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Effects of Charging Infrastructure Characteristics on Electric Vehicle Preferences of New and Used Car Buyers in the United States

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Abstract

The used car market is a critical element for the mass adoption of electric vehicles (EVs). However, most previous studies on EV adoption have focused only on new car markets. This article examines and compares the effects of charging infrastructure characteristics on the preferences for EVs among both new and used car buyers. This study is based on an online stated preference choice experiment among private car owners in the U.S., and the results of comparable binomial logistic models show that new and used car buyers generally share similar patterns in preferences for EVs, with exceptions for sensitivity toward fast charging time, and home charging solutions. Respondents' stated willingness to adopt an EV increases considerably with improvements in driving range, and the effects on new and used car buyers are similar. The study also finds that better availability of charging infrastructure largely increases preference for EVs. The results further reveal that slow and fast charging have complementary effects on encouraging EV adoption as the combination of public slow and fast charging can compensate for the unavailability of home charging.

Many jurisdictions worldwide have set ambitious goals for continued growth and mass adoption of all-electric vehicles (EVs) and significant new public and private investments in expanding EV markets are expected. To sustain market growth, EVs must be practical and attractive not only to new car buyers, but to used car buyers too. It is generally accepted that the relative attractiveness of EVs and other alternative fuel vehicles (AFVs) depends on several factors. These include up-front cost, operating costs including fuel (electricity) and maintenance, range, refueling/recharging time, the availability of refueling infrastructure, environmental impacts, and government incentives, as well as those factors that affect any vehicle purchase decision, such as vehicle size, performance, and features (*1–4*). In the case of EVs, many of these factors are determined by the characteristics of the charging infrastructure, that is, the number, type, locations, and pricing of charging stations.

Charging infrastructure has a significant effect on the adoption of EVs. Prior research generally indicates that to make EVs more attractive to consumers, charging opportunities should be made ubiquitous, fast, and inexpensive. However, in a world with budget constraints, tradeoffs must be made between these goals. Fortunately, many charging needs can be satisfied through relatively inexpensive infrastructure such as home-based level 1 charging (120 V, typically 2–5 mph of connection time), and workplace and other intracity charging provided mostly by less costly level 2 charging (208–240 V, typically 10–20 mph of connection time) (*5*). Although they serve relatively few charging events, expensive, high power direct current fast charging (DCFC) and extreme fast charging (XFC) are a key to making EVs feasible for longer, interurban trips, which is necessary if EVs are to attract mainstream consumers (*6–8*).

Home and workplace charging are found to be the most frequently used and the most influential charging infrastructure for encouraging consumers to purchase EVs (*9, 10*). Beyond private charging, Axsen and Kurani suggest that installation of public charging infrastructure

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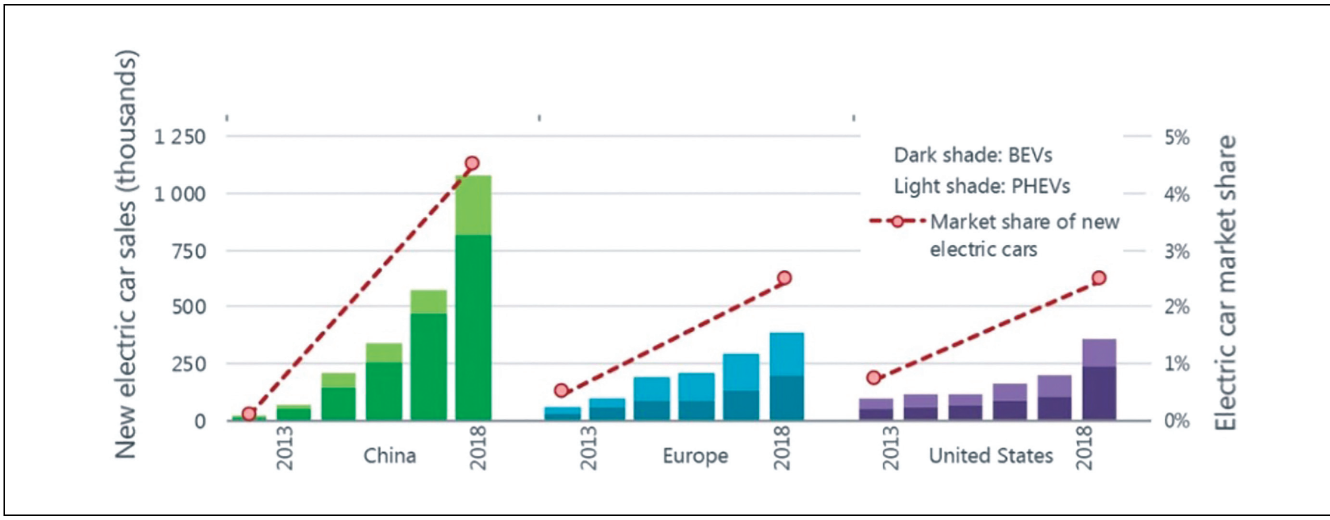

Figure 1. Global electric car sales and market share of selected regions, 2013–2018.
Note: BEVs = battery electric vehicles; PHEVs = plug-in hybrid electric vehicles.
Source: IEA Global EV Outlook 2019 (*15*).

may alleviate some of the functional concerns of car buyers (*11*). Neaimeh et al. found that fast chargers enabled battery electric vehicles (BEVs) to be used on journeys above their single-charge range, which would have been impractical using regular slow chargers (*12*). This suggests that fast chargers could help overcome perceived and actual range barriers, making BEVs more attractive to future users. While consumer preferences for EVs and EV charging infrastructure have been broadly studied previously, there is little consensus on how to direct investments to get the greatest public benefit per dollar spent on new charging infrastructure. Hardman et al. further indicate that in some areas of study, the literature is not sufficiently mature to draw any conclusions from, and suggests that more research is especially needed to determine how much infrastructure is needed to support the roll out of EVs (*9*).

Moreover, it has been almost a decade since the first release of commercially available EVs in 2010, and as more early adopters sell and replace their EVs, the used market for EVs will expand. However, most previous studies have focused on new car buyers and new EV markets, while less attention is paid to used EV adoption and secondary EV markets. A study in the Netherlands shows that secondhand AFV buyers are roughly twice as price sensitive as new AFV buyers, while preferences for other attribute levels including driving range, charging time, and detour time for charging are very comparable for buyers of new and secondhand cars (*1*). A study examining the status of the nascent secondary EV market in California shows that short-range used EV owners are charging their vehicles less than they could and early used EV buyers have significant knowledge gaps, such as being unaware of new EV purchase incentives, which reduces their ability to compare price options (*13*).

According to an Edmunds report, nearly 70% of all U.S. vehicle sales in 2018 were for used vehicles (*14*). Therefore, used EV sales have the potential to be very significant in the market as a whole (*13*). To reach the goal of mass adoption of EVs, the used car market is a critical element. Figure 1 shows global sales and market share of new EVs (including both BEVs and plug-in hybrid electric vehicles [PHEVs]) from 2013 to 2018 (*15*). The size of the used EV market should be expected to lag that of the new EV market, since it involves vehicles that are at least a year or two old. Growing the market for used EVs is essential to supporting resale values and maintaining demand for new EVs.

To shift used car buyers toward used EVs, it is necessary to understand used car buyers' preferences for and concerns about used EVs. Used car buyers are more likely to be low-income people who cannot afford a brand new EV, and "garage orphans" who do not have an off-street home parking space or accessible electricity outlets for home charging (*16*). Used EVs tend to be less expensive and so would be favored by potential used car buyers who want to adopt new technology at an affordable price, but the barrier of charging, especially home charging, still exists in most cases. Nevertheless, few prior studies have compared how new and used car buyers respond to the availability of charging infrastructure.

To fill in the gaps and for the purpose of providing a more forward-looking study toward a future with a wider range of EVs on both the used and new car markets, a stated preference choice experiment among new car buyers and used car buyers in the U.S. was conducted, via an online survey, to examine the effects of charging infrastructure characteristics on preferences for EVs. This study further attempts to provide potential charging solutions for encouraging garage orphans to adopt EVs.

This study contributes to the existing literature in several ways. First, it is one of the earliest nationwide investigations of preferences for used EVs in the U.S., which could provide a more comprehensive analysis and a broader insight into EV adoption. While it is currently not possible to find reliable data on the used EV sales and market share, this survey provides some insights into this. In this sample, 72 respondents own an EV. Among them, 11 respondents are used EV owners. Though the share of used EV owners (15%) is relatively small in the survey data, the forward-looking work is considering a future when EVs may be more competitive on both the used and new car markets, because of longer range, lower battery costs, and faster recharging times.

Second, this study reduces the choice burden of respondents by showing two purchase options, a conventional car versus an EV. Binary choices also have the potential to reduce hypothetical bias which arises when the results of a hypothetical experiment deviate from real market evidence. Previous studies explained that when there are only two choices, "the respondent has no incentive not to pick the one that maximizes their utility." With three or more alternatives, respondents may not always choose their most preferred option. For example, they may want to signal the importance of a low price even though the lowest price option is not their overall preferred alternative (*17–20*). So binary choices could lead to responses that are incentive compatible to truth revelation, allowing for collecting data of better quality and more accurate model results (*17*, *19*).

Third, this study focuses on charging infrastructure in more detail including location, type, and charging duration, enabling a more reliable inference of the effects of charging infrastructure characteristics on EV adoption, and could function as a reference for charging network design and infrastructure planning.

The rest of the paper is organized as follows. The next section explains the survey design and the data collection process, including attributes and attribute levels used in the choice experiment. Data analysis and model results are presented in the results and analysis section. The final section discusses findings and summarizes the paper with potential suggestions for future studies.

Survey Design and Data Collection

The choice experiment of this study is set in a context where respondents are buying their next personal car. Before the choice experiment, respondents answered questions about their socio-economic background and were asked about their preferences for a new car or a used car for next car purchase, and then were directed to scenarios of new car options or used car options accordingly. Respondents were also required to go through an introduction page before the experiment, which provided some basic information on EVs including energy source, different charging option technologies, and their charging speeds.

The choice experiment required respondents to make repeated choices between a conventional car powered by gasoline and an EV that runs solely on electricity but is otherwise identical to the conventional car. While existing studies show that financial, technical, infrastructure, and policy attributes all affect consumers' preferences for EVs, this study focuses on attributes of the charging infrastructure. Key attributes included in the study are purchase price, driving range, walking distance from the nearest slow charging options to home and to work, fast charging time, fast charging availability in town, and fast charging availability on the highway. The gasoline car option is the reference alternative with all attribute levels fixed throughout the entire experiment. All attributes and levels of the choice experiment are summarized in Table 1.

To avoid situations where the car purchase prices are too high for respondents to afford to buy, which would obscure the effects of other attributes on choices, respondents were asked first about the highest amount of money they anticipated spending on their next car purchase, for which they were provided eight price categories in a drop-down menu. Purchase prices in the choice experiment were pivoted around this maximum price, and prices would never exceed a respondent's selected budget limit. While BEV prices are at present significantly higher than those of comparable conventional vehicles, the interest is in understanding EV adoption in a future with lower price premiums (due, for example, to some combination of falling battery costs and sales quotas), so scenarios were included where the EV costs the same, or even less, than the gasoline car.

Driving range is one of the most important attributes of an EV and is likely to be related to car buyers' demand for charging infrastructure. Considering both the driving range of current EV models in market and the continuous improvement of battery technology, this choice experiment employed EV driving ranges from 100 mi to 400 mi while keeping the driving range of the gasoline car fixed at 400 mi.

Charging infrastructure availability in prior work has been operationalized as refueling distance, detour time to a fueling station, percentage of gas stations carrying an alternative fuel, and presence in common destinations (*1, 2, 21–24*). However, those measures are not conducive to providing specific recommendations to decision makers

Table 1. Attribute Levels Used in Choice Experiment

Attribute	Alternative	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7
Price (U.S. dollar)	Gasoline car	0.85×budget[a]	na	na	na	na	na	na
	EV	1.0×budget	0.85×budget	0.7×budget	na	na	na	na
Fuel cost (per 100 mi)	Gasoline car	$12	na	na	na	na	na	na
	EV	$4	na	na	na	na	na	na
Driving range (miles)	Gasoline car	400	na	na	na	na	na	na
	EV	400	300	200	100	na	na	na
Slow charging to home (minutes)	EV	0	1	2	3	5	10	20
Slow charging to work (minutes)	EV	0	1	2	3	5	10	20
Fast charging time	EV	5 min	15 min	30 min	1 h	na	na	na
Fast charging density in town	EV	5 min	10 min	15 min	No fast charging in town	na	na	na
Highway fast charging spacing (miles)	EV	30	50	70	No fast charging on highway	na	na	na

Note: EV = electric vehicle; na = not applicable (attribute doesn't have this level).
[a]Respondents' anticipated highest amount of money they would spend on their next car purchase.

for infrastructure investment (*25*). While Liao et al. tried to address this by noting the difference of distribution of charging stations in urban areas and on highways, they only specified fast charging stations and excluded slow charging options in their study (*25*). Therefore, this study includes both slow charging and fast charging solutions to enable policymakers to make tradeoffs between these different charging solutions.

Slow charging availability was presented as walking distance to home and to work measured in minutes, to examine car owners' preferences for public slow charging and their willingness to walk. It is assumed car owners park their EV at a nearby slow charging station and then walk back home or to work while waiting for a slow charge. The choice experiment also explained to respondents that it normally took 4–10 h to charge an electric car from empty to full using slow charging.

Similar to Liao et al., fast charging options were shown in relation to in-town density and highway spacing, measured in driving distance to a fast charging station from any place in town, and as distance between two fast charging stations along the highway, respectively. In this way, an optimal charging infrastructure distribution for both slow versus fast charging, and in-town versus highway, can be estimated (though it is left to future work) (*25*).

On top of location and density of fast charging, fast charging time is also shown in choice tasks. Many previous studies, such as Chorus et al. and Hackbarth and Madlener, did not distinguish between slow and fast charging and applied a wide range of charging times (usually 10 min–8 h) (*22, 23*). Rarely did they investigate the impact of a shorter charging time, where most of them have a lower bound of 10 min of full charge. Therefore, considering that XFC has made great technical progress, this study applies fast charging times ranging from 5 min to 1 h, aiming to enable a more reliable inference of the effects of reduced charging time on EV adoption, and to anticipate the benefits of advanced fast charging technologies.

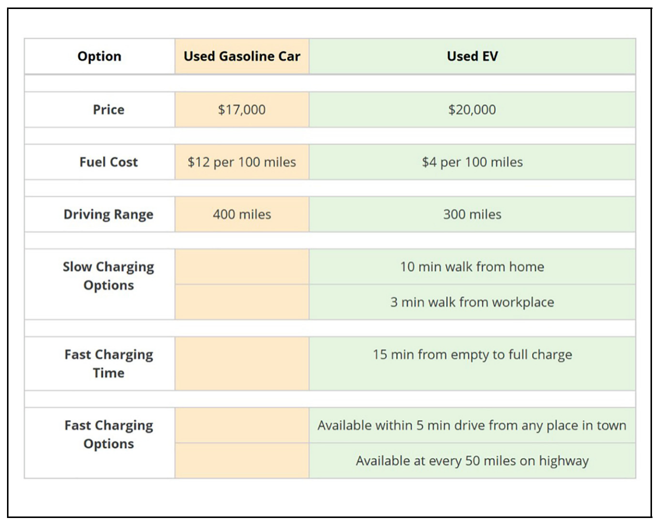

Figure 2. Screenshot of an example choice task.
Note: EV = electric vehicle.

The choice tasks were generated using an orthogonal design with 240 fractional factorial scenarios extracted from the full factorial combinations. Each respondent was randomly assigned to six of the 240 tasks. Figure 2 shows an example of a choice scenario for a respondent who prefers to buy a used car and would spend at most $20,000 for their next car purchase.

The survey was designed and implemented in SurveyMonkey, an online survey tool, and was distributed

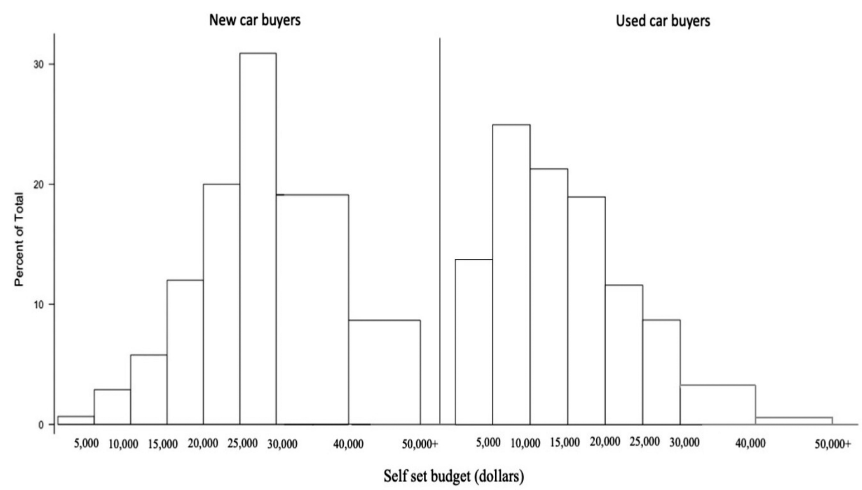

Figure 3. Distribution of respondents' self-set budgets.

through Amazon Mechanical Turk (MTurk), a crowd-sourcing system which has become increasingly popular as a tool for research, where the working population is found to be diverse across several notable demographic dimensions such as age, gender, and income (*26*). Respondents recruited were qualified as car owners who have completed 100 tasks on MTurk with a minimum 95% acceptance rate. MTurk workers who did not own a car, had completed fewer than 100 previous tasks on Mturk, or had an acceptance rate lower than 95% were excluded from recruitment. Respondents were sampled in proportion to population in the four time zones in the contiguous U.S.

To protect respondents' privacy and mitigate social desirability bias, the survey is anonymous (*27*, *28*). The respondents only provided their worker ID in Amazon Mturk to the researchers for the purpose of getting compensation after completing the survey. The researchers have no way to link the worker ID to an individual. Data anonymity is emphasized in the survey consent form before respondents could start answering questions and doing the choice experiment.

Data collection was conducted from June 28 to July 9, 2019. A total of 1,158 respondents started the survey, and 1,028 respondents completed it. Incomplete responses and responses containing contradictory answers were excluded. Finally, 983 responses were usable in the analysis. Table 2 summarizes the socio-demographics and basic characteristics of parking situation and personal car usage of the sample. Table 2 also presents socio-demographic characteristics of the U.S. population from the American Community Survey 2017 (5-year estimates) for comparison.

Table 2 shows that respondents intending to buy a used car reported a slightly lower level of education and lower income, and were less likely to be employed than the overall sample. Compared with the national population, the sample contains a higher proportion of employed people and people with higher education levels. Household income level of $25,000–$74,999 might be overrepresented in the sample. The proportion of all respondents identified as "garage orphans" (respondents who answered they only had on-street home parking space or had no accessible electricity outlet for home charging) was 78%, while this proportion is even higher among used car buyers (82%).

Figure 3 shows the distribution of respondents' self-set budgets. The median self-reported budget of all respondents is $20,000. Among the respondents, used car buyers' median budget is $15,000, and new car buyers' budget is $30,000. The mean new car purchase price in the U.S. was $37,401 in August 2019, according to a report from Kelley Blue Book (*29*). This discrepancy in new car prices is likely due in part to the comparison of a mean with a median in a right-skewed distribution.

Results and Analysis

To identify how preferences for EVs differ between new car and used car buyers, separate choice models were estimated for these two groups. The outcome variable in this study is the stated choice between a gasoline car and an electric car. Thus, a binomial logit model was employed in this study with the gasoline car set as the reference alternative. To convey the model results to a broader audience, counterfactual scenarios were simulated to examine and visualize the effects of variables of interest. Simulation is performed with the Simcf R package and visualized using the tile package.

Table 2. Background Characteristics for the 983 Respondents

Variable	Used car buyers	New car buyers	All respondents	National population
Time zone				
Eastern	46.7%	49.1%	47.8%	47.6%
Central	28.9%	28.7%	28.8%	29.0%
Mountain	5.4%	6.7%	6.0%	6.3%
Pacific	18.8%	15.7%	17.4%	17.1%
Total count	533	450	983	321,004,407
Gender				
Female	50.7%	48.3%	49.6%	49.2%
Male	49.3%	51.7%	50.4%	50.8%
Education level				
Less than bachelor's degree	49.9%	41.2%	45.9%	69.1%
Bachelor's degree and higher	50.1%	58.8%	54.1%	30.9%
Employment status				
Employed	82.0%	87.9%	84.7%	58.9%
Not employed	8.8%	3.3%	6.3%	4.3%
Other	9.2%	8.8%	9.0%	36.8%
Household income level				
Under $25,000	17.3%	7.0%	12.6%	21.3%
$25,000–$49,999	35.1%	26.4%	31.1%	22.5%
$50,000–$74,999	23.8%	27.7%	25.6%	17.7%
$75,000–$99,999	11.1%	17.0%	13.8%	12.3%
$100,000–$149,999	9.3%	15.6%	12.2%	14.1%
$150,000 or more	3.5%	5.7%	4.5%	12.1%
Vehicle ownership				
1	56.7%	49.9%	53.6%	45.8%
2	32.5%	40.8%	36.3%	27.2%
3	8.4%	8.0%	8.2%	6.3%
4 or more	2.4%	1.1%	1.8%	2.2%
Age	Min.: 19; mean: 40.1; median: 37; max.: 75	Min.: 19; mean: 40.6; median: 37; max.: 76	Min.: 19; mean: 40.3; median: 37; max.: 76	Median: 38
Used car owner				
Yes	87.6%	38.0%	64.9%	NA
No	12.4%	62.0%	35.1%	NA
Garage orphan				
Yes	82.2%	71.9%	77.5%	NA
No	15.6%	23.9%	19.4%	NA
Other	2.2%	3.9%	3.0%	NA
EV owner				
Yes	3.8%	11.4%	7.3%	NA
No	96.2%	88.6%	92.7%	NA
Monthly long-distance trip				
0	33.6%	23.3%	28.9%	NA
1	27.0%	26.3%	26.7%	NA
2	19.5%	28.5%	23.6%	NA
3	8.1%	9.2%	8.6%	NA
4 or more	11.8%	12.7%	12.2%	NA

Note: EV = electric vehicle; NA = not available; min. = minimum; max. = maximum.

The raw distributions of the outcome variable are presented in Figure 4 for used car and new car buyers. In this hypothetical choice experiment, EV prices and charging infrastructure attributes were presented that were more attractive than those in today's market, so the percentage of respondents choosing an EV as opposed to a gasoline car is higher than the current EV market share in the U.S.

Table 3 shows the estimation results of the final models for new and used car buyers. Preliminary modeling analysis showed that the proximity of slow charging to home has a significant positive effect on used car buyers' preferences for EVs, but a similar effect was not observed for new car buyers. Rather, new car buyers were sensitive to whether or not a charging option is available at their current home parking space. It is speculated that this

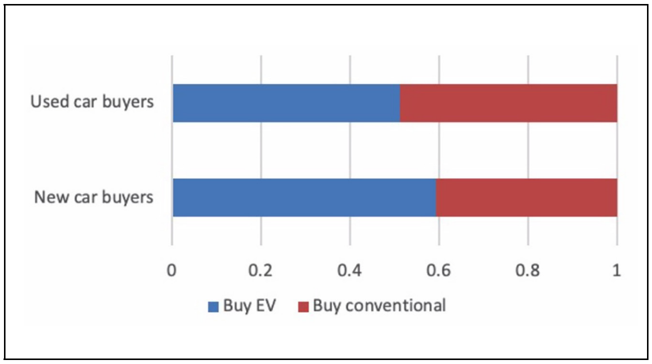

Figure 4. Distribution of respondents' stated choices.
Note: EV = electric vehicle.

difference may be because of the higher fraction of garage orphans among used car buyers (82% in the sample) than among new car buyers (72%). In Table 3, the final models with the best fit for new and used car buyers, respectively, are presented, which include the same set of explanatory variables, except for the specification of home-based slow charging. To examine whether the effects of slow charging will be affected by fast charging availability and vice versa, interactions between slow and fast charging are also added to the models. The results of the two binomial logit models are sensible, with all coefficients having the expected sign and most variables significant at the usual critical significance levels. The results also show similar patterns in preferences for EVs between new and used car buyers, which is consistent with conclusions by Hoen and Koetse (*1*).

Individual-Related Variables

In relation to car buyers' characteristics, results show that age plays an important role with non-linear effects as both linear and quadratic effects of age are significant. The model indicates that younger and older car buyers might be more likely to buy an EV than middle-aged people, all else equal. Figure 5 shows that the turning point for new car buyers is at about age 50 and the turning point for used car buyers is at around age 60. The findings suggest that the young and the elderly may be more likely to adopt EVs, which is consistent with the findings of Sovacool et al. (*30*). The model also suggests that, on average, male car buyers are more likely to buy EVs than

Table 3. Model Results

	New EV buyer model		Used EV buyer model	
Variables	Estimate	Standard error	Estimate	Standard error
Constant	0.6978	0.5568	1.2396	0.4664**
Vehicle related variables				
Price difference[a] (in $1,000)	−0.0877	0.0114**	−0.1176	0.0165**
Driving range of EV (mile)	0.0039	0.0004**	0.0035	0.0003**
Charging infrastructure variables				
Charging is available at home: 1; else: 0	0.6529	0.2270**	na	na
Walking distance from home to nearest slow charging (min)	na	na	−0.0603	0.0125**
Walking distance from work to nearest slow charging (min)	−0.0422	0.0133**	−0.0263	0.0110*
Fast charging time (min)	−0.0006	0.0020	−0.0048	0.0018**
Driving time to fast charging in town ≤15 min drive: 1; else: 0	0.6979	0.1375**	0.3545	0.1426*
Number of fast charging stations per 100 mi of highway	0.0476	0.0380	0.0220	0.0338
Individual characteristic variable				
Age	−0.0877	0.0246**	−0.0827	0.0206**
Age^2	0.0009	0.0003**	0.0007	0.0002**
Male	0.2740	0.0843**	0.2215	0.0749**
Person has an EV: 1; else: 0	0.7091	0.1454**	0.4833	0.2027*
Interactions				
Charging is available at home: 1; else: 0, and driving time to fast charging in town ≤15 min drive: 1; else: 0	−0.3430	0.2696	na	na
Walking distance from home to nearest slow charging (min) and driving time to fast charging in town ≤15 min drive: 1; else: 0	na	na	0.0286	0.0143*
Walking distance from work to nearest slow charging (min) and driving time to fast charging in town ≤ 15 min drive: 1; else: 0	0.0307	0.0152*	0.0097	0.0129
Number of observations	2,700		3,198	
Log-likelihood	−1660.83		−2056.54	
AIC	3349.7		4141.1	

Note: EV = electric vehicle; AIC = Akaike information criterion; na = not applicable (the variable is not included in the model).
[a]Purchase price of EV minus purchase price of gasoline car.
*$p < 0.05$; **$p < 0.01$.

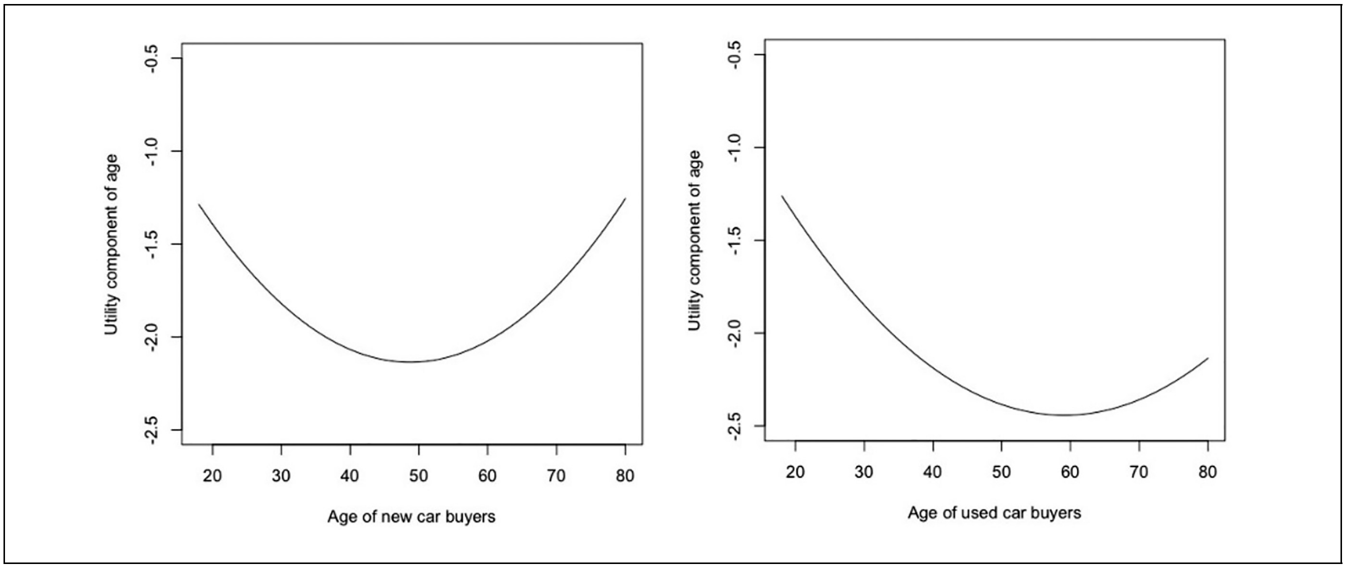

Figure 5. Utility component associated with age in the new car buyers' model.

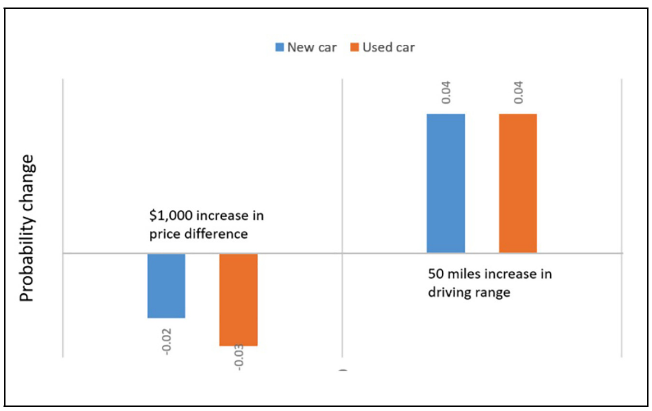

Figure 6. Marginal effect of price difference and driving range.

female buyers, and car buyers who are EV owners are significantly more likely to choose an EV for their next car purchase than individuals who currently do not own an EV.

Vehicle-Related Attributes

Using the marginal effects analysis, Figure 6 shows that as EV price gets relatively higher than the regular car, car buyers get less likely to buy the EV, and sensitivity toward price difference is similar for new and used car buyers. Figure 6 shows that, on average, for a $1,000 increase in the price premium of an EV, the probability of buying an EV decreases by 2 percentage points for new car buyers and by 3 percentage points for used car buyers.

As for driving range, Figure 6 shows that a 50 mi increase in EV driving range increases the probability of buying an EV by about 4 percentage points for both new and used car buyers, which suggests that increasing the driving range of EVs increases the probability of buying an EV significantly. The effects are quite similar for both new and used car buyers.

Charging Infrastructure

Through preliminary modelling, it appeared that new car buyers' preferences are not significantly affected by the walking distance from home to a slow charging opportunity. Rather, new car buyers are sensitive to whether they have a charging option at their current home parking space or not. On the other hand, for used car buyers, the proximity of slow charging to home has significant positive effects on the utility of an EV.

Based on this initial analysis and on model fit, in the final models, home charging attribute was thus modeled in two ways: a home charging availability dummy variable for new car buyers; and walking distance from slow charging to home for used car buyers. While an attempt was made to also capture any non-linear effect of the proximity of slow charging infrastructure, as well as other charging infrastructure related variables, the non-linear terms did not show significant influence at a 0.05 significance level. Also, by comparing log-likelihood and Akaike information criterion (AIC) values, those terms barely improved the model. Therefore, only linear teams were included in the final models. Preliminary model results are available from the authors on request.

As for work charging options, based on the estimation results in Table 3, new and used car buyers respond similarly to the negative effects of the proximity to workplace slow charging. When comparing the effects of the

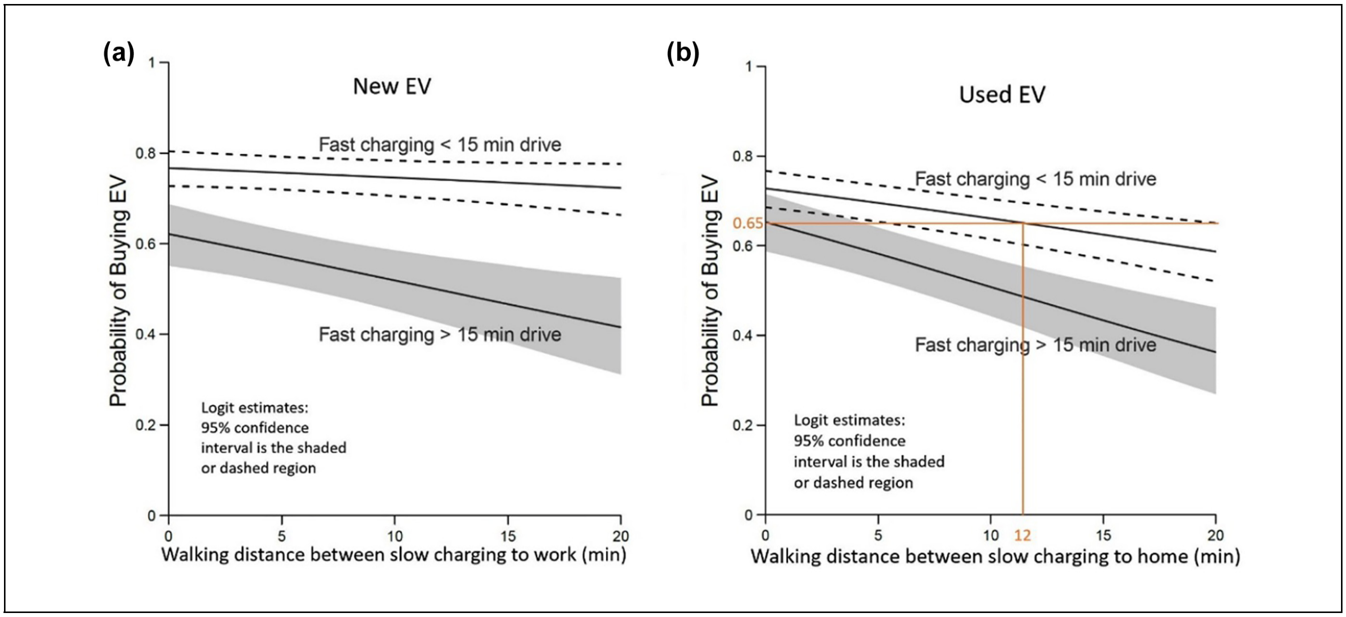

Figure 7. Interaction effects of fast charging and slow charging.
Note: EV = electric vehicle.

proximity of slow charging to home and to work, the coefficients of the used car buyer model show that the proximity to home has a larger effect than the proximity to work. Marginal effect analysis shows that a 1 min reduction in walking time from slow charging to home increases the probability of buying EV by 0.009, while it is 0.004 for 1 min change in proximity to work. This suggests that for the purposes of charging, used car buyers' sensitivity to walking distance from slow charging to home are roughly twice the sensitivity to walking distance from slow charging to work.

Table 3 shows that denser distributions of fast charging options around town and on the highway have positive effects on preferences for EVs among both new and used car buyers. Model results also show that a shorter fast charging time significantly increases used car buyers' preferences for EVs while the effect is not significant for new car buyers. The marginal effects were calculated which indicate that a 1 min decrease in fast charging time increases probability of buying an EV of new car buyers by 0.0001. This relatively small effect might suggest that within the range of fast charging times (5 min–1 h) provided in this choice experiment, varying fast charging duration has little effect on new car buyers' preferences for EVs. This result is in line with results provided by Liao et al. who also found that the duration of fast charging does not significantly affect the utility of EV for new car buyers (*25*).

Furthermore, the interactions between slow and fast charging options show that they have complementary effects. Significantly, better access to in-town fast charging reduces the disutility of having to walk between charging locations and work or home. Counterfactual scenarios were simulated to illustrate this effect while controlling for other factors. How the probability of buying an EV varies with slow and fast charging availability was simulated while holding everything else constant: price difference is zero, EV driving range is 400 mi, fast charging time is 30 min, and fast charging stations available every 50 mi on the highway. The car buyer is held as 40 years old, male, and owning no EVs currently. For new car buyers, home charging is held unavailable and for used car buyers, work charging is held available at workplace.

Figure 7 shows that with a denser distribution of in-town fast charging (available within a 15 min drive), the effects of slow charging proximity are smaller as the slope of the line between the dashed lines is flatter than in the shaded area (fast charging >15 min drive). These patterns show that the negative effects of the distance of slow charging to work (for new car buyers) and to home (for used car buyers) are mitigated by a denser distribution of fast charging in town.

Figure 7*b* also suggests that the combination of a dense distribution of in-town fast charging, with slow charging available 12 min away from home, can provide the same utility as having ubiquitous home charging with sparsely distributed fast charging in town. These interaction effects shed light on potential solutions to encouraging garage orphans to purchase EVs, especially for used car buyers. The combination of public slow and fast charging could possibly compensate for a lack of home charging for garage orphans. It is worth noting that it is not necessarily expected that the EV buying probability reported in Figure 7 will reflect current market shares, since in today's vehicle market, there are EVs in a relatively limited number of segments, EVs are more expensive than conventional vehicles, and charging infrastructure is relatively sparse.

Discussion and Conclusion

This paper analyzed the results from an online stated preference choice experiment among private car owners in the U.S., aiming to examine and compare the effects of charging infrastructure characteristics on preferences for EVs among new and used car buyers. Most prior studies focused only on new car markets while the differences between new and used car buyers have been ignored. In addition, detailed analysis of charging infrastructure characteristics is provided to support the roll out of EVs. The results show that while new and used car buyers share similar patterns in preferences for EVs, their sensitivity toward fast charging time and home charging solutions are different. This study also finds that slow and fast charging have complementary effects in alleviating concerns for charging.

The results indicate that used car buyers tend to respond to the distance of slow charging from their homes, whereas new car buyers respond simply to whether they can charge at home or not. It is speculated that this may be because they are more concerned about the safety of parking their brand new car overnight outside home parking space than used car buyers, or to the higher fraction of garage orphans (who are accustomed to parking away from their homes) among used car buyers. If this is the case, an effective public slow charging network would need to not only adopt an optimal density distribution, but also provide a parking environment that is safe for long-time parking and charging. In this way, both used and new EV owners would make good use of the facilities. This study also finds that people's willingness to walk for parking and charging at public slow charging stations is likely to be different for "near-home" than for "near-work" charging, with consumers being more sensitive to the distance from home to charging than to the distance from work to charging. This suggests that in general, to increase EV adoption rate, especially among used car buyers, slow charging infrastructure investment might need to prioritize residential areas and apply a denser distribution design. In addition to safety concerns, people's current parking behavior at home and at work may also play an important role in finding the optimal charging station distribution for different land use types.

While home and workplace charging are usually the top choices of charging for current EV owners, evidence from this study shows that the presence of fast charging significantly increases preferences for EVs and could compensate for sparsity of home or workplace charging. This indicates that a combination of public slow and fast charging could potentially be a charging solution for garage orphans whose home parking space is on the street or does not have access to electricity.

Since this study is based on a stated preference choice experiment, hypothetical bias may be present in the data, and the binary choice setting does not necessarily guarantee a reduction of such biases (*19*). Therefore, it should be noted that the results of this study may not precisely reflect respondents' preferences. Nevertheless, they can still be useful in identifying the relative importance of the attributes of interest and in directing future work (*31*).

Recognizing the limitations as well as the findings of this study, several future research opportunities in relation to the impact of charging infrastructure on consumer preferences for EVs are recommended. First, in addition to proximity, factors such as slow charging time and parking safety that affect car buyers' preferences for slow charging at public charging stations can be explored. Second, this study did not distinguish charging cost of slow and fast charging. Investigating the effects of charging costs and how they interact with charging type and location would add to the design of a more effective charging network, given the very different costs of constructing slow versus fast chargers. Lastly, local context is very important for any infrastructure investment. Future research on EV charging infrastructure could build on this nationwide study to conduct location-specific analyses in detail.

Author Contributions

The authors confirm contribution to the paper as follows: study concept and design: T. Zou, D. MacKenzie, M. Khaloei; data collection: T. Zou; analysis and interpretation of results: T. Zou, M. Khaloei, D. MacKenzie; draft manuscript preparation: T. Zou, M. Khaloei. All authors reviewed the results and approved the final version of the manuscript.

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Data Accessibility Statement

The data that support the findings of this study are available at https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/MOT6PN.

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