How Does Charging Network Design Affect Electric Vehicle Adoption?

FINAL PROJECT REPORT

by

Moein Khaloei
Tianqi Zou
Don MacKenzie
University of Washington, Department of Civil & Environmental Engineering

Sponsorship
Pacific Northwest Transportation Consortium (PacTrans)
Washington State Department of Transportation (WSDOT)

for
Pacific Northwest Transportation Consortium (PacTrans)
USDOT University Transportation Center for Federal Region 10
University of Washington
More Hall 112, Box 352700
Seattle, WA 98195-2700

In cooperation with U.S. Department of Transportation,
Research and Innovative Technology Administration (RITA)

DISCLAIMER

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle How Does Charging Network Design Affect Electric Vehicle Adoption?	**5. Report Date** 1/1/2020 **6. Performing Organization Code**
7. Author(s) and Affiliations Moein Khaloei Tianqi Zou Don MacKenzie University of Washington, Department of Civil & Environmental Engineering	**8. Performing Organization Report No.**
9. Performing Organization Name and Address PacTrans Pacific Northwest Transportation Consortium University Transportation Center for Federal Region 10 University of Washington More Hall 112 Seattle, WA 98195-2700	**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.**
12. Sponsoring Organization Name and Address United States Department of Transportation Research and Innovative Technology Administration 1200 New Jersey Avenue, SE Washington, DC 20590	**13. Type of Report and Period Covered** **14. Sponsoring Agency Code**

15. Supplementary Notes
Report uploaded to: www.pactrans.org

16. Abstract
The used car market is a critical element of the mass adoption of electric vehicles (EVs). However, most previous studies on EV adoption have focused only on new car markets. This report examines and compares the effects of charging infrastructure characteristics on preferences for electric vehicles among both new and used car buyers. This study used an online stated preference choice experiment among private car owners in the U.S. Two separate latent class models with 3 classes were built for used and new car buyers. The latent class model suggests that different groups of car buyers respond to different types of EV charging infrastructure. In addition, a detailed analysis of EV and charging infrastructure characteristics was provided to support the roll-out of EVs. The results of this work can be applied to quantify the tradeoffs between different types of investments in charging infrastructure. For example, the models can be used to determine what has the greatest effects on purchase choices: neighborhood slow charging near homes and workplaces, in-town fast charging stations, highway corridor fast charging, and conventional fast-charging versus extreme-fast-charging.

17. Key Words	**18. Distribution Statement**		
Electric Vehicle (EV), Charging Infrastructure, Used EV market, Latent class model, DCFC			
19. Security Classification (of this report)	**20. Security Classification (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified.	Unclassified.	28	N/A

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized.**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

The authors would like to acknowledge the Pacific Northwest Transportation Consortium (PacTrans) and Washington State Department of Transportation (WSDOT) for their support.

EXECUTIVE SUMMARY

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.

This study reports a choice experiment 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. Choice tasks designed in this study provide two purchase options, a conventional car powered by gasoline, and an electric version of the conventional car, identical in all ways except that it runs solely on electricity. While existing studies show that financial, technical, infrastructure, and policy attributes all affect consumers' preferences for EVs, this study focuses on attributes of the EV and the charging infrastructure. Key attributes included in the study are purchase price, driving range, walking distance of the nearest slow charging options to home and to work, fast charging time, fast charging availability in town, and fast charging availability on highway.

The online stated preference choice experiment collected data from 983 private car owners in the U.S. Each respondent was randomly assigned to 6 of the 240 tasks generated using an orthogonal design. In order to identify how preferences for EVs differ between new car and used car buyers, we estimated separate choice models for used car buyers and new car buyers. Then latent class logit model was chosen as the best model for further analysis. The latent class model suggests that different groups of car buyers respond to different types of EV charging infrastructure. The largest groups respond to having fast-charging stations available in town, and to having shorter walking access from charging stations to home and work. Smaller groups of both used and new car buyers are more sensitive to fast-charging time and to the spacing of fast-charging stations along the highway.

After building the choice model, a sensitivity analysis was conducted to examine how the vehicle choices of respondents vary with changes in different predictor variables. Then, the effects of varying different attributes including characteristics of EVs and charging infrastructures as well as the trade-off between these characteristics on the probability of buying new and used EVs rather than buying new and used gasoline cars were examined and compared in several scenarios while other predictors are assigned consistent values in all the scenarios.

The results of this work can be applied to quantify the tradeoffs between different types of investments in charging infrastructure. For example, the models can be used to determine what has the greatest effects on purchase choices: neighborhood slow charging near homes and workplaces, in-town fast charging stations, highway corridor fast charging, and conventional fast-charging versus extreme-fast-charging.

1. Introduction

Many jurisdictions worldwide have set ambitious goals for continued growth and mass adoption of 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 (Hoen and Koetse, 2014; Tanaka et al., 2014; Coffman et al., 2017; Liao et al., 2017). In the case of EVs, many of these factors are determined by the characteristics of the charging infrastructure, i.e. the number, type, locations, and pricing of charging stations.

Since charging infrastructure has a significant effect on the adoption of electric vehicles, prior research generally indicates that to make EVs more attractive to consumers, we should make charging opportunities 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 level 1 and level 2 charging points at homes, workplaces, and other intracity locations (TRB and National Research Council, 2015). Although they serve relatively few charging events, expensive, high power direct current fast charging (DCFC) and extreme fast charging (XFC) stations are a key to making EVs feasible for longer, interurban trips, which is necessary if EVs are to attract mainstream consumers (Fontaine, 2008; Botsford and Szczepanek, 2009; Jabbari et al., 2018).

Home and workplace charging are found to be the most frequently used and the most influential charging infrastructure that encourages consumers to purchase an EV (Dunckley and Tal, 2016; Hardman et al., 2018). Beyond private charging, Axsen and Kurani (2013) suggest that the installation of public charging infrastructure may alleviate some of the functional concerns of car buyers. Neaimeh et al. (2017) 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. 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 in order to get the greatest public benefit per dollar spent on new charging infrastructure. Hardman et al. (2018) 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.

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 (Hoen and Koetse, 2014). 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 reduce their ability to compare price options (Tal et al., 2017).

According to an Edmunds report (Edmunds, 2019a, 2019b), nearly 70% of all U.S. vehicle sales in 2018 were for used vehicles. Therefore, used EV sales have the potential to be very significant in the market as a whole (Tal et al., 2017). To reach the goal of mass adoption of EVs, the used car market is a critical target. To shift used car buyers towards 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 off-street home parking space or accessible electricity outlets for home charging (Seattle Office of Sustainability and Environment, 2014). 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, how the availability of charging infrastructure affects use car buyer's preference for used EVs and how those effects are different than on new car buyers are rarely investigated in prior studies.

To fill in the gaps, this study conducted a stated preference choice experiment among new car buyers and used car buyers in the U.S. 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 to 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. Second, this study reduces choice burden of respondents by showing two purchase options, a conventional car versus an EV, allowing for collecting data of better quality and more accurate model results. 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 report is organized as follows. The next section explains the survey design and the data collection process, including attributes and attribute levels used in our choice experiment. Data analysis and model results are presented in the results and analysis section. The final section discusses findings and summarizes the report with potential suggestions for future studies.

2. 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.

Choice tasks designed in this study provide two purchase options, a conventional car powered by gasoline, and an electric version – assuming everything else identical – of the conventional car, which runs solely on electricity. While existing studies show that financial, technical, infrastructure, and policy attributes all affect consumers' preferences for EVs, this study focuses on attributes of the EV and the charging infrastructure. Key attributes included in the study are purchase price, driving range, walking distance of the nearest slow charging options to home and to work, fast charging time, fast charging availability in town, and fast charging availability on 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 2.1.

Table 0.1 Attribute levels used in the choice experiment

Attribute	Alternative	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7
Price (US Dollar)	Gasoline car	0.85 *budget[1]						
	EV	1.0 *budget	0.85 *budget	0.7 *budget				
Fuel Cost (Per 100 Miles)	Gasoline car	$12						
	EV	$4						
Driving Range (Miles)	Gasoline car	400						
	EV	400	300	200	100			
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	5min	15 min	30 min	1h			
Fast Charging Density in Town	EV	5min	10 min	15 min	Not available			
Highway Fast Charging Spacing (Miles)	EV	30	50	70	Not available			

1 Respondent's anticipated highest amount of money they would spend on their next car purchase

To avoid situations where the car purchase prices are too high for respondents to afford to buy, resulting in ineffective detection of the effects of other attributes on preferences, respondents were asked about their anticipated highest amount of money they would spend on their next car purchase in advance, for which they were provided 8 price categories in a drop-down menu to choose from. Purchase prices in the choice experiment were pivoted around this maximum price, and prices would never exceed a respondent's selected budget limit.

Driving range is one of the most important attributes of an EV and is very much likely to be related to car buyers' demand for charging infrastructure. According to the driving range of current EV models in the market, and considering prospects for continued improvements in battery technology, this choice experiment varied the driving range of the EV from 100 miles to 400 miles while keeping the driving range of the gasoline car fixed at 400 miles.

Charging infrastructure availability in prior work has been operationalized as refueling distance, additional detour time beyond that needed to reach a gas station, percentage of the number of gas stations, and presence in common destinations (Chorus et al., 2013; Hoen and Koetse, 2014; Jensen et al., Tanaka et al., 2014; Valeri and Danielis, 2015). However, those measures are not conducive to providing specific implications to decision-makers for infrastructure investment (Liao et al., 2018). While Liao et al. (2018) 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. Therefore, this study includes both slow charging and fast charging solutions to enable policymakers to inform tradeoffs between investments in these different charging solutions.

Slow charging availability was presented as the walking distance (in minutes) to a charging point from home and from work. We assume 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 to 10 hours to charge an electric car from empty to full using slow charging.

Similar to Liao et al. (2018), fast charging options were shown in terms of in-town density and highway spacing. In-town density was specified as the driving distance to a fast charging station from any place in town, while highway spacing was specified as the distance between consecutive fast charging stations along the highway. In this way, an optimal charging infrastructure distribution for both slow vs. fast charging, and in-town vs. highway, can be estimated.

On top of location and density of fast charging, fast charging time is also shown in choice tasks. Previous studies (Chorus et al., 2013; Hackbarth and Madlener, 2013) did not distinguish between slow and fast charging and applied a wide range of charging times (usually 10 min – 8h). Rarely did they investigate the impact of a shorter charging time, where most of them have a lower bound of 10 minutes for a full charge. Therefore, considering that extreme fast charging has made great technical progress, this study applies fast charging times ranging from 5 minutes to 1 hour, 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.

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 6 of the 240 tasks. Figure 2.1 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 his or her next personal car purchase.

The survey was designed and implemented in SurveyMonkey, an online survey tool, and was distributed through Amazon Mechanical Turk (MTurk), a crowdsourcing 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 (Ross et al., 2010). Respondents recruited were qualified as car owners who have completed 100 tasks on MTurk with a minimum 95% acceptance rate, and were sampled in proportion to population in the four time zones in the U.S. Data collection was conducted from June 28 to July 9, 2019, and overall, 983 respondents completed the full survey with valid responses. Table 2.2 summarizes the socio-demographics and basic characteristics of parking situation and personal car usage of the sample. Table 2.2 also presents socio-demographic characteristics of the U.S. population reported by American Community Survey 2017 (5-year estimates) for comparison.

Table 2.2 shows that respondents intending to buy a used car reported a slightly lower level of education, lower income, and were less likely to be employed than the overall sample. Compared to the national population, our 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 out sample. 78% of all respondents are identified as garage orphans (respondents who answered they only had on-street home parking space or had no accessible electricity outlet for home charging), while this proportion is even higher among used car buyers (82%).

Option	Used Gasoline Car	Used EV
Price	$17,000	$20,000
Fuel Cost	$12 per 100 miles	$4 per 100 miles
Driving Range	400 miles	300 miles
Slow Charging Options		10 min walk from home
		3 min walk from workplace
Fast Charging Time		15 min from empty to full charge
Fast Charging Options		Available within 5 min drive from any place in town
		Available at every 50 miles on highway

Figure 0.1 Screenshot of an example choice task

Table 0.2 Background characteristics for the 983 respondents

Variable	Value	Used Car Buyers	All Respondents	National Population
Time Zone	Eastern	46.7%	47.8%	47.6%
	Central	28.9%	28.8%	29.0%
	Mountain	5.4%	6.0%	6.3%
	Pacific	18.8%	17.4%	17.1%
	Total count	**533**	**983**	
Gender	Female	50.7%	49.6%	49.2%
	Male	49.3%	50.4%	50.8%
Education level	Less than bachelor's degree	49.9%	45.9%	69.1%
	Bachelor's degree and higher	50.1%	54.1%	30.9%
Employment Status	Employed	82.0%	84.7%	58.9%
	Not employed	8.8%	6.3%	4.3%
	Other	9.2%	9.0%	36.8%
Household income level	Under $25,000	17.3%	12.6%	21.3%
	$25,000-$49,999	35.1%	31.1%	22.5%
	$50,000-$74,999	23.8%	25.6%	17.7%
	$75,000-$99,999	11.1%	13.8%	12.3%
	$100,000-$149,999	9.3%	12.2%	14.1%
	$150,000 and up	3.5%	4.5%	12.1%
Vehicle ownership	1	56.7%	53.6%	45.8%
	2	32.5%	36.3%	27.2%
	3	8.4%	8.2%	6.3%
	4 or more	2.4%	1.8%	2.2%
Age		Min: 19; Mean: 40.1; Median: 37; Max: 75	Min: 19; Mean: 40.3; Median: 37; Max: 76	Median:38
Used car owner	Yes	87.6%	64.9%	
	No	12.4%	35.1%	
Garage orphan	Yes	82.2%	77.5%	
	No	15.6%	19.4%	
	Other	2.2%	3.0%	
EV owner	Yes	3.8%	7.3%	
	No	96.2%	92.7%	
Monthly long-distance trip	0	33.6%	28.9%	
	1	27.0%	26.7%	
	2	19.5%	23.6%	
	3	8.1%	8.6%	
	4 or more	11.8%	12.2%	

3. Results

To identify how preferences for EVs differ between new car and used car buyers, we estimated separate choice models for used car buyers and new car buyers. The outcome variable in this study is the stated choice between a gasoline car and an electric car. Thus, binomial logit models and latent class logit models were employed in this study with the gasoline car set as the reference alternative. Table 3.1 shows the estimation results of the binomial models for new and used car buyers. The two models include the same set of variables except for home-related slow charging availability. 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.

Table 0.1 Binomial logit choice model results for new EV buyers and used EV buyers (Choice = 1 for EV, 0 for conventional vehicle).

Variables	New EV Buyer Model		Used EV Buyer Model	
	Estimate	Std. Error	Estimate	Std. Error
Constant	0.6978	0.5568	1.2396	0.4664**
Vehicle-related variables				
Price Difference[1] (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**	-	-
Walking distance from home to nearest slow charging (min)	-	-	-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**
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 miles 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 & Fast charging in town ≤ 15 min drive: 1; Else: 0	-0.3430	0.2696	-	-
Walking distance from home to nearest slow charging (min) & Fast charging in town ≤ 15 min drive: 1; Else: 0	-	-	0.0286	0.0143*
Walking distance from work to nearest slow charging (min) & 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	
Adjusted McFadden Pseudo R-squared	0.111		0.072	

1 Purchase price of EV minus purchase price of gasoline car

Note: *: significance at α=0.10. **: significance at α=0.05. ***: significance at α=0.01.

The latent class logit models were estimated by the "poLCA" package in RStudio. First, the appropriate number of classes was identified by comparing AIC, CAIC, and BIC for models with different number of classes. Table 3.2 indicates that despite the AIC and CAIC are decreasing as number of classes increase, the BIC is significantly increasing from three-classes model to the four and five-classes models. We made the choice of the optimal number of classes based on the BIC due to BIC's greater emphasis on model parsinomy, and the easier interpretability this provides. Thus, we selected the three-class models.

Table 0.2 Information criteria for various number of classes

Model	**Number of Classes**	**Log-Likelihood**	**AIC**	**CAIC**	**BIC**
New EV Buyers	2	-1405.9	2849.9	2850.1	2962.0
New EV Buyers	3	-1337.9	2735.8	2736.5	2912.8
New EV Buyers	4	-1317.2	2716.3	2717.6	2958.2
New EV Buyers	5	-1300.8	2705.6	2707.7	3012.4
Used EV Buyers	2	-1640.4	3318.7	3319.0	3434.0
Used EV Buyers	3	-1592.5	3245.0	3245.6	3427.1
Used EV Buyers	4	-1549.1	3180.1	3181.2	3429.0
Used EV Buyers	5	-1527.0	3157.9	3159.7	3473.6

Table 3.3 presents the estimation results of the three-class models for the new and used car buyers. The utility of class 3 was normalized as the reference level for both new and used EV buyers' models, so the estimates for these three variables are zero. Furthermore, the two models include the same set of variables and the estimates show high degrees of variation in tastes across the three classes. At first, all the demographic variables were included in the class allocation model. However, many were dropped because of multicollinearity and finally, age and gender were retained in the class allocation models.

According to the results, the latent class models show a better fit relative to the binomial logit models as well as the fact that latent class model is able to capture the heterogeneity of the respondents. Therefore, here we discuss the results of the latent class model as the final model for further analysis.

3.1. New EV Buyers' Model

The results in Table 3.3 indicate three classes of new EV buyers. Class 1 is the largest class, with about 45% of the respondents. Among EV-related attributes, the utility of a new EV for respondents in class 1 is mainly influenced by the price difference versus an equivalent gasoline car, and range. Also, respondents in class 1 weigh the range of an EV more than respondents in class 2 and class 3. Among charging infrastructure attributes, they are significantly affected by walking distance from home to nearest slow charging, walking distance from work to nearest slow charging, and whether an in-town fast charging station is available within a 15-minute drive. As can be seen, class 1 respondents consider in-town fast charging situation the most compared to other classes. According to the class allocation model, respondents in class 1 are more likely to be younger than 40 years old.

Class 2 represents about 35% of the respondents. Among EV-related attributes, class 2 respondents consider price difference and EV range as significantly important factors to buy a new EV. From the charging infrastructure perspective, class 2 respondents mainly respond to away-from-home charging opportunities including work and in-town fast charging. Based on the class allocation model, respondents in class 2 tend to be younger than 40 years old and male.

Table 0.3 Latent class choice model results for new EV buyers and used EV buyers

	New EV Buyer Model						Used EV Buyer model					
	Class 1		Class 2		Class 3		Class 1		Class 2		Class 3	
Variables	Estimate	P-value	Estimate	P-value	Estimate	P-value	Estimate	P-value	Estimate	P-value	Estimate	P-value
Result for Three-Class Model												
Constant	-3.005***	0.000	1.462***	0.004	-4.096***	0.000	-2.230***	0.000	-4.494***	0.000	2.002***	0.000
Vehicle related variables												
Price Difference1 (in $1,000)	-0.163***	0.000	-0.110**	0.032	-0.258***	0.000	-0.282***	0.000	-0.054	0.522	-0.259***	0.000
Driving range of EV (mile)	0.009***	0.000	0.004**	0.030	0.003	0.190	0.008***	0.000	0.006***	0.002	0.006***	0.000
Charging infrastructure variables												
Walking distance from home to nearest slow charging (min)	-0.034***	0.005	-0.020	0.353	-0.007	0.825	-0.049***	0.000	-0.432*	0.089	-0.089***	0.000
Walking distance from work to nearest slow charging (min)	-0.036***	0.004	-0.046**	0.041	-0.010	0.757	-0.022*	0.054	-0.043	0.430	-0.053***	0.004
Fast charging in town ≤ 15 min drive: 1; Else: 0	1.891***	0.000	1.021***	0.004	0.549	0.301	0.911***	0.000	1.213**	0.048	0.726**	0.014
Number of fast charging stations per 100 miles of highway	0.062	0.390	0.010	0.888	0.317*	0.098	0.014	0.470	0.317*	0.102	0.044	0.932
Fast charging time (min)	-0.003	0.561	-0.001	0.192	-0.003**	0.024	-0.006*	0.085	0.0003	0.967	-0.016**	0.016
Class Allocation Model												
Constant	1.043***	0.000	0.655**	0.034	0.000	fixed	0.197	0.372	-0.469*	0.053	0.000	fixed
Age of respondent ≥ 40	-0.623**	0.040	-0.848***	0.006	0.000	fixed	0.198	0.439	0.951***	0.000	0.000	fixed
Male respondent: 1; Else: 0	0.160	0.592	0.553*	0.066	0.000	fixed	-0.191	0.437	-0.453*	0.075	0.000	fixed
Membership Probability	0.451		0.346		0.203		0.401		0.261		0.338	
N	2700						3198					
AIC	2735.8						3245.0					
LL	-1337.9						-1592.5					
Adjusted McFadden Pseudo R-squared	0.27						0.27					

1 Purchase price of EV minus purchase price of gasoline car; *: significance at α=0.10. **: significance at α=0.05. ***: significance at α=0.01.

Class 3 is the smallest class, with about 20% of the respondents. Compared to class 1 and class 2, Class 3 respondents appear to be the most affected respondents by the price difference. Aside from price, Class 3 respondents are sensitive to fast-charging time and the spacing if fast-charging stations along the highway.

3.2. Used EV Buyers' Model

The results in Table 3.3 indicate three classes of used EV buyers. Class 1 is the largest class, with about 40% of the respondents. Respondents in this class appear to consider a larger number of factors when they decide whether to buy a used EV: EV price and range, walking distance from home and work to slow charging, fast-charging time and the availability of fast charting stations around town. The only variable that is not a significant predictor of choice in class 2 is number of fast charging stations per 100 miles of highway. Respondents in class 1 are less likely to be male and more likely to be over 40.

Class 2 is the smallest class, comprising about 26% of the respondents. Among this group, price is not a significant predictor of choice, but EV range is. From the infrastructure perspective, Class 2 respondents are sensitive to home charging access, in-town fast-charging, and highway fast charging accessibility. Notably, Class 2 is the only class in which number of fast charging stations per 100 miles of highway was significant. According to the class allocation model, respondents in class 2 tend to be older than 40 years old and female.

Class 3 represents about 34% of the used car buyers, and this group responds to the same factors as Class 1 respondents. While they are similarly sensitive to price and range, Class 3 respondents are more sensitive to walking distance from home and work to charging stations, and to fast charging time. They are less sensitive to the presence of fast-charging stations in town, though this factor still influences their choice.

4. Sensitivity Analysis

After building the choice model, a sensitivity analysis was conducted to examine how the vehicle choices of respondents vary with changes in different predictor variables. In this section, the effects of varying different attributes including characteristics of EVs and charging infrastructures as well as the trade-off between these characteristics on the probability of buying new and used EVs rather than buying new and used gasoline cars are examined and compared in several scenarios. It should be noted that whenever in the following scenarios one or two of the predictors are varied, other predictors are assigned the values indicated in Table 4.1. Probabilities are calculated by averaging over all respondents in our sample probabilities predicted by the the latent class choice models in Table 3.3.

The probability estimated using all the variables with the values in this table are 47.0% probability of choosing an EV for used car buyers, and 51.2% for new car buyers. This represents a baseline or reference point for the scenarios that follow.

Table 4.1. The value assigned to other variables when one/two of the variables are varied

Predictor	**Value**
Fast charging in town ≤ 15 min drive: 1; Else: 0	0
Number of fast charging stations per 100 miles of highway	1
Fast charging time	30 min
EV Range	200 miles
Price difference (Purchase price of EV minus purchase price of gasoline car) in $1000	$0
Walking distance from home to nearest slow charging (min)	0 (at-home charging)
Walking distance from workplace to nearest slow charging (min)	0 (at-workplace charging)

4.1. Characteristics of Charging Infrastructures

In a set of scenarios, the impacts of slow and fast charging infrastructure characteristics on the probability of buying an EV are examined.

4.1.1. Fast Charging Facilities

Using the model built in this study, the impact of fast charging station availability (including in-town and highway charging stations) on the probability of buying a used EV rather than a used gas car and a new EV rather than a new gas car has been explored separately.

Figure 4.1 presents the change in the probability of buying a new EV and a used EV if an in-town DC fast charging station with different charging times is accessible by driving no more than 15 minutes. The solid lines show how the average choice probabilities vary with fast-charging time at in-town charging stations. The dashed lines show the reference level choice probabilities, without fast-charging being available in-town. Several features of Figure 4.1 are notable. Both used and new car buyers are sensitive to in-town fast charging. Used car buyers are somewhat more sensitive to charging time than are new car buyers. However, both groups are influenced much more by the simple presence of in-town fast charging, than they are by the actual charging time (at least over the range of charging times considered in this work).

The impact of a highway fast charging station available in every 100 miles of highways with different charging times on the probability of buying an EV is displayed in Figure 4.2. In contrast to in-town fast charging, the effect of charging time at highway fast charging stations is greater on new car buyers than on used car buyers, but both are less sensitive than they are to in-town fast-charging times.

4.1.2. Trade-off between Fast Charging Facilities

Comparing Figure 4.1 with Figure 4.2 for used car buyers, it is possible to estimate the number of fast charging stations per 100 miles on the highway that provides the same utility as having fast charging available within a 15-minute drive in town. The results are summarized in Table 4.2 for different fast-charging times. Since a highway fast charging station only slightly impacts the new car buyers, they are excluded from Table 4.2.

Table 0.2 The spacing of highway fast charging stations that provides equivalent utility to having in-town fast charging available within 15 minutes from anywhere in town. (For used car buyers.)

Fast charging time	Equivalent number of highway fast charging stations in 100 miles	Spacing of highway fast charging stations (miles)
5	3.8	26.3
10	4.5	22.2
15	5.5	18.2
20	7.5	13.3
25	12.6	7.9

4.1.3. Slow Charging facilities

In this scenario, the effect of decreased walking time to the nearest slow charging facility on EV choice probabilities has been assessed both for home and workplace charging opportunities.

As shown in Figure 4.3, decreasing the walking time from home to the nearest slow charging facility available, has a stronger effect on used car buyers than on new car buyers. However, the decreased walking time from workplace to the nearest slow charger available, as shown in Figure 4.4, has a similar effect on both used and new car buyers to choose an EV over a gas car.

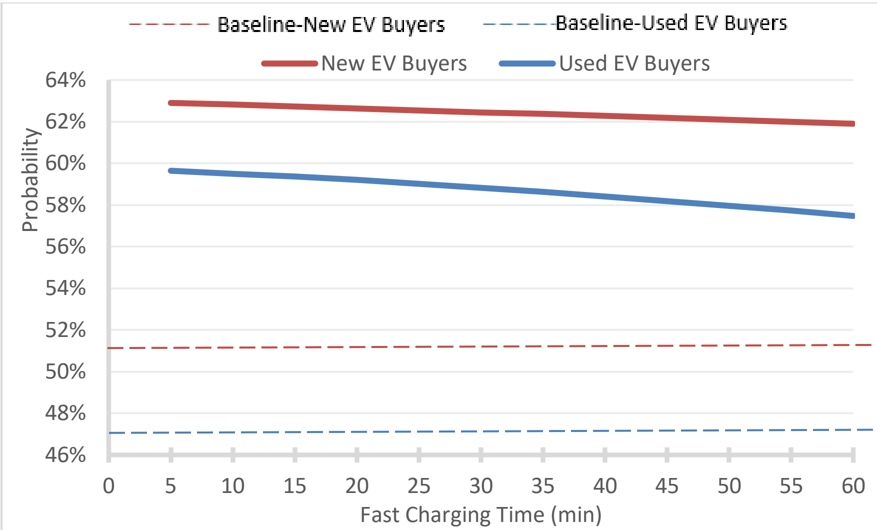


Figure 0.1 Impact of an in-town fast charging station with different charging times on the probability of buying an EV

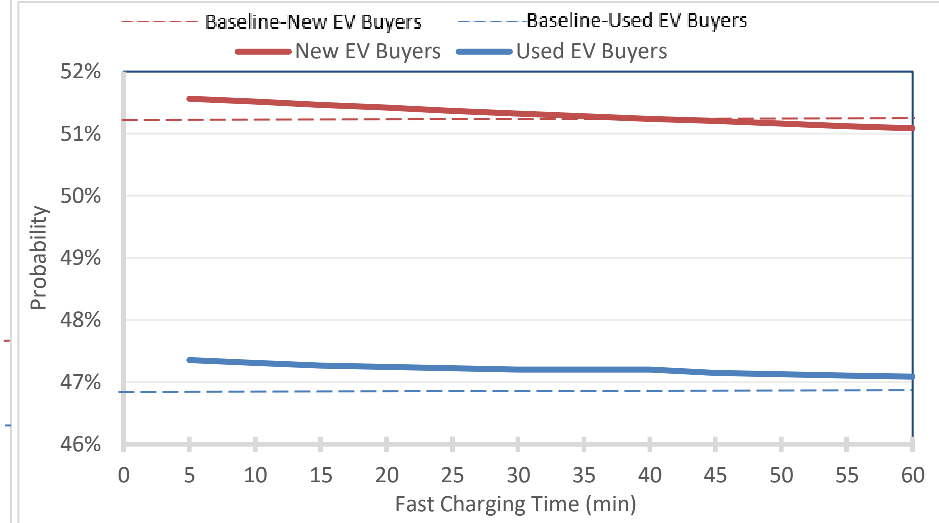


Figure 0.2 Impact of a highway fast charging station in 100 miles with different charging times on the probability of buying an EV

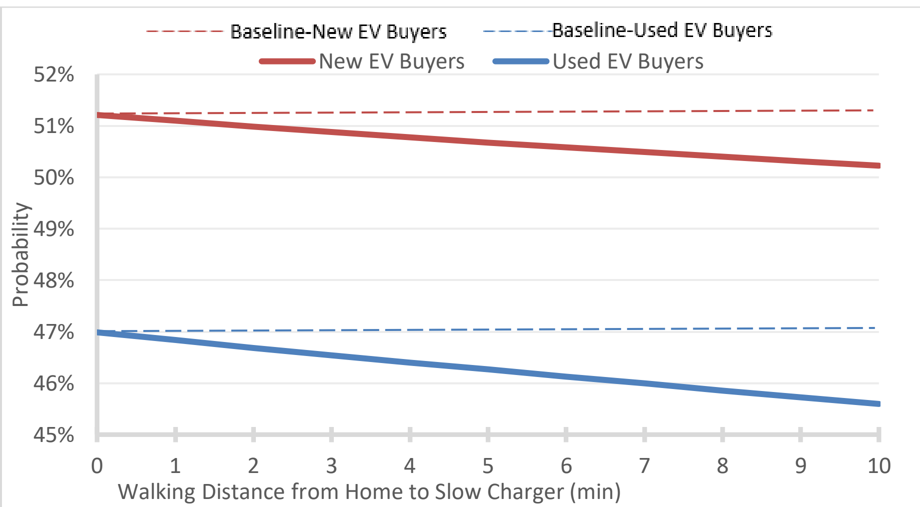


Figure 0.3 Impact of different walking times from home to the nearest slow charging facility on the probability of buying an EV

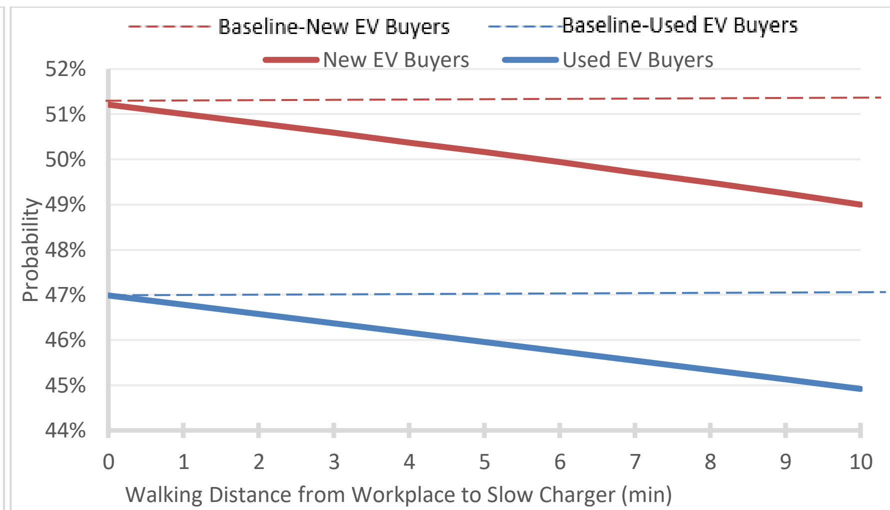


Figure 0.4 Impact of different walking times from workplace to the nearest slow charging facility on the probability of buying an EV

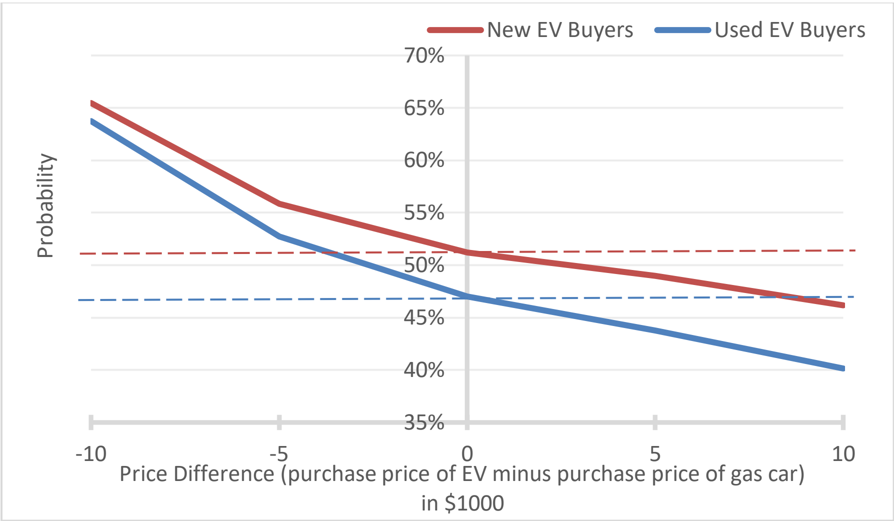
4.2. Characteristics of Electric Vehicles

The two main characteristics of an electric vehicle found as significant in the final model were (1) the price difference between an EV and an equivalent gasoline car, and (2) the range of EV. In this section, the impact of each EV characteristic separately and as a trade-off between them is examined.

4.2.1. Electric Vehicle Price and Range

The effects of varying price difference and range of EV on the probability of buying an EV for both used and new car buyers have been displayed in Figures 4.5 and 4.6, respectively. As can be seen, used EV buyers are slightly more sensitive to the price difference than new EV buyers.

In addition, Figure 4.6 indicates that increased EV range has virtually the same effect on the probability of buying an EV rather than a gas car for both used and new car buyers.



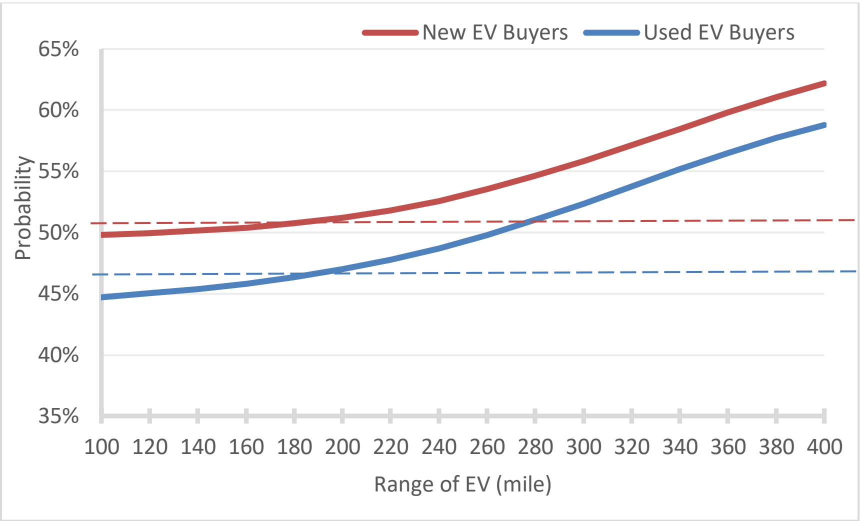


Figure 0.5 Impact of various price differences on the probability of buying an EV

Figure 0.6 Impact of EV range on the probability of buying an EV

4.3. Trade-off between Characteristics of Electric Vehicle and Charging Infrastructure

4.3.1. Electric Vehicle Price and Home Slow Charging Facilities

As mentioned, one of the important factors that could encourage a potential buyer to choose an EV, either new or used, over a gasoline car is home charging availability and/or proximity to a slow charging facility for those who are not able to charge their car at home. In this scenario, we calculated the change in price needed to maintain the utility constant as walking time from home to the charging location increases by one minute. Results show that if the purchase price difference is decreased about $176 for new car buyers and $194 for used car buyers with every one minute increase in the walking time from home to the nearest slow charging facility, the utility of buying an EV does not change. This finding suggests that for a potential buyer who is not able to charge at home, a minimum decrease of $176 for new car buyers and $194 for used car buyers in the purchase price of an EV might persuade them to consider buying an EV rather than a gasoline car.

5. Conclusion

This study 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 EV and charging infrastructure characteristics on preferences for EVs of new and used car buyers. Most efforts of previous studies focused only on new car markets while the differences between new and used car buyers have been ignored. In this regard, two separate latent class models with 3 classes were built for used and new car buyers. In addition, a detailed analysis of EV and charging infrastructure characteristics was provided to support the roll-out of EVs. Our results show that while new and used car buyers share similar patterns in preferences for EVs, their sensitivity towards price difference between EV and gasoline car, and characteristics of charging infrastructures including fast charging time, accessibility to in-town fast charging, highway fast charging, and home charging facilities are different.

The latent class model suggests that different groups of car buyers respond to different types of EV charging infrastructure. The largest groups respond to having fast-charging stations available in town, and to having shorter walking access from charging stations to home and work. Smaller groups of both used and new car buyers are more sensitive to fast-charging time and to the spacing of fast-charging stations along the highway. Results from sensitivity analysis show that used EV buyers are slightly more sensitive to the price difference than new EV buyers while increased EV range has virtually the same effect on the probability of buying an EV rather than a gas car for both used and new car buyers.The results of this work can be applied to quantify the tradeoffs between different types of investments in charging infrastructure. For example, the models can be used to determine what has the greatest effects on purchase choices: neighborhood slow charging near homes and workplaces, in-town fast charging stations, highway corridor fast charging, and conventional fast-charging versus extreme-fast-charging.

Since the study is based on a stated preference choice experiment, in order to reduce respondent's choice burden, among many charging infrastructure characteristics only a limit number of attributes of interest were included in choice tasks. Based on this limitation and findings of this study, we recommend several future research opportunities regarding the impact of charging infrastructure on consumer preferences for electric vehicles. 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 station 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. Lastly, local context is very important for any infrastructure investment. Future research on EV charging infrastructure could build on this nationwide study to conduct local-specific analysis in detail.

6. References

Axsen, J. and K. S. Kurani. Hybrid, Plug-in Hybrid, or Electric — What Do Car Buyers Want ? Energy Policy, 2013. 61: 532–543.

Botsford, C. and A. Szczepanek. Fast Charging vs. Slow Charging: Pros and Cons for the New Age of Electric Vehicles. EVS24 Symposium, Stavanger, Norway, 2009.

Chorus, C. G., M. J. Koetse, and A. Hoen. Consumer Preferences for Alternative Fuel Vehicles: Comparing a Utility Maximization and a Regret Minimization Model. Energy Policy, 2013. 61: 901–908.

Coffman, M., P. Bernstein, and S. Wee. Electric Vehicles Revisited: A Review of Factors That Affect Adoption. Transport Reviews, 2017. 37(1): 79–93.

Dunckley, J. and G. Tal. Plug-in Electric Vehicle Multi-State Market and Charging Survey. EPRI, Palo Alto, CA, 2016. 3002007495.

Edmunds. Automotive Industry Trends: Midyear Update. 2019a. https://www.edmunds.com/industry/insights/. Accessed July 13, 2019.

Edmunds. Used Vehicle Market Poised for Record Sales in 2019, According to New Report from Edmunds. 2019b. https://www.edmunds.com/industry/press/used-vehicle-market-poised-for-record-sales-in-2019-according-to-new-report-from-edmunds.html. Accessed July 13, 2019.

Fontaine, P. J. Shortening the Path to Energy Independence: A Policy Agenda to Commercialize Battery-Electric Vehicles. Electricity Journal, 2008. 21(6): 22–42.

Hackbarth, A. and R. Madlener. Consumer Preferences for Alternative Fuel Vehicles: A Discrete Choice Analysis. Transportation Research Part D: Transport and Environment, 2013. 25: 5–17.

Hardman, S., A. Jenn, G. Tal, J. Axsen, G. Beard, N. Daina, E. Figenbaum, N. Jakobsson, P. Jochem, N. Kinnear, P. Plötz, J. Pontes, N. Refa, F. Sprei, T. Turrentine, and B. Witkamp. A Review of Consumer Preferences of and Interactions with Electric Vehicle Charging Infrastructure. Transportation Research Part D, 2018. 62: 508–523.

Hoen, A. and M. J. Koetse. A Choice Experiment on Alternative Fuel Vehicle Preferences of Private Car Owners in the Netherlands. Transportation Research Part A: Policy and Practice, 2014. 61:199–215.

Jabbari, P., M. Khaloei, and D. MacKenzie. Locating Fast Charging Stations for Safe and Reliable Intercity Electric Vehicle Travel in Washington. Presented at 97th Annual Meeting of the Transportation Research Board, Washington, D.C., 2018.

Jensen, A. F., E. Cherchi, and S. L. Mabit. On the Stability of Preferences and Attitudes before and after Experiencing an Electric Vehicle. Transportation Research Part D: Transport and Environment, 2013. 25: 24–32.

Liao, F., E. Molin, H. Timmermans, and B. van Wee. The Impact of Business Models on Electric Vehicle Adoption: A Latent Transition Analysis Approach. Transportation Research Part A: Policy and Practice, 2018. 116: 531–546.

Liao, F., E. Molin, and B. van Wee. Consumer Preferences for Electric Vehicles : A Literature Review. Transport Reviews, 2017. 37(3): 252–275.

Neaimeh, M., S. D. Salisbury, G. A. Hill, P. T. Blythe, D. R. Scoffield, and J. E. Francfort. Analysing the Usage and Evidencing the Importance of Fast Chargers for the Adoption of Battery Electric Vehicles. Energy Policy, 2017. 108: 474–486.

Noparumpa, T. and K. Saengchote. The Impact of Tax Rebate on Used Car Market: Evidence from Thailand. International Review of Finance, 2017. 17(1): 147–154 10.

Ross, J., A. Zaldivar, L. Irani, and B. Tomlinson. Who Are The Turkers? Worker Demographics in Amazon Mechanical Turk. CHI EA, 2010.

Seattle Office of Sustainability and Environment. Removing Barriers to Electric Vehicle Adoption by Increasing Access to Charging Infrastructure. 2014.

Tal, G., M. A. Nicholas, T. S. Turrentine, and T. Turrentine. First Look at the Plug-in Vehicle Secondary Market. EVS30 Symposium, Stuttgart, Germany, 2017.

Tanaka, M., T. Ida, K. Murakami, and L. Friedman. Consumers' Willingness to Pay for Alternative Fuel Vehicles: A Comparative Discrete Choice Analysis between the US and Japan. Transportation Research Part A: Policy and Practice, 2014. 70: 194–209.

TRB and National Research Council. Overcoming Barriers to Deployment of Plug-in Electric Vehicles. Washington, DC: The National Academies Press, 2015. https://doi.org/10.17226/21725.

Turrentine, T., G. Tal, and D. Rapson. The Dynamics of Plug- in Electric Vehicles in the Secondary Market and Their Implications for Vehicle Demand, Durability, and Emissions. UC Davis: National Center for Sustainable Transportation. 2018.

Valeri, E. and R. Danielis. Simulating the Market Penetration of Cars with Alternative Fuelpowertrain Technologies in Italy. Transport Policy, 2015. 37: 44–56.