those facing 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 7 percentage points as the electricity rate goes up. We can hypothesize that as the cost of vehicle charging at home goes up, people substitute towards workplace charging or use other non-PEVs in their fleet. Less usage of the EV leads to lower number of charging events.

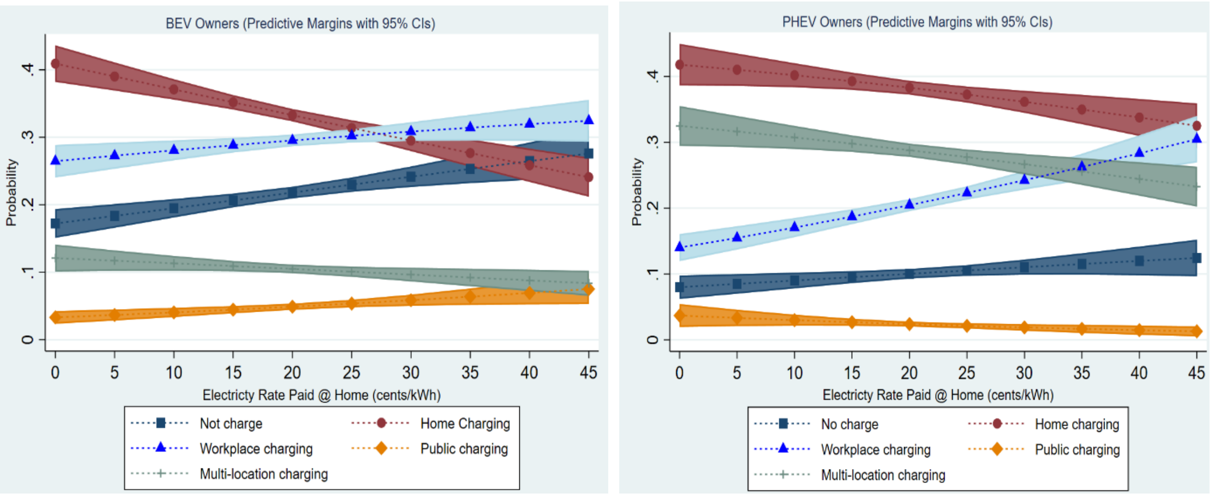

Figure 5: Predicted probability of Choice of Charging Location by Electricity Rate paid at Home

Price elasticity of demand is an alternative way of measuring the impact of electricity price on the choice decision. Calculating the elasticity of choice of each alternative with respect to the cost of charging at home (Table 2), we observe that a 10 percentage points increase in cost of charging at home leads to a 3-percentage point decrease in probability of home charging for BEV owners while the probability of workplace charging goes up by 1.4 percentage points. When we compare the elasticity of choice of charging location under free workplace charging to when it is paid, we observe that BEV owners are more responsive in the former scenario. Like the BEV commuters, those with PHEVs also shift away from home charging in response to higher residential electricity price.

Table 2: Elasticity of Demand for PEV Owners

		EV Owners		**PHEV Owners**	
		ey/ex	Std. Err	ey/ex	Std.Err
No Charge		0.202*	0.058	0.222**	0.103
Home	Overall	-0.292*	0.051	-0.176*	0.052
	When paid work charge	-0.23*	0.039	-0.114*	0.037
	When free work charge	-0.35*	0.064	-0.239*	0.065
Workplace		0.138*	0.051	0.438*	0.068
Public		0.374*	0.128	-0.480***	0.247
Multi-location		-0.187**	0.091	-0.184*	0.060

Note: * 1 % , ** 5 %, and *** 10 % level of significance

In general, characteristics of workplace charging have strong marginal effects on the choice of charging location. Free workplace charging has a significant positive effect on a commuter's probability of choice of their workplace as the charging location. As we observe in Table 4 below, when workplace charging is free, on an average the probability of choice of a workplace as the charging location goes up by 19 percentage points. Also, the probability of charging at multiple locations goes up marginally. On the other hand, the probability of home charging falls by 17 percentage points and public charging falls by 1.6 percentage points. This result conforms with the finding of Tal et al. (2013) that free workplace charging may incentivize BEV owners to shift to workplace charging. Along with free workplace charging, the number of chargers at the workplace, time limits on charging, the possibility of congestion, and having to swap cars affect the choice of charging location as expected.

Table 4: Marginal Effects of Workplace Charging Characteristics (BEV and PHEV commuters)

		BEV		**PHEV**	
		Delta Method (dy/dx)		**Delta Method (dy/dx)**	
Factor	**Outcome**	**Marginal Effect**	**Std. Error**	**Marginal Effect**	**Std. Error**
Congestion @ Workplace	No charging	0.007	0.010	0.012	0.008
	Home charging	-0.015	0.010	0.001	0.011
	Workplace charging	-0.007	0.009	-0.024**	0.009
	Public charging	0.002	0.005	0.010**	0.004
	Multi-location charging	0.012	0.007	0.001	0.011
Free Charging @ Workplace	No charging	-0.015	0.009	-0.019**	0.008
	Home charging	-0.174*	0.010	-0.222*	0.012
	Workplace charging	0.192*	0.009	0.127*	0.010
	Public charging	-0.016*	0.005	-0.007**	0.004
	Multi-location charging	0.014**	0.007	0.121*	0.011
# of Chargers @ Workplace	No charging	0.001*	0.0002	0.001***	0.0003
	Home charging	-0.001*	0.0003	-0.005*	0.001
	Workplace charging	0.001*	0.0002	0.002*	0.0003
	Public charging	-0.0002	0.0002	-0.0003	0.0002
	Multi-location charging	-0.001**	0.0002	0.002*	0.0004
Swap parking @ Workplace	No charging	-0.005*	0.001	-0.001**	0.0005
	Home charging	-0.015*	0.001	-0.016*	0.001
	Workplace charging	0.014*	0.0005	0.007*	0.0005
	Public charging	-0.001	0.0004	-0.001**	0.0003
	Multi-location charging	0.005*	0.0004	0.010*	0.001
Time Limit on Charging @ Workplace	No charging	0.028*	0.009	0.019**	0.008
	Home charging	0.056*	0.010	0.105*	0.011
	Workplace charging	-0.056*	0.009	-0.022**	0.010
	Public charging	-0.002	0.005	0.002	0.004
	Multi-location charging	-0.026*	0.006	-0.105*	0.0105

Note: * 1 % , ** 5 %, and *** 10 % level of significance

Among the household characteristics, we find that dwelling type, access to Level 2 chargers at home, and solar cell ownership affect the probability of home charging with the former two having a stronger influence (Table 5). PEV owners require membership of charging network like ChargePoint or EVgo to be able to use the public charging stations. Thereby, all other factors held constant, if a BEV commuter has a membership to one of the charging networks the probability of choice of public infrastructure increases by 3 percentage points. Unlike BEV owners, PHEV drivers cannot use the DC Fast charging infrastructure available at public stations. This can explain the insignificant effect of network membership on the choice of public locations for this group.

Table 5: Marginal Effects of Household Characteristics (BEV and PHEV commuters)

		BEV		**PHEV**	
		Delta Method (dy/dx)		**Delta Method (dy/dx)**	
Factor	**Outcome**	**Marginal Effect**	**Std. Error**	**Marginal Effect**	**Std. Error**
Dwelling Type-Detached Home	No charging	0.205*	0.005	0.089*	0.004
	Home charging	0.345*	0.005	0.394*	0.006
	Workplace charging	0.291*	0.005	0.195*	0.005
	Public charging	0.046*	0.003	0.017*	0.002
	Multi-location charging	0.112*	0.004	0.305*	0.006

Dwelling Type-Condominium	No charging	0.223*	0.012	0.108*	0.010
	Home charging	0.327*	0.013	0.389*	0.014
	Workplace charging	0.298*	0.012	0.201*	0.011
	Public charging	0.072*	0.008	0.035*	0.006
	Multi-location charging	0.079*	0.008	0.267*	0.013
Dwelling Type-Apartment	No charging	0.334*	0.019	0.180*	0.016
	Home charging	0.228*	0.018	0.257*	0.019
	Workplace charging	0.330*	0.015	0.321*	0.016
	Public charging	0.042*	0.007	0.065*	0.012
	Multi-location charging	0.066*	0.010	0.177*	0.015
`Solar @ Home	No charging	-0.026*	0.010	-0.011	0.009
	Home charging	0.018 ***	0.011	0.040*	0.013
	Workplace charging	0.003	0.011	-0.051*	0.012
	Public charging	0.002	0.006	0.003	0.006
	Multi-location charging	0.003	0.007	0.019	0.013
Charging Network Membership	No charging	0.030**	0.012	0.028**	0.013
	Home charging	-0.062*	0.012	-0.060*	0.019
	Workplace charging	-0.037*	0.010	0.031***	0.016
	Public charging	0.033*	0.007	-0.006	0.005
	Multi-location charging	0.036*	0.008	0.008	0.019
Level 2 charger @ Home	No charging	-0.027*	0.010	-0.010	0.008
	Home charging	0.185*	0.011	0.055*	0.013
	Workplace charging	-0.195*	0.010	-0.089*	0.010
	Public charging	-0.034*	0.006	-0.014*	0.004
	Multi-location charging	0.072*	0.008	0.059*	0.012

Note: * 1 % , ** 5 %, and *** 10 % level of significance

Among the driver characteristics, we observe female drivers have a lower probability of charging in public locations and older drivers are less likely to charge their vehicle at home or workplace. Finally, vehicle range plays an important role in driving charging needs and therefore the choice of charging location. As the range of BEVs go up, the probability of home and workplace charging on a particular day goes down. The probability of charging at multiple locations also goes down for higher range BEVs and PHEVs. However, the probability of choice of public locations goes up indicating that long-range PHEV owners use their vehicle for longer commutes and may need to use public chargers to complete these trips. Commute distance is not observed to have a significant marginal effect on the probability of choice of home or workplace location. However, there is a significant negative effect on the probability of not charging and a positive effect on charging in public locations.

4. Discussion

Even though there is a broad array of literature addressing the need for charging infrastructure to support adoption of PEVs, our work 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 (vehicle 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 range and long range PEVs would help in the evaluation of future infrastructure needs. Table 6 below summarizes the key results from the choice model and their policy relevance.

Table 6: Policy Implications of the MNL model Results

Result	Policy Implication
Characteristics of Charging Infrastructure at Home and Work	
Access to Level 2 charger at home encourages home charging. Reduces the probability of choice of workplace and public locations mostly for BEVs	Incent Incentives to households for Level 2 installation at home for BEVs can help reduce the need for expensive investment in building public infrastructure as well as reduce congestion at charge points in the future.
Drivers who are apartment dwellers are more dependent on workplace charging.	Build Building charging infrastructure at workplace and near multi-family apartments can encourage adoption and usage of PEVs among renters and apartment dwellers.
Roof Rooftop solar has a small but positive effect on the probability of home charging for both BEV and PHEV drivers.	Incentives promoting adoption of complementary technology can allow households to further lower the cost of vehicle charging and encourage PEV usage. In future, along with battery storage rooftop solar can have a stronger influence on the choice decision.
Role of Role of Electricity and Infrastructure Pricing	
High electricity price at home disincentivize charging at home and increases the probability of not charging. Not charging can imply low usage of the PEV. High electricity price at home also encourages shifting charging 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 17 percentage points and increases the probability of workplace charging by 19 percentage points	Free 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

5. 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 EV 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. The location of the infrastructure must be strategic as well. As our results indicate, apartment dwellers are more dependent on workplace and public infrastructure. 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 (38). Compared 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 plug-in unnecessarily. In 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 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.

6. References

[1]. Nicholas, M., G. Tal, and W. Ji. Lessons from In-Use Fast Charging Data: Why Are Drivers Staying Close to Home. Inst. Transp. Stud, 2017.
[2]. Dong, J., C. Liu, and Z. Lin. Charging Infrastructure Planning for Promoting Battery Electric Vehicles: An Activity-Based Approach Using Multiday Travel Data. Transportation Research Part C: Emerging Technologies, Vol. 38, 2014, pp. 44–55. https://doi.org/10.1016/j.trc.2013.11.001.
[3]. Plötz, P., and S. A. Funke. Mileage Electrification Potential of Different Electric Vehicles in Germany. 2017, p. 8.
[4] Morrissey, P., P. Weldon, and M. O’Mahony. Future Standard and Fast Charging Infrastructure Planning: An Analysis of Electric Vehicle Charging Behaviour. Energy Policy, Vol. 89, 2016, pp. 257–270.
[5]. Tal, G., M. A. Nicholas, J. Davies, and J. Woodjack. Charging Behavior Impacts on Electric Vehicle Miles Traveled: Who Is Not Plugging In? Transportation Research Record, Vol. 2454, No. 1, 2014, pp. 53–60
[6]. Zhang, Yingjie, et al. "The impact of car specifications, prices and incentives for battery electric vehicles in Norway: Choices of heterogeneous consumers." Transportation Research Part C: Emerging Technologies 69 (2016): 386-401.
[7]. Hagerty, J.R., Ramsey, M., 2011. Charging stations multiple but electric cars are few. Wall Street Journal
[8]. Russo, E., 2015. Public electric-car charging stations sit idle most of time, The Seattle Times
[9]. Guo, Zhaomiao, Julio Deride, and Yueyue Fan. "Infrastructure planning for fast charging stations in a competitive market." Transportation Research Part C: Emerging Technologies 68 (2016): 215-227.
[10]. Nie, Yu Marco, and Mehrnaz Ghamami. "A corridor-centric approach to planning electric vehicle charging infrastructure." Transportation Research Part B: Methodological 57 (2013): 172-190.
[11]. Gnann, Till, et al. "Fast charging infrastructure for electric vehicles: Today’s situation and future needs." Transportation Research Part D: Transport and Environment 62 (2018): 314-329.
[12]. Liu, Changzheng, and Zhenhong Lin. "Value of public charging: understanding the linkage between charging network coverage and charging opportunity." (2015).
[13]. Nicholas, Michael A., Gil Tal, and Justin Woodjack. California statewide charging assessment model for plug-in electric vehicles: learning from statewide travel surveys. No. UCD-ITS-WP-13-01. Institute of Transportation Studies, University of California, Davis, 2013.
[14]. Tal, Gil, et al. "Charging behavior impacts on electric vehicle miles traveled: who is not plugging in?." Transportation Research Record 2454.1 (2014): 53-60.
[15]. Yang, Yang, et al. "Modeling the charging and route choice behavior of BEV drivers." Transportation Research Part C: Emerging Technologies 65 (2016): 190-204.
[16]. Daina, Nicolò, Aruna Sivakumar, and John W. Polak. "Electric vehicle charging choices: Modelling and implications for smart charging services." Transportation Research Part C: Emerging Technologies 81 (2017): 36-56.
[17]. Xu, Min, et al. "Joint charging mode and location choice model for battery electric vehicle users." Transportation Research Part B: Methodological 103 (2017): 68-86.
[18]. Franke, Thomas, and Josef F. Krems. "Understanding charging behaviour of electric vehicle users." Transportation Research Part F: Traffic Psychology and Behaviour 21 (2013): 75-89.
[19]. Jabeen, Fakhra, et al. "Electric vehicle battery charging behaviour: findings from a driver survey." Proceedings of the Australasian Transport Research Forum. 2013.
[20]. Zoepf, Stephen, et al. "Charging choices and fuel displacement in a large-scale demonstration of plug-in hybrid electric vehicles." Transportation Research Record: Journal of the Transportation Research Board 2385 (2013): 1-10.
[21]. Anderson, John E., Marius Lehne, and Michael Hardinghaus. "What electric vehicle users want: Real-world preferences for public charging infrastructure." International Journal of Sustainable Transportation 12.5 (2018): 341-352.
[22]. Jae Hyun Lee et al. “Identifying Heterogeneous Electric Vehicle Charging Behavior - Mixed usage of L1, L2, DC fast chargers at different locations.” The 31st International Electric Vehicle Symposium & Exhibition & International Electric Vehicle Technology Conference 2018
[23]. Hardman, Scott, et al. "A review of consumer preferences of and interactions with electric vehicle charging infrastructure." Transportation Research Part D: Transport and Environment 62 (2018): 508-523.
[24]. Idaho National Laboratory. Plugged In: Understanding How and Where Plug-in Electric Vehicle Drivers Charge Up. Energy.gov. https://www.energy.gov/eere/articles/plugged-understanding-how-and-where-plug-electric-vehicle-drivers-charge. Accessed Jul. 6, 2018.
[25]. Ji, W., M. Nicholas, and G. Tal. Electric Vehicle Fast Charger Planning for Metropolitan Planning Organizations. Transportation Research Record: Journal of the Transportation Research Board, Vol. 2502, 2015, pp. 134–143. https://doi.org/10.3141/2502-16.

[26]. Nicholas, M., G. Tal, and W. Ji. Lessons from In-Use Fast Charging Data: Why Are Drivers Staying Close to Home. Inst. Transp. Stud, 2017.
[27]. California Air Resources Board. California’ s Advanced Clean Cars Midterm Review Appendix G: Plug-in Electric Vehicle In-Use and Charging Data Analysis. 2017, p. 29.
[28]. Nicholas, M., and G. Tal. Charging for Charging at Work: Increasing the Availability of Charging through Pricing. Institute of Transportation Studies, UC Davis, 2014.
[29]. Dunckley, J., and G. Tal. Plug-In Electric Vehicle Multi-State Market and Charging Survey. Presented at the EVS29, 2016.
[30]. Delmas, Magali A., Matthew E. Kahn, and Stephen L. Locke. "The private and social consequences of purchasing an electric vehicle and solar panels: Evidence from California." Research in Economics 71.2 (2017): 225-235.
[31]. Nicholas, Michael. "Ensuring Driving on Electricity Is Cheaper Than Driving on Gasoline." (2018).
[32]. Wu, Xing. "Role of workplace charging opportunities on adoption of plug-in electric vehicles–Analysis based on GPS-based longitudinal travel data." Energy Policy 114 (2018): 367-379.
[33]. Zhang, Qi, et al. "Factors influencing the economics of public charging infrastructures for EV–A review." Renewable and Sustainable Energy Reviews 94 (2018): 500-509.
[34]. Ge, Yanbo, and Don MacKenzie. Modeling Vehicle Choices and Charging Behavior of Plug-In Electric Vehicle Owners Jointly Using Dynamic Discrete Choice Model. No. 18-05951. 2018.
[35]. Williams, Brett, and J. DeShazo. "Pricing workplace charging: financial viability and fueling costs." Transportation Research Record: Journal of the Transportation Research Board 2454 (2014): 68-75.
[36]. Winn, Ryan. “Electric Vehicle Charging at Work Understanding Workplace PEV Charging Behavior to Inform Pricing Policy and Investment Decisions” UCLA Luskin Center for Innovation Report
[37]. Li, Shanjun, et al. "The market for electric vehicles: indirect network effects and policy design." Journal of the Association of Environmental and Resource Economists 4.1 (2017): 89-133.
[38]. “Electric power sales, revenue, and energy efficiency Form EIA-861 detailed data files,” U.S. Energy Information Administration, https://www.eia.gov/electricity/data/eia861
[39]. Davis, Lucas W. "Evidence of a homeowner-renter gap for electric vehicles." Applied Economics Letters (2018): 1-6.
[40]. Train, Kenneth E. Discrete choice methods with simulation. Cambridge university press, 2009.

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