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Full Length Article

Toward just and equitable mobility: Socioeconomic and perceptual barriers for electric vehicles and charging infrastructure in the United States

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ABSTRACT

Based on a large-scale public survey, we identify and quantify the significance of key factors associated with the deployment of electric vehicles and charging infrastructure. Our results indicate that individual characteristics, such as income, age, region, and single vs. multi-family housing type can significantly affect electric vehicle purchase preferences, especially those concerning overnight charging and perceptions of benefits and barriers. Moreover, our results challenge earlier findings in the literature by showing how certain elements, such as expected electric driving range, certain travel behaviors (e.g., driving distance, destination types), the most common perceived benefits (e.g., cleaner air) or barriers (e.g., reliability concerns), and preferred location for public charging seem to not vary much or at all with the socioeconomic, demographic, and geographical variables examined in this study. We conclude with the implications for policies to advance equitable vehicle electrification. Our findings underscore the importance of lower-cost models of electric vehicles, home and public charging access, charging infrastructure planning, more integrated analysis of interlinked housing and transportation needs and solutions, the availability of alternative transportation modes, and the potential role of gas stations for electric vehicles. We encourage others to build on these results and have shared our complete survey instrument as an added contribution.

1. Introduction

In August 2021, President Biden signed an Executive Order 14,037 that sets a target to make half of all new vehicles sold in the United States in 2030 “zero emission” (including plug-in and fuel cell electric vehicles) [1]. Given that emissions of carbon dioxide from transportation accounted for the largest portion (38 %) of energy-related emissions of any sector of the U.S. economy that year [2], it is not hard to see why vehicle electrification – in conjunction with decarbonization of electricity production – is a key element in national climate change mitigation strategies. Certain states have set even more ambitious targets, such as in California [3] and New Jersey [4], where state governments have declared that by 2035, 100 % of new cars sold in the state will be “zero-emission.”

How do these ambitious goals compare with progress to date? As of October 2023, about 10 % of all new light-duty vehicles sold in the United States were plug-in electric vehicles (PEVs) including plug-in hybrid electric vehicles (2 % market share) and battery-electric vehicles (BEVs, 8 % market share) [5]. PEVs are becoming less and less expensive, partly owing to the significant decrease in PEVs’ high-voltage traction battery prices, e.g., from $1200 per kWh of energy storage in 2010 to $130 per kWh in 2021 [6]. Market penetration of PEVs is projected to increase exponentially over the next few decades, potentially accounting for 50 % or more of all new light-duty vehicle sales in the US by 2035 [7].

An impending tide of vehicle electrification is on the horizon [8], but

Abbreviations: BEV, battery-electric vehicle; MFH, multifamily housing; NHTS, national household travel survey; PEV, plug-in electric vehicle; SFH, single-family home; SUV, sport utility vehicle; π_{ij}, multinomial distribution for the *i*-th response and *j*-th category; β, logistic regression coefficient; *X*, independent variable; *ROR*, relative odds (or risk) ratio.

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various challenges stand in the way of sufficiently rapid expansion. For example, the supply and recycling of raw materials for batteries remains an issue [9]. In addition, despite the significant drop in PEV battery price, PEVs (BEVs in particular) still tend to be more expensive to own compared to their internal combustion engine vehicle counterparts [10]. Also, concerns regarding electric driving range persist for BEVs. Today's onboard battery capacity, 30–100 kWh, for BEVs provides 100–400 miles per full charge [11], which is relatively shorter than their internal combustion engine vehicle counterparts (250–700 miles per full tank) [12]. The lack of widespread, affordable, reliable, and reasonably fast charging infrastructure is another prime contributor to the persistence of concerns about electric driving range, especially beyond the boundaries of cities and towns.

While vehicle electrification is important for climate change mitigation, it is critical to ensure that the transition is equitable for all communities, as acknowledged by an Executive Order by President Biden [13]. Up to the present time, however, most PEVs have been adopted by a limited socioeconomic and demographic group of consumers (principally high-income homeowners) [14]. This may be attributable to expensive purchase prices of PEVs and the issues around home charging access. As of November 2023, the U.S. (new) PEV market is dominated by BEVs (as opposed to plug-in hybrid electric vehicles), of which Tesla represents around 57 % [15], slightly down from about 65 % of sales in 2022 [16]. The cheapest Tesla BEV is the Model 3 (20 % of market share in 2023), which costs $40,000 to $53,000 (without any PEV rebates) [17]. This price range, without any rebates, is similar to the conventional gasoline-powered BMW 3 series, for which manufacturer's suggested retail price starts at around $42,000 [17], meaning that the BEV market is largely driven by luxury cars – entry-level and/or high-end pricewise. For BEVs under $30,000, the bestselling car is the Chevy Bolt EUV (6 % market share), which starts at $27,000, similar in price to the Nissan Leaf with 1 % market share [17]. This is relatively cheaper, but the market share/impact within the BEV market is very small (3 %). Purchasing a brand new Tesla with a price tag of $50,000 (average of Model 3 and Model Y) would result in $830 monthly payment, with $7500 federal rebates [18], whereas average monthly consumer expenditure for a new and used vehicle was $730 and $533, respectively, in 2023 [19]. By and large, most new BEVs available in the market today would be simply out of reach for many households, as median household income in the United States is just over $70,000 [20].

Unequal access to home charging is another factor that contributes to the domination of PEV deployment by a limited socioeconomic group of consumers [21]. High-income earners are not only more likely to have the means to purchase PEVs, but also more likely to live in single-family homes (SFHs), rather than homes in multifamily units. Residents of SFH are more likely to have dedicated personal parking spaces or at least parking spaces with access to electricity that is charged to their personal utility bills. This makes owning PEVs more straightforward, in contrast to the lack of such facilities facing residents of multi-family housing (MFH).

The core objective of this study is to identify and assess equity implications of the underlying socioeconomic, behavioral, and perceptual barriers and preferences associated with the deployment of electric vehicles and charging infrastructure in the U.S. via a large-scale public survey. This includes five interconnected questions: What are PEV purchase preferences? How does our sample of respondents use their vehicles? What do they perceive about the benefits and barriers to PEVs? What do respondents think about home charging access? What do they think about public or workplace charging access?

In answering these questions, our study thus has both confirmatory and exploratory dimensions. We confirm findings from earlier research that individual characteristics, such income, age, region, and single vs. multi-family housing type can significantly affect electric vehicle purchase preferences, especially those concerning overnight charging and perceptions of benefits and barriers. However, our results also open up exploratory dimensions as they challenge earlier findings in the literature by showing how certain elements, such as expected electric driving range, certain travel behaviors (e.g., driving distance, destination types), the most common perceived benefits (e.g., cleaner air) or barriers (e.g., reliability concerns), and preferred location for public charging seem to not vary much or at all with the socioeconomic, demographic, and geographical variables examined in this study. A core part of the value of the study is the dataset we are providing to the community based on an extensive survey. The analysis in the paper, including numerous graphs and visualizations, are there to demonstrate some first-order insights that can be obtained from the dataset, including insights that might run counter to the standard storyline of electric mobility adoption and EV diffusion.

2. Background: justice, equity, and electric mobility

Justice and equity are both fundamentally concerned with fairness. In both scholarly and common usage, the distinction between these terms (if it is made at all) is drawn in varying ways. Equity can be understood to be a comparative or relational term, generally concerning present conditions and often more concerned with means than ends. Justice, often conceived in terms of rights, is a more systemic principle, with a deeper time horizon that entails addressing the historical causes of injustice and taking the well-being of future generations into account [22].

Scholarship has understood both justice and equity to be multi-scalar principles and to incorporate multiple dimensions, which have been variously described as distributional, procedural, and contextual or structural, among others [22–27]. Whereas procedural equity (or justice) has to do with fairness, representation and voice in decision-making, distributional equity (or justice) refers to the fair distribution of benefits and costs. Given the aspiration to inform practical, near-term policies, this paper focuses primarily on equity, rather than justice *per se,* and more specifically on *distributional equity* (equitable outcomes), rather than procedural equity (equitable policy-making).

A terminological clarification can aid in understanding the distributional dimension. Equity is closely associated with *equality*, yet these terms are distinguished in important ways. A "fair share," the measure of equity, is not necessarily an equal share. Whereas equality is about treating everyone the same way (equally), equity is about "fair" treatment, and so may involve treating people differently to meet their different needs [22,28].

Another important methodological implication of this distinction is that while the degree of equality characterizing an outcome, such as PEV adoption, can be measured, equity itself, as a normative and relational concept, cannot be measured directly. One can make testable propositions, such as, "if access to PEVs was equitable, then there would be an equal (proportional) distribution of PEV ownership among different income, racial, ethnic and age groups;" however, actual distribution data would be an indirect measure of the multiple dimensions of equity, concerning for example, equitable opportunity, rights, or satisfaction of needs.

Applied to public policy to promote vehicle electrification, achieving an equitable distribution of outcomes requires providing *customized* support systems that are tailored to the varying needs and challenges of different individuals and households. To that end, it is essential to have better understanding of who has which particular barriers and needs: to which this study aims to contribute. Taking an equity-oriented approach will help us assess how we can ultimately achieve not only equity, but justice, by removing barriers to address some of the root causes of inequality. To this end, equity may be viewed as lens through which to evaluate people's needs, challenges, and potential benefits (or risks) in order to develop and implement strategies, pathways, and policies that work toward justice, individually and collectively.

As widespread adoption occurs, vehicle electrification will move us towards justice at multiple scales. Collective adoption of electric vehicles advances *environmental justice* at the community scale, by removing a major source of air pollution in heavily trafficked neighborhoods. At a global scale, vehicle electrification will advance *climate justice* by slowing the pace of the emissions that drive climate change and thereby lessening its disproportionate impact on low-income, black and brown, and other vulnerable communities.

3. Research design and limitations

3.1. Existing evidence and research gaps

Numerous public survey studies have examined electric vehicle adoption around the world, including in the United States [29–39], Korea [40], Europe [41–44], and China [45–47]. These existing analyses provide useful insights as to socioeconomic, demographic, and other factors that may influence the adoption of electric vehicles. As a more concrete example, Egbue and Long conducted a survey in the U.S. and investigated consumer attitudes and perceptions for electric vehicles [48] and identified driving range, cost, and charging infrastructure as major barriers, but without particular focus on equity. A similar survey-based study for Spain by Junquera, Moreno, and Alvarez [49] demonstrated that charging time, driving range, perceived price of electric vehicles, and charging infrastructure are the main hurdles for a wider adoption of electric vehicles, yet again with little emphasis on or mention of equity aspects.

Hsu and Fingerman [50] studied the disparity in access to public chargers in California in terms of income, race, and housing type, but did not consider home charging access which is an important element for equitable deployment of electric vehicles [14]. Including or beyond housing, more recent equity-focused studies indeed reveal that adoption of electric vehicles and charging is not supposed to be viewed as an isolated technological transition. Rather it is deeply intertwined with housing [51], food [52], and other aspects of our daily lives. This is another reason why an integrated approach is crucial for equity analysis to incorporate housing and other factors associated with the built environment as well as consumer behavior and perception.

All in all, these previous studies tend to focus on one dimension – either electric vehicle adoption or charging infrastructure, not both; or they do not explicitly address equity elements. Given that the deployment of electric vehicles goes hand in hand with charging preferences, behavior, and infrastructure (home, work, and public), they must be considered together when evaluating and equitable vehicle electrification. Furthermore, as not all electric vehicles are created equal, when it comes to equity analysis, the consideration of the type and vintage of electric vehicles is vital [53], because their price and affordability is vastly different. To our knowledge, this study is one of the first that quantifies the importance of vehicle type and vintage for the equity of electric mobility. Similarly, home charging access is deeply intertwined with housing type, tenure, and parking options, which in turn affect electric vehicle adoption and public charging needs. Additionally, underlying socioeconomic, behavioral, and perceptual factors must be considered simultaneously and collectively when evaluating equitable electric vehicle adoption and charging infrastructure.

To our knowledge, there is little (if any) integrated analysis with explicit emphasis on equity that holistically evaluates the critical elements of electric mobility in the U.S. – electric vehicles (type and vintage), housing (type and tenure), residential parking options, home charging access, public charging preferences, refueling behaviors, socioeconomic factors, and perceptual aspects. This study is designed to fill that knowledge gap by holistically investigating preferences and barriers (socioeconomic, housing-related, perceptual, and behavioral), focusing on equitable distribution of electric vehicles and charging infrastructure (home and public).

3.2. Data collection

This study is based on comprehensive up-to-date data on vehicle ownership and utilization, vehicle purchase preferences, housing, residential parking options, power outlet availability, and public refueling behavior and preferences across the U.S.

For data collection, we conducted an online public survey of 7266 adults (18 or older), with informed consent, across the United States. The survey was administered by Alchemer (formerly SurveyGizmo) [54] between February 8 and March 15, 2022. We originally received 23,111 responses in our survey, of which 15,845 were dropped based on data filtering criteria such as the completeness of responses and sufficient time spent to finish the survey.

The questionnaire, available in the Appendix A, consisted of five sections in addition to the informed consent form at the beginning: basic information, housing and parking, vehicle ownership and purchase, vehicle utilization and refueling, and preferences and perceptions. The parameters evaluated in each of those five sections are listed in Table 1. The list of parameters (or questions) was developed based on broader project scope [55], stakeholder input, findings in previous studies, and expert judgement, while limiting the length of the survey to prevent fatigue of respondents. Respondents were selected randomly within each of various socioeconomic and demographic quotas used to make the overall sample consistent with census data in terms of the distribution of household income, gender, age, region, race, and ethnicity. The respondents were selected randomly within each of various socioeconomic and demographic quotas used to make the overall sample consistent with census data in terms of the distribution of household income, gender, age, region, race, and ethnicity. As the descriptive statistics provided in Table 2 demonstrate, the resulting sample was broadly representative of the population according to the U.S. Census. Appendix B shows other demographic attributes of our sample.

3.3. Data analysis and visualization

To evaluate the collected data via survey, we employ both statistical analysis and visualization. For the reliance on used vehicle purchase preferences and home charging access, we utilize a multinomial and binomial logistic regression analysis method because many of our parameters (including dependent variables) are categorical. Admittedly, we could have used other techniques such as ANOVA, MANOVA, k-means cluster analysis, or structural equation modeling, but we felt regression analysis was best suited due to its ability to test clear hypotheses and avoid omitted variable bias. Naturally, future work can apply these other techniques in their own surveys.

Table 1
The multiple variables and parameters collected in the survey.

Section	Parameters
Basic information	▪ Region (Midwest, Northeast, South, West) ▪ Gender ▪ Age ▪ Household size ▪ Annual income ▪ Race and ethnicity ▪ Education
Housing and parking	▪ Housing type ▪ Tenure (own or rent) ▪ Parking options available at home
Vehicle ownership and purchase	▪ The number of vehicles in household ▪ Non-PEV and PEV purchase pattern—new vs. used vehicle market ▪ Preferred PEV type (e.g., small sedan, pickup truck)
Vehicle utilization and refueling	▪ Expected PEV range for daily short trips and long-distance travel ▪ Internal combustion engine vehicle refueling pattern (location and amount) at gas stations ▪ Power outlet availability and location for home charger ▪ Comfortable distance from home to park and charge (when no home charger is available) ▪ Relative importance of safety vs. convenience for park-and-charge away from home
Preferences and perceptions	▪ Benefits of PEVs ▪ Barriers to PEV adoption ▪ Criticality of home charging availability for multi-unit dwellers ▪ Preferred charging locations

Table 2
Basic descriptive statistics of survey respondents – categories for age and income are simplified.

Parameter		Observations	Percentage (%)	U.S. census (%)
Region	Midwest	1628	22.4 %	21 %
	Northeast	1285	17.7 %	17 %
	South	2621	36.1 %	39 %
	West	1732	23.8 %	23 %
Gender	Male	3661	50.4 %	50 %
	Female	3564	49 %	50 %
	Other	22	0.3 %	–
	Prefer not to answer	19	0.3 %	–
Age	18–29	1023	14 %	15 %
	30–39	1376	19 %	19 %
	40–49	1445	20 %	24 %
	50–69	2389	32.8 %	30 %
	70 or older	1019	14 %	12 %
	Prefer not to answer	14	0.2 %	–
Race/ ethnicity	White (non-Hispanic)	4645	64 %	66 %
	Hispanic	869	12 %	10 %
	Black	797	10.9 %	12 %
	Asian	499	6.8 %	6 %
	Native	195	2.7 %	1 %
	Other	261	3.6 %	5 %
Annual income	Less than $25,000	1114	15.3 %	17 %
	$25,000–$50,000	1705	23.5 %	20 %
	$50,000–$75,000	1803	24.8 %	17 %
	$75,000–$100,000	1154	15.9 %	14 %
	$100,000–$125,000	492	6.8 %	7 %
	More than $125,000	998	13.7 %	17 %
Education	High school or less	1607	22.1 %	36 %
	College	4077	56.1 %	50 %
	Graduate degree	958	13.2 %	14 %
	Other	624	8.6 %	–

The primary objective of employing such machine learning methods is not necessarily to predict some variables as a function of the other ones, but rather to provide a sensitivity analysis (see Lee, Thomas, and Brown [56] as an example) and to reveal the significance of relationships between key parameters. Multinomial (including binomial) logistic regression models can be characterized as:

$$\log\left(\frac{\pi_{ij}}{\pi_{ij^*}}\right) = \beta_{0j} + \beta_{1j}X_{i1} + \ldots + \beta_{pj}X_{ip},\ j \neq j^* \tag{1}$$

$$\pi_{ij} = Pr\{Y_i = j\} \tag{2}$$

where π is multinomial distributions, $\log\left(\frac{\pi_{ij}}{\pi_{ij^*}}\right)$ is the log-odds (or logit) of being in the j-th category relative to the base (j^*) category to which the other categories are compared in terms of the log-odds, β is regression coefficients, X is independent/explanatory variables, i is the row or index of the data set, and p is the number of independent/explanatory variables.

To help readers interpret the multinomial logistic regression results, along with other common statistical metrics (e.g., p-value), we also use relative odds (or risk) ratio characterized as:

$$ROR = \frac{\frac{\Pr(Y=j-th\ category\ |X+1)}{\Pr(Y=base\ category\ |X+1)}}{\frac{\Pr(Y=j-th\ category\ |X)}{\Pr(Y=base\ category\ |X)}} \tag{3}$$

where *ROR* (relative odds ratio) represents the marginal effect of one unit change in the independent/explanatory variable on the probability of falling in the *j*-th category, as opposed to the base category, with everything else being equal.

3.4. Limitations

Overall, except cases for which we utilize a logistic regression method, we primarily focus on visualizing the survey results, showing meaningful patterns graphically as much as possible, so that a more diverse group of readers in the general public can easily understand the findings. Also, applying more advanced methodologies, including nested logistic regression, to investigate the relationships between variables is left for future study. Lastly, it is worth stating that this study is mostly concerned with correlation, rather than causality or predictive modeling.

Admittedly, our research design has some important limitations. The results contain multiple logistic regression models and a large collection of figures, given that we wanted to report all relevant data and also that this is the only paper written based on the survey. In simpler terms: we wanted to pursue one big and bold paper rather than writing a series of smaller, more peripheral outputs. We believe this complexity of variables and parameters also matches PEV adoption in the real world, where variables confound each other and where preferences coevolve with vehicle utilization patterns and perceptions about benefits, barriers, and charging access. For this reason, we encourage future researchers to look further at the interaction effects that we have begun to unravel in our study. Moreover, while our data analysis has been executed correctly mathematically, there are other possible specifications that would make sense that go beyond the set of independent variables we are currently using. And those specifications could lead to deeper or even different conclusions.

4. Results and discussion

4.1. Electric vehicle purchase preferences

Survey results were analyzed in light of our core research questions to assess how strongly population characteristics correlate with preferences for purchases of different types of PEV. As detailed above, the population characteristics of interest include demographic, geographic, and socioeconomic factors, with a particular focus on housing (type and tenure). As illustrated in Fig. 1(a), when considering potential purchase of PEVs, respondents stated that sedans and sport utility vehicles (SUVs) would be the most popular choices. This reflects the current popularity of SUVs (compact or large) in the U.S. auto market, which seems to carry over to PEV purchase preferences. Interestingly, income demonstrates a negative correlation with small sedans, vans, and pickup trucks—the higher the income, the less popular these vehicle types become. On the other hand, large sedans, compact SUVs, and large SUVs exhibit a strong positive correlation with income.

The multinomial logistic regression model in Table 3 confirms the trend illustrated in Fig. 1(a). Income has a statistically significant relationship with the types of vehicles that respondents would want to buy. With all other variables kept constant, one unit increase in income (i.e., $20,000) decreases the odds of wanting to buy a small sedan, compared to a compact SUV, by 2.5 % (relative odds ratio 0.975). Put differently, the lower the income, the higher the reliance on small sedans. Similarly, one unit increase in income ($20,000) diminishes the odds of wanting to buy a pickup truck, compared to a compact SUV, by 2.3 % (relative odds ratio of 0.977).

It is also interesting to see the significant relationship between residing in a MFH unit and preferring to buy small sedans. All other variables being equal, living in MFH increases the odds of wanting to buy a small sedan, compared to a compact SUV, by 34 % (relative odds ratio of 1.341). However, living in MFH decreases the odds of wanting to

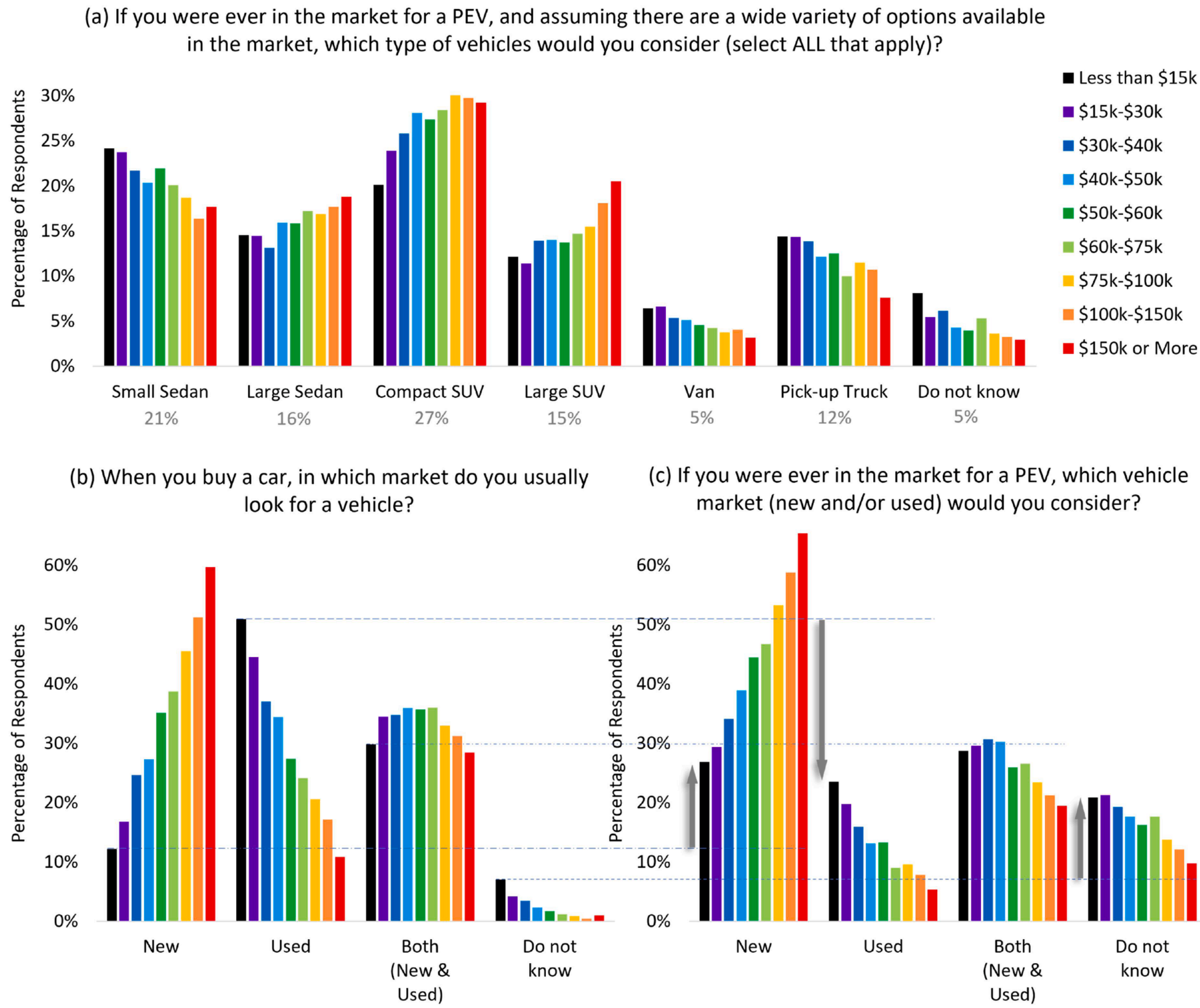

Fig. 1. (a) Survey respondents' preferences for vehicle type (e.g., small sedan, pickup truck) when considering the purchase of PEVs; (b) preferences for new vs. used vehicle market, regardless of vehicle technology; and (c) preferences for new vs. used vehicle market for PEVs, differentiated by annual income. For each income group, the total sums to 100 %.

purchase pickup trucks, compared to compact SUVs, by 36 % (relative odds ratio of 0.637).

When it comes to respondents' choice of the new vs. used vehicle market, the influence of income is apparently significant (Fig. 1). For purchasing any vehicle technology, as shown in Fig. 1(b), income shows a strong positive correlation with the new vehicle market, meaning that higher-income respondents prefer purchasing new vehicles much more than their lower-income counterparts. Conversely, lower income seems to result in a higher reliance on the used vehicle market.

The relative magnitude is also worth noting. About 60 % of respondents with an income of $150,000 or more stated that they will look for their cars in the new vehicle market, whereas only 10 % of those with an income of $15,000 or less would do so. The situation flips in the case of preferences for the used vehicle market. Around 10 % of respondents with an income of $150,000 or more would be interested in the used vehicle market when buying cars, while about 50 % of respondents with an income of $15,000 or less will look in the used vehicle market.

The visual inspection of the trend in Fig. 1(b) is confirmed by multinomial logistic regression analysis, as summarized in Table 4. Income was found to have a statistically significant relationship with vehicle markets, with a multinomial logistic regression on "Used" and "Both" in which "New" was treated as the reference/baseline category. For example, with all other variables held equal, a one unit decrease in income ($20,000) increases the odds of preferring to look in the used vehicle market by approximately 9 % compared to the new vehicle market. Similarly, living in MFH increases the odds of wanting to rely on the used (vs. new) vehicle market by 71 % (relative odds ratio of 1.708). In other words, the logistic regression indicates that households who have lower income and/or live in MFH are significantly more likely to rely on the used vehicle market vs. the new vehicle market.

The preferences for new vs. used vehicle markets change drastically when asked specifically about buying PEVs, as opposed to respondents' typical or general vehicle purchases. Fig. 1(c) shows several notable changes in the pattern of vehicle purchase preferences, compared to Fig. 1(b). First, across all income groups, when considering buying PEVs, a significant increase in the reliance on the new vehicle market can be observed, with that increase being higher the lower the income.

Second, for PEVs, as a result of a significant increase in the interest in or reliance on the new vehicle market, we see a notable decrease in preferences for the used vehicle market. This decreasing interest in the used vehicle market for PEVs is also confirmed by multinomial logistic regression in Table 4. For PEVs, by decreasing income by one unit ($20,000) with all things equal, the odds of preferring to look in the used vehicle market, as opposed to the new vehicle market, increase by 7 % (relative odds ratio of 0.93). Note that the corresponding odds ratio for general vehicles (PEVs and non-PEVs) was 9 % (relative odds ratio of

Table 3
Multinomial logistic regression analysis results for vehicle type preferences.

	Dependent variable[a]				
	Small sedan	Large sedan	Large SUV	Van	Pickup truck
Intercept	**−0.738***** [0.059] {0.478} (<10^{-6})	**−1.302***** [0.067] {0.272} (<10^{-6})	**−0.641***** [0.052] {0.527} (<10^{-6})	**−1.686***** [0.084] {0.185} (<10^{-6})	**−0.193***** [0.049] {0.824} (<10^{-6})
Income[b]	**−0.025***** [0.007] {0.975} (0.0003)	**0.002** [0.006] {1.002} (0.72)	**0.017***** [0.004] {1.017} (0.0001)	**−0.017*** [0.009] {0.983} (0.072)	**−0.023***** [0.006] {0.977} (<10^{-6})
SFH–attached	**0.245*** [0.129] {1.278} (0.057)	**0.248*** [0.151] {1.281} (0.099)	**0.109** [0.122] {1.115} (0.371)	**−0.012** [0.199] {0.988} (0.953)	**−0.354***** [0.128] {0.702} (0.006)
MFH	**0.293***** [0.105] {1.341} (0.0052)	**0.118** [0.13] {1.125} (0.365)	**−0.187*** [0.109] {0.829} (0.087)	**0.184** [0.152] {1.202} (0.227)	**−0.451***** [0.107] {0.637} (<10^{-6})
Other	**0.26** [0.184] {1.297} (0.157)	**0.163** [0.226] {1.178} (0.469)	**−0.402*** [0.212] {0.669} (0.058)	**0.303** [0.254] {1.354} (0.234)	**0.433***** [0.151] {1.541} (0.004)
Chi-square	67.1 (p-value: 1.14 × 10^{-9})				

Bold: coefficients, []: standard error, {}: relative odds ratio, (): p-value.
*: p-value < 0.1, **: p-value < 0.05, ***: p-value < 0.01.
[a] Base category: compact SUV.
[b] Scaled by $20,000 (to make coefficients more interpretable).

Table 4
Multinomial logistic regression analysis results for vehicle market (new vs. used) preferences.

	Dependent variable[a]			
	All (PEV and non-PEV)		PEV	
	Both	Used	Both	Used
Intercept	**0.088**** [0.039] {1.092} (0.024)	**0.029** [0.048] {1.03} (0.54)	**0.076**** [0.036] {1.079} (0.034)	**−1.118***** [0.062] {0.327} (<10^{-6})
Income[b]	**−0.031***** [0.004] {0.969} (<10^{-6})	**−0.092***** [0.008] {0.912} (<10^{-6})	**−0.035***** [0.004] {0.965} (<10^{-6})	**−0.075***** [0.01] {0.928} (<10^{-6})
SFH–attached	**−0.002** [0.095] {0.998} (0.98)	**0.14** [0.1] {1.151} (0.159)	**−0.058** [0.088] {0.944} (0.051)	**0.508***** [0.115] {1.663} (<10^{-6})
MFH	**0.426***** [0.082] {1.53} (<10^{-6})	**0.535***** [0.086] {1.708} (<10^{-6})	**0.167**** [0.072] {1.182} (0.02)	**0.376***** [0.103] {1.457} (<10^{-6})
Other	**0.774***** [0.153] {2.169} (<10^{-6})	**1.143***** [0.151] {3.137} (<10^{-6})	**0.568***** [0.122] {1.765} (<10^{-6})	**0.831***** [0.16] {2.296} (<10^{-6})
Chi-square	533 (p-value: 2.2 × 10^{-16})		214 (p-value: 2.2 × 10^{-16})	

Bold: coefficients, []: standard error, {}: relative odds ratio, (): p-value.
*: p-value < 0.1, **: p-value < 0.05, ***: p-value < 0.01.
[a] Base category: New.
[b] Scaled by $20,000 (to make coefficients more interpretable).

0.91), meaning that the level of reliance on the used vehicle market declines for PEVs in comparison with general vehicles. It is also worth noting that the decreased interest in the used vehicle market, when considering buying PEVs rather than general vehicles (including both PEVs and non-PEVs), becomes even more evident for MFH dwellers. For general vehicles, MFH dwellers are 71 % (relative odds ratio of 1.708) more likely to look in the used vehicle market rather than the new vehicle market, whereas it diminishes to 46 % (relative odds ratio of 1.457) for PEVs.

Lastly, it is interesting to see a dramatic increase in the percentage of respondents who chose “Do not know” in Fig. 1(c), compared to the almost negligible share in Fig. 1(b). This illustrates that respondents are not very sure about which market they would be using when buying PEVs. This may also imply that the general public (based on the responses in this survey) is not yet familiar with and/or has certain concerns about PEV technologies. Despite this, a negative correlation with income indicates that the lower the income, the less sure people are about their potential PEV purchase preferences in terms of relying on the new vs. used vehicle market. To address this, various public education programs may be useful. Public education could help lower the perceptual barriers, including the lack of understanding or trust regarding the reliability of (used) PEV; see also Section 4.3: Perceived Benefits and Barriers of PEVs.

4.2. Vehicle utilization

Survey results were analyzed to assess how strongly population characteristics correlate with current vehicle ownership and use patterns and expected (hypothetical) EV use. As shown in Fig. 2, survey respondents stated that they would expect to drive their PEVs 20 to 30 miles per vehicle per day on average (median values) for daily short-distance travel. This is consistent with other independent surveys, including the National Household Travel Survey (NHTS) [57,58]. It is also worth noting that there is a meaningful correlation between the expected daily short-distance travel distance (per vehicle per day) and income, which is also consistent with the NHTS.

In terms of long-distance travel, e.g., weekend getaways, by PEVs, the respondents stated that they would drive 200 to 300 miles per day (median values). As was the case for short-distance travel, a meaningful correlation exists between the expected driving distance for long-distance travel (by PEVs) and income. Given the electric range, 100–500 miles, of today’s BEVs [11], driving 200–300 miles per day would require zero to two on-route charging sessions, depending on battery size and charge level upon departure.

Beyond the expected driving distance shown in Figs. 2(a) and (b), personal vehicle utilization has other important dimensions to note in

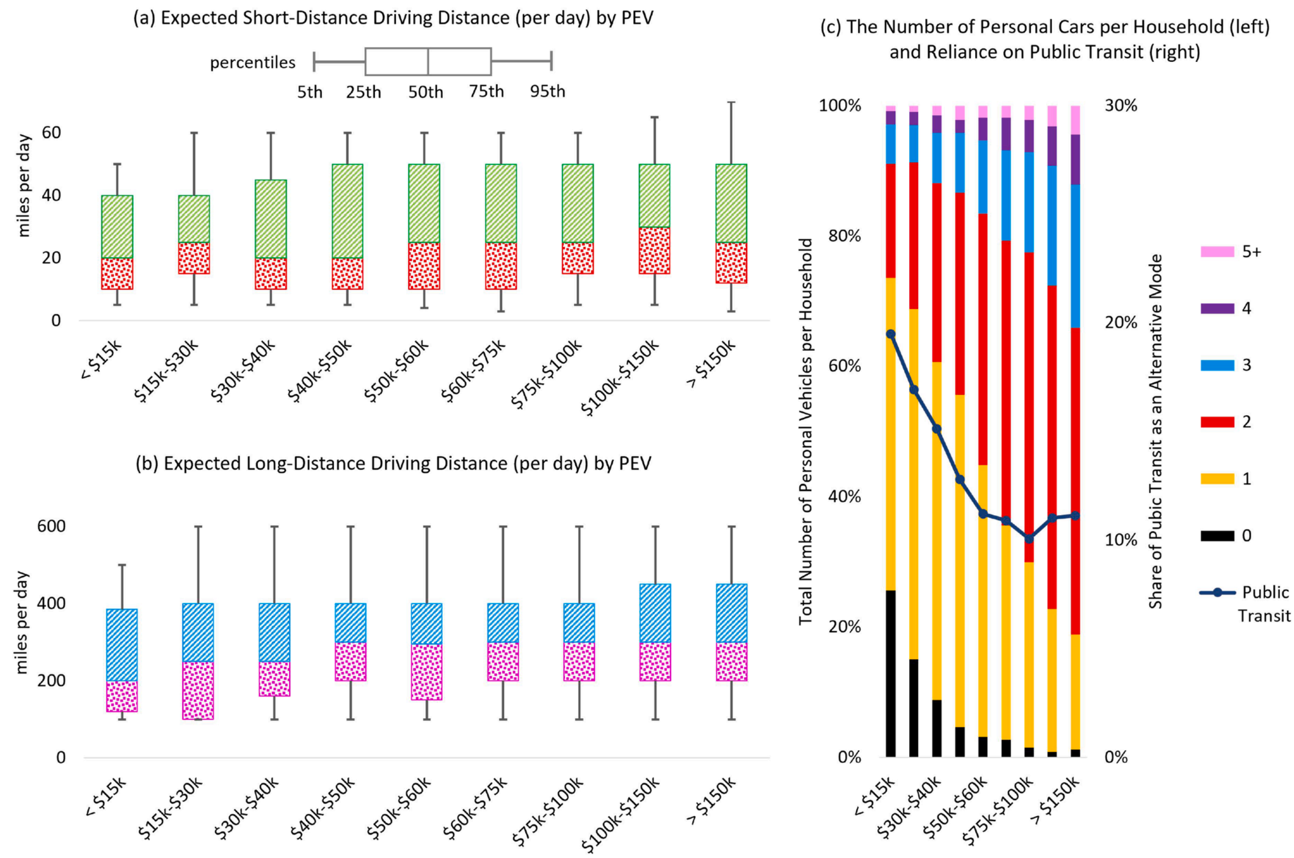

Fig. 2. Expected per-day driving distance by income, when buying PEVs, for (a) daily short-distance trips (e.g., commute) and (b) long-distance travel (e.g., weekend getaways); and (c) the number of personal cars per household, as well as reliance on public transit, by income. The box and whisker plots in (a) and (b) display the 5th, 25th, 50th, 75th, and 95th percentiles.

relation to equitable vehicle electrification. First, as illustrated in Fig. 2(c), a greater percentage of low-income households or individuals do not own any personal cars. For example, about 20 % of households with an annual income of $30,000 or less have no personal cars. For those (low-income and no personal cars) households or individuals, personal PEVs may not have a direct impact. Therefore, to ensure that those households/individuals benefit from vehicle electrification in their daily travel, it is important to support electrifying both personal cars and other alternative transportation modes, e.g., transit buses, taxis, ride-hailing, that may play a more significant role in meeting their daily travel needs, as shown in Fig. 2(c). This is also demonstrated in Fig. A1, showing an increasing reliance for lower-income households on transit bus, walk, and other transportation methods than personal cars, although the distribution of destination types does not vary much across income groups.

An additional equity implication of Fig. 2(c) is the potential significance of multi-vehicle households in PEV adoption. The average household in the United States owns two or three personal vehicles. As the penetration rate of PEVs increases, many households may adopt more than one PEV per household. It would therefore be worth examining whether and how those households who want to own multiple PEVs could have access to adequate or sufficient home charging capability for multiple PEVs.

4.3. *Perceived benefits and barriers of PEVs*

Survey results were analyzed to identify the benefits and barriers of PEV adoption and to assess how strongly they correlate with different population characteristics. When asked to cast a vote on all potential benefits of PEVs (Fig. 3), “Cleaner air” was the most popular choice (20 %), followed by “Generally, better for the environment” (17 %) and “Cheaper fuel cost” (16 %). Approximately 4 % of all votes were for “I do not think there are benefits to electric vehicles over conventional gasoline cars.” All in all, environmental aspects (e.g., cleaner air) and cost savings seem to be the most popular perceived benefits. Technological elements, e.g., better efficiency, noise reduction, better acceleration, are relatively less popular among the perceived benefits.

In terms of the variation in perceived benefits of PEVs, we find that respondent age is an influential variable. The variation also depends on the choice items (e.g., cleaner air vs. better acceleration). For example, the collective benefit of “Cleaner air” consistently accounts for about 20 % across age groups (Fig. 3). However, the perceived individual benefit of cost savings, fuel cost in particular, appears to be more popular in younger respondents compared to older counterparts. A similar, age-dependent pattern can be seen for “Better driving efficiency” and “Better acceleration.” These variations related to technological elements may be due to younger respondents being relatively more familiar with or having a better understanding of PEVs than their older counterparts, although no conclusive remarks on this can be made based upon our survey. Lastly, it is notable that a higher percentage of older respondents see no benefits of PEVs (about 10 % for the age groups $\geq$ 70 years old), in comparison with seemingly more positive perceptions of PEVs among younger respondents (3 % for the age group $\leq$ 40 years old).

Fig. 4 shows that the most significant perceived barrier to PEVs is “Higher upfront/purchase price,” accounting for 20 % of all the votes. This choice is followed by “Shorter range” (16 %), “Lack of home charger” (14 %), and “Lack of public charging station” (14 %). With home charger and public charging station combined, charging infrastructure appears to represent 28 % of all votes on the most significant perceived barrier to vehicle electrification. Overall, purchase cost and

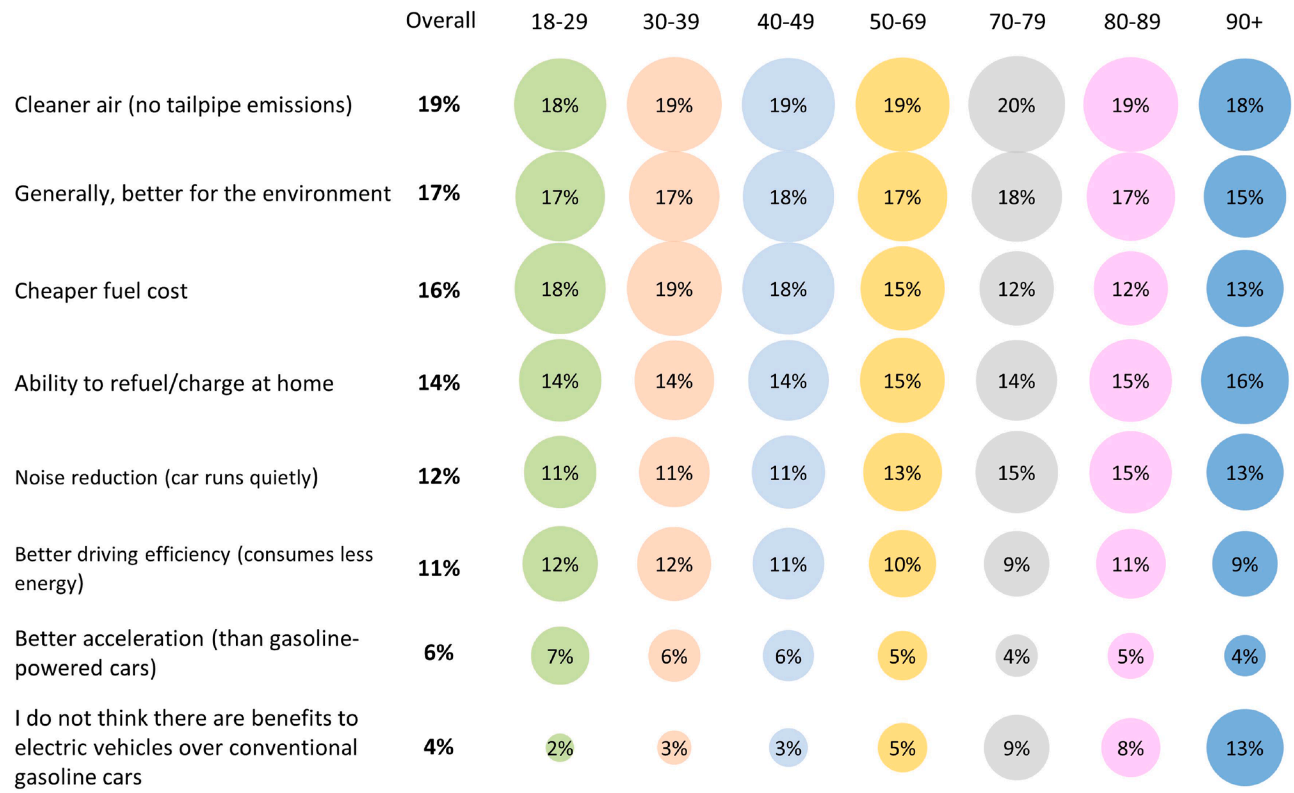

Fig. 3. Perceived benefits of PEVs by respondent age (as well as overall values in bold on the left), based on the responses to the question: What do you see as a benefit of (potentially) owning or driving a plug-in electric vehicle in comparison with conventional gasoline car (Select all that apply)?.

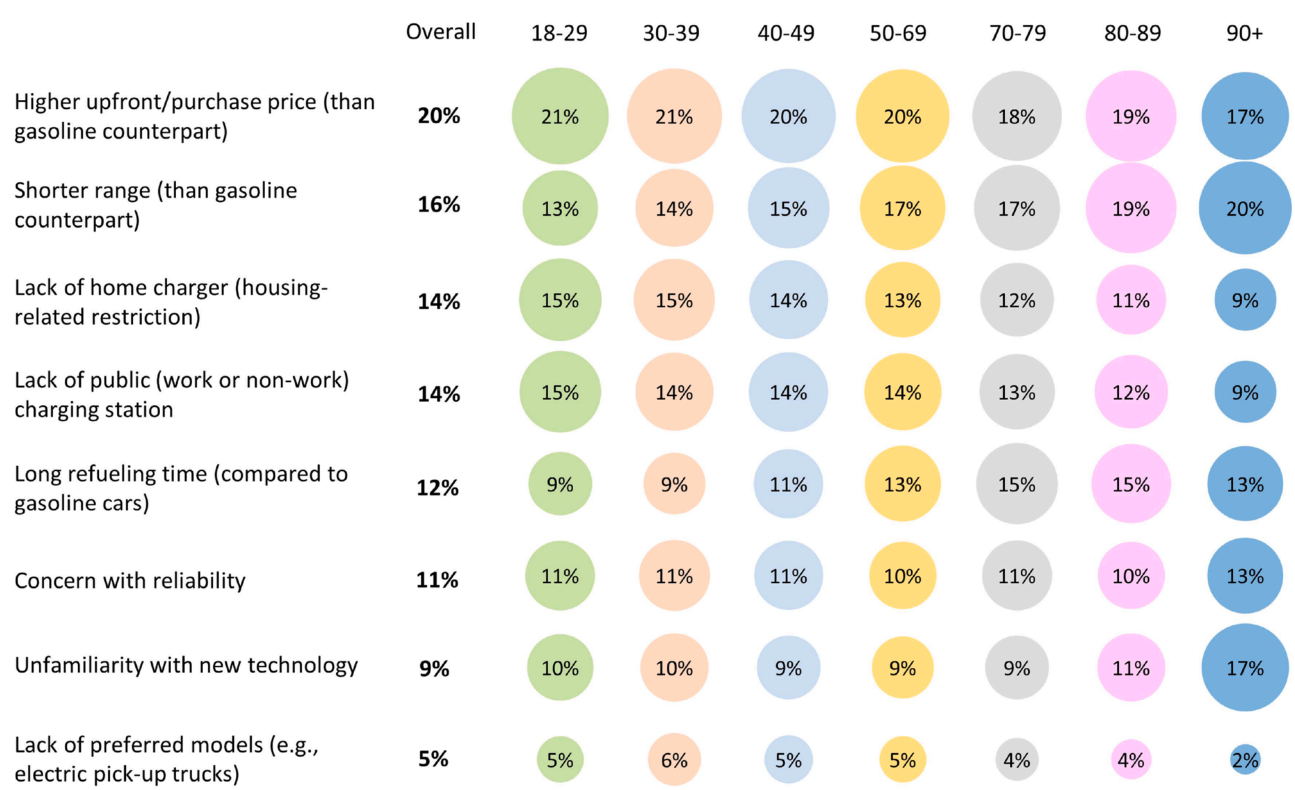

Fig. 4. Perceived barriers to PEVs by respondent age (as well as overall values in bold on the left), based on the responses to the question: What do you see as a barrier that prevents you from buying a plug-in electric vehicle (Select all that apply)?.

concerns associated with range, i.e., shorter range and/or access to charging infrastructure, seem to top the list of perceived barriers. Long refueling time compared to gasoline cars (12 %), concerns around reliability (11 %), and the lack of familiarity with PEV technology (9 %) are also deemed significant perceived barriers. At the other end, the lack of preferred models in the PEV market makes up the smallest percentage (5 % overall) among the perceived barrier choices.

In comparison with the perceived benefits of PEVs (Fig. 3), perceived barriers (Fig. 4) demonstrate a more complex pattern in terms of variations between different age groups and individual choice items. For example, the second most popular choice among perceived benefits (representing 17 % overall), the collective benefit of “Better for the environment,”, shows almost no variation across the age groups. On the other hand, the second most popular choice for perceived barriers, “Shorter range,” accounting for 16 % overall, varies from 13 % to 20 %, depending on the age group. In general, barriers related to cost, charging infrastructure, and the lack of preferred models in the PEV market are relatively more significant among younger respondents compared to their older counterparts. Concerns associated with shorter range, unfamiliarity with PEV technology, and long refueling time tend to be more prevalent in the older age groups as compared to their younger counterparts.

Our findings on the perceived benefits and barriers, particularly the influence of age, raise questions related to equity across generations. Although the difference between age groups is negligible for the largest perceived benefit (cleaner air) or barrier (higher upfront/purchase price), it is evident that different age groups generally have different perceptions of the benefits and barriers of PEVs. As income or wealth,

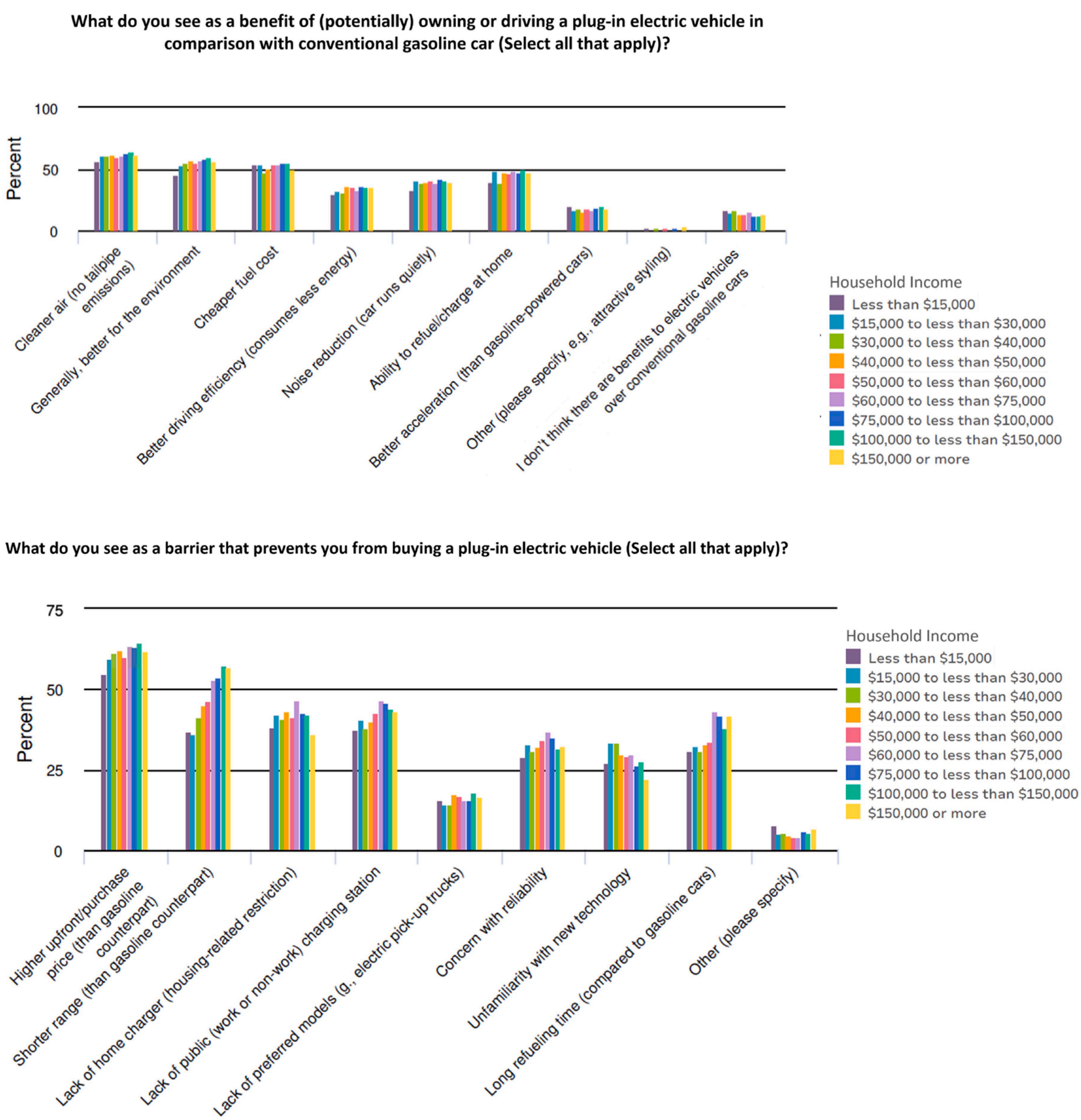

Fig. 5. Perceived benefits of PEVs (top) and barriers to PEVs (bottom) by respondent household income. Note that the total across the choices (horizontal axis) for each income group may exceed 100 %, as the respondents were asked to select all that apply.

one of the most influential factors for PEV adoption, tends to have a positive correlation with age, the current PEV market may be driven by older age groups, while the future of vehicle electrification may depend on younger counterparts. To encourage the younger generation to adopt more PEVs, developing different strategies for those age groups by addressing their concerns and barriers could help ensure that the benefits of PEVs are enjoyed by various age groups.

Another perceived concern with important implications for equity is the reliability of PEV technologies (11 % of the total votes). If potential consumers see reliability as a significant barrier to adopting PEVs, that may have more negative impact on the households that have only one vehicle and/or that prefer the used vehicle market. For instance, those households that rely on a single vehicle for their transportation may have a higher level of sensitivity or concern with the potential reliability issues of PEVs, as their transportation needs may be significantly affected if the only vehicle that they own becomes unavailable due to certain failures or performance issues. This perceived barrier, concern with reliability, in the context of single-vehicle households and the reliance on the used vehicle market, would need to be alleviated, especially if we want to encourage more PEV adoption in low-income communities with a greater reliance on the used vehicle market (Fig. 1) and a higher probability of single vehicle ownership (Fig. 2) and thereby improve equity with regard to vehicle electrification.

In addition to age, we also examine the perceived benefits of and barriers to PEVs in terms of household income. Fig. 5 shows that the most or least outstanding perceived benefit or barrier is the same across different income groups. For example, higher upfront/purchase price and cleaner air are the most outstanding barrier andef, rectively, for each income group. However, different income groups may view secondary potential benefits or barriers in different ways. For example, shorter range of PEVs, compared to gasoline counterparts, is the second most popular choice among barriers for the high-income group, whereas home and public charging infrastructure is the second most popular choice among lower income groups. This example clearly illustrates why adopting different approaches to address different needs that may stem from different perceptions of potential benefits or barriers would be critical to improving equitable vehicle electrification across different socioeconomic or demographic groups.

4.4. Home charging access

Survey results were analyzed to assess how home charging access correlates with housing characteristics (type, tenure, and parking) and how perceptions of the benefits and barriers to PEV adoption are associated with home charging capability and other charging options.

The ability to refuel personal cars at home is one of the most important factors that differentiate PEVs from conventional gasoline cars. Home charging is an essential part of vehicle electrification, and

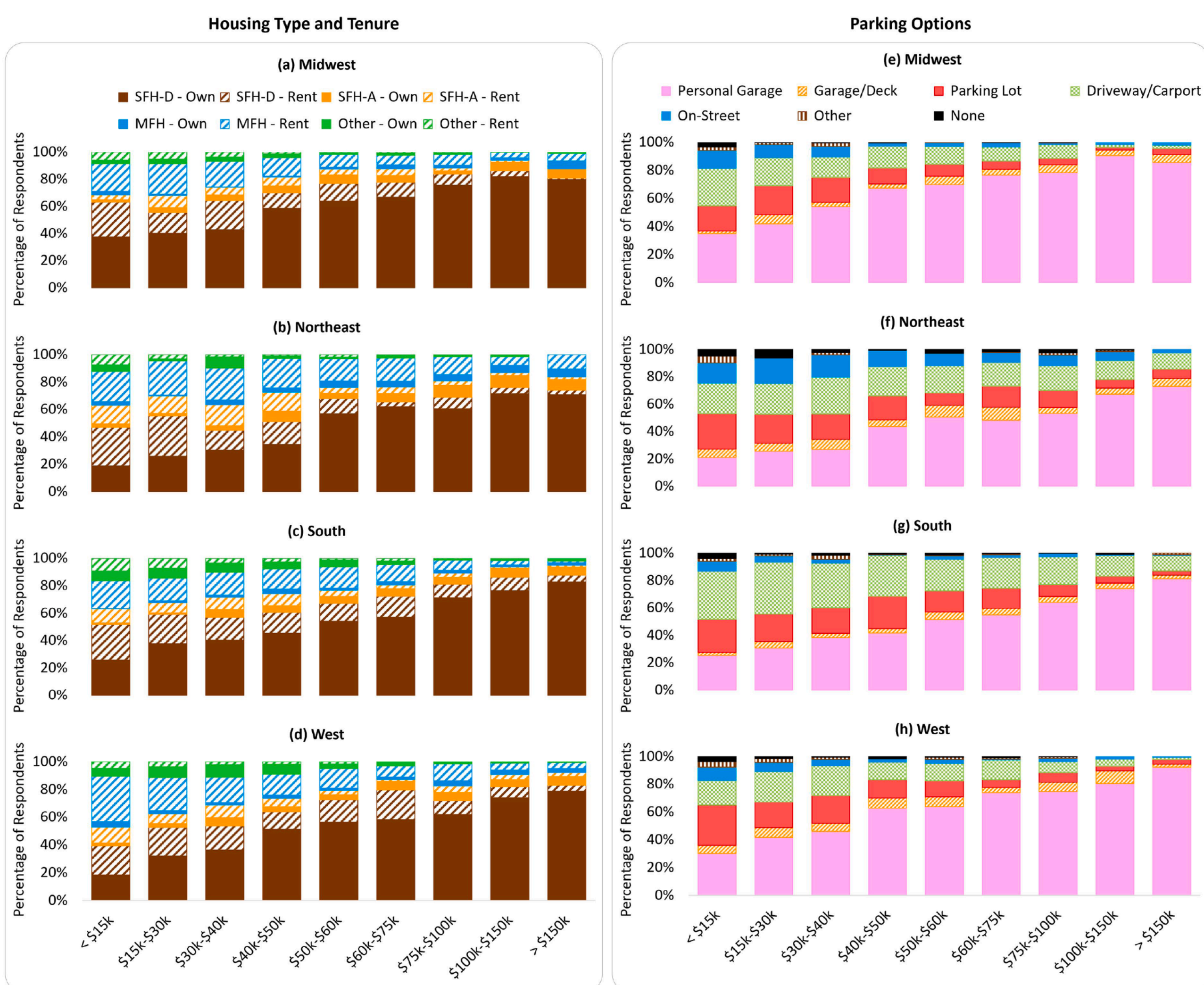

Fig. 6. Housing type (SFH-D: single-family home detached; SFH-A: single-family home attached) and tenure (own [solid] vs. rent [dashed]) by region and income (left); and corresponding weighted parking options by region and income (right).

the majority of current PEV owners do most of their charging at home [21]. As discussed above, a significant portion of the public perceives home refueling capability as an important benefit of PEVs (Fig. 3), but also one of the most significant barriers (see "Lack of home charger" in Fig. 4).

Home charging access depends on housing type (e.g., apartments) and corresponding parking options (e.g., personal garage), along with the availability of proper power outlets for chargers (110–120 Volt for Level 1; 208–240 Volt for Level 2) in those parking locations. Fig. 6 shows the variation in housing type and tenure as a function of region and annual income. It appears that different regions may have different characteristics in housing type and tenure for the same income groups, which may be related to regional population density, or rural vs. urban settlement patterns.

Income has a very strong influence on housing type and tenure. Higher-income groups have a greater share of detached SFHs that are owned by the respondents. On the other hand, for lower-income groups, we see an increase in the share of MFH and rented homes. The significance of the relationship between income and housing type is also confirmed by the multinomial logistic regression analysis in Table 5-A. One unit decrease in income ($20,000) increases the odds of living in MFH (as opposed to detached SFHs) by 6 % or in attached SFHs by 2 %. In other words, the lower the income, the more likely to live in MFH or attached SFHs rather than detached SFHs.

This housing type distribution directly affects available parking options across different regions and income groups. The availability of a personal garage—probably the most convenient location for overnight charging at home—increases with income (proportional to the share of detached SFHs). Also, as shown in Fig. 6 (right), some regional variation in parking options beyond the effect of housing type and tenure is evident.

For the nationwide housing type and parking options, Table 5-B clearly demonstrates the significant and intertwined relationship between housing type and parking options. For example, people living in MFH are 95 % (relative odds ratio of 0.05) less likely to have a personal garage than those living in detached SFHs, but 5.2 times more likely to have access to a parking garage/deck/lot instead.

Some housing types (e.g., detached SFH) and/or parking options (e.g., personal garage) are more conducive to home charging access than others. Our survey data suggest that 77 % of households living in SFHs have outlets that could be used to plug in or install Level 1 or 2 chargers, whereas it drops to 36 % for those living in MFH. If only for power outlets suitable for Level 2, the corresponding percentage diminishes to 42 % for SFH and 23 % for MFH. Among SFHs (detached vs. attached), 80 % of SFH–detached, and 60 % of SFH–attached have power outlets for (Level 1 or 2) home charging. The corresponding likelihoods for Level 2 are 43 % for SFH–detached and 34 % for SFH–attached.

Table 6 clearly shows the significant relationship between income, housing type, parking options, and power outlet availability for home/overnight charging. With respect to housing type (Table 6-A), one unit increase in income ($20,000) improves the odds of having a power outlet for home charging by 5 %.

Compared to SFH–detached, living in MFH makes it 85 % less likely to have power outlets, while those living in SFH–attached have 63 % lower odds (relative to SFH–detached). As for parking options, recall that Table 5-B showed that living in MFH, as opposed to SFH–detached, results in 5.3 times higher odds of having parking garage/deck/lot as a parking option, but this particular parking option is 90 % less likely to have power outlets, compared to the case of having a personal garage, as illustrated in Table 6-B. For the other types of parking options, Table 6-B

Table 5
Multinomial logistic regression analysis results for housing type and parking options.

Table 5-A	Dependent variable: housing type [a]		
	SFH–attached	MFH	Other
Intercept	**−1.826*****	**−1.233*****	**−1.609*****
	[0.048]	[0.045]	[0.096]
	{0.161}	{0.291}	{0.2}
	($<10^{-6}$)	($<10^{-6}$)	($<10^{-6}$)
Income [b]	**−0.021*****	**−0.063*****	**−0.327*****
	[0.006]	[0.009]	[0.034]
	{0.979}	{0.939}	{0.721}
	($<10^{-6}$)	($<10^{-6}$)	($<10^{-6}$)
Chi-square	240 (p-value: 2.2×10^{-16})		

Table 5-B	Dependent variable: parking options [c]				
	Personal garage	Parking garage, deck, or lot	Driveway or carport	On-street	Other
Intercept	**3.947*****	**1.768*****	**3.852*****	**3.456*****	**0.707*****
	[0.168]	[0.18]	[0.168]	[0.169]	[0.204]
	{51.77}	{5.86}	{47.1}	{31.69}	{2.027}
	($<10^{-6}$)	($<10^{-6}$)	($<10^{-6}$)	($<10^{-6}$)	(0.0005)
SFH–attached	**−1.513*****	**0.953*****	**−1.67*****	**−1.011*****	**−0.93****
	[0.318]	[0.322]	[0.32]	[0.318]	[0.438]
	{0.22}	{2.594}	{0.188}	{0.364}	{0.395}
	($<10^{-6}$)	(0.003)	($<10^{-6}$)	(0.0015)	(0.003)
MFH	**−3.082*****	**1.659*****	**−2.754*****	**1.218*****	**−1.32*****
	[0.296]	[0.275]	[0.29]	[0.273]	[0.4]
	{0.046}	{5.255}	{0.064}	{0.296}	{0.267}
	($<10^{-6}$)	($<10^{-6}$)	($<10^{-6}$)	($<10^{-6}$)	(0.001)
Other	**−3.618*****	**−0.564***	**−1.41*****	**−2.657*****	**−0.101**
	[0.352]	[0.324]	[0.298]	[0.33]	[0.357]
	{0.027}	{0.569}	{0.244}	{0.07}	{0.904}
	($<10^{-6}$)	(0.081)	($<10^{-6}$)	($<10^{-6}$)	(0.78)
Chi-square	2700 (p-value: 2.2×10^{-16})				

Bold: coefficients, []: standard error, {}: relative odds ratio, (): p-value.
*: p-value < 0.1, **: p-value < 0.05, ***: p-value < 0.01.
[a] Base category: SFH–Detached.
[b] Scaled by $20,000 (to make coefficients more interpretable).
[c] Base category: None (no parking available).

Table 6
Binomial logistic regression analysis results for home charging access (Level 1 or Level 2).

Dependent variable: power outlet availability for home charging [a]			
Table 6-A: With respect to housing type		Table 6-B: With respect to parking options	
Intercept	**1.16***** [0.043] {3.19} (<10^{-6})	Intercept	**2.149***** [0.083] {8.575} (<10^{-6})
Income [b]	**0.051***** [0.006] {1.052} (<10^{-6})	Income [b]	**0.048***** [0.006] {1.05} (<10^{-6})
SFH–attached	**−0.991***** [0.084] {0.371} (<10^{-6})	Parking garage, deck, or lot	**−2.735***** [0.098] {0.065} (<10^{-6})
MFH	**−1.929***** [0.072] {0.145} (<10^{-6})	Driveway or carport	**−1.565***** [0.092] {0.209} (<10^{-6})
Other	**1.172***** [0.109] {0.31} (<10^{-6})	On-street	**−1.498***** [0.096] {0.224} (<10^{-6})
		Other	**−1.99***** [0.195] {0.136} (<10^{-6})
		None	**−14.251***** [0.000] {0.000} (<10^{-6})
Chi-square	1022 (p-value: 2.2 × 10^{-16})	Chi-square	1400 (p-value: 2.2 × 10^{-16})

Bold: coefficients, []: standard error, {}: relative odds ratio, (): p-value.
*: p-value < 0.1, **: p-value < 0.05, ***: p-value < 0.01.
[a] Base category: No home charging access.
[b] Scaled by $20,000 (to make coefficients more interpretable).

also shows a similar level of impact of decreased odds of having power outlets for home charging.

The significantly lower odds of having power outlets for certain parking options (e.g., parking garage/deck/lot) highlight the importance of building codes, especially for new construction. This would have particularly important implications for people living in MFHs. For example, building codes could require the installation of full circuit (power outlets ready for plug-in) or electrical panel capacity and conduit that is capable of accommodating power outlets in parking spaces. This could help improve home charging access for those living in MHFs.

When no home charging is available, for any reason, PEV drivers would need to rely on alternative locations for charging. In those cases, it is possible that some would park their cars away from home for charging. However, as shown in Fig. 7, more than half of the respondents stated that they would never be willing to park their cars away from their homes for charging. Only a little more than 20 % indicated that they would park their vehicles for charging a few blocks (0.25 miles) away from home.

The lack of willingness to park their cars away from home for charging as a solution to the lack of overnight/home charging seems to originate from concerns regarding safety and convenience, with safety perhaps being more important than convenience (Fig. 7). Overall, our results imply that most people do not want to park their cars away from home for charging, which further highlights the importance of home charging access, as well as the potential challenges for people living in rented properties, whether SFHs or MFH.

It is possible that people may be able to adjust their "business-as-usual" behavior and/or preferences over time (Fig. 7). However, it is also possible that people's lack of appetite for parking their vehicles away from home, even as necessary for overnight charging, may be hard to change. For example, in the United States, drive-thru represents more than half of fast-food restaurant sales, meaning that many people tend to not want to get out of their vehicles. Therefore, it may be unrealistic to expect people to park and leave their vehicles a few blocks or miles away from their home for overnight charging and walk back and forth to/from home. Moreover, it may be that EV owners and potential owners prefer the control that home charging provides, in contrast with logistical constraints posed by public chargers, such wait-times and non-functioning units. This raises concerns as to the potential effectiveness of public charging stations, especially those located farther away from PEV drivers' homes, as a measure to compensate for the lack of overnight/home charging access.

4.5. *Workplace and public charging access*

Survey results were analyzed to identify preference for the location of away-from-home charging facilities and to assess how strongly they correlate with different population characteristics. Personal cars are parked for most of their lifetime, with a workplace being one of the most common locations; also note that workplace is one of the most common destination types, as shown in Fig. A1(c). Therefore, for those who work outside the home, the workplace provides a great opportunity for charging while parked. Beyond workplace, as in Fig. A1(c), there are other locations or destinations that can be used for "opportunity" charging.

It is not clear, however, which of those locations would be preferred the most by potential PEV adopters. To evaluate those preferences, we asked the respondents to rank the away-from-home locations that they prefer for charging. For simplicity, we chose five different locations: chargers in retail locations, including grocery stores and shopping centers, a street/curbside charger in your neighborhood, a workplace charger, chargers at transit stations, such as park-and-ride, and chargers at gas stations that provide both gasoline and electricity fuels (which could be faster but also more expensive than the other options).

As illustrated in Fig. 8, chargers located in retail locations seem to be the most preferred options for respondents, regardless of their income—consistent with the popularity of those destination types in Fig. A1 (c). On the other hand, transit stations are the least preferred locations for charging, which may simply reflect the fact that a very small percentage of people utilize so-called "park-and-ride." The popularity of retail locations for charging is consistent with the existing public charging infrastructure, which is mostly concentrated in retail locations. Interestingly, the second most preferred option was a street/curbside charger in the respondents' neighborhoods. This may suggest that installing street/curbside chargers can help alleviate not only public charging needs, but also the challenges associated with overnight/home charging access, especially for those residing in MFHs.

The third most popular preferred location is gas stations, perhaps because respondents do not want to change their refueling behavior, or perhaps because they are just too accustomed to gasoline cars and corresponding refueling habits. The challenge with locating PEV charging facilities in gas stations, however, is that parking for an extended period is required. Although the time required is starting to drop with technological innovation in both PEVs and chargers, when starting from nearly "empty," it can take up to approximately 30 min to recharge completely at a DC fast charging and from a few to several hours for Level 2 charging. Gas stations in urban areas tend to have only small parking lots, as filling gas takes typically less than 10 min, requiring relatively small buffer space for waiting. Also, the price and availability of land is a factor contributing to the relatively small parking space in gas stations, particularly in urban areas.

Workplace charging is not one of the top two options that survey respondents preferred. Of the five options asked in the survey,

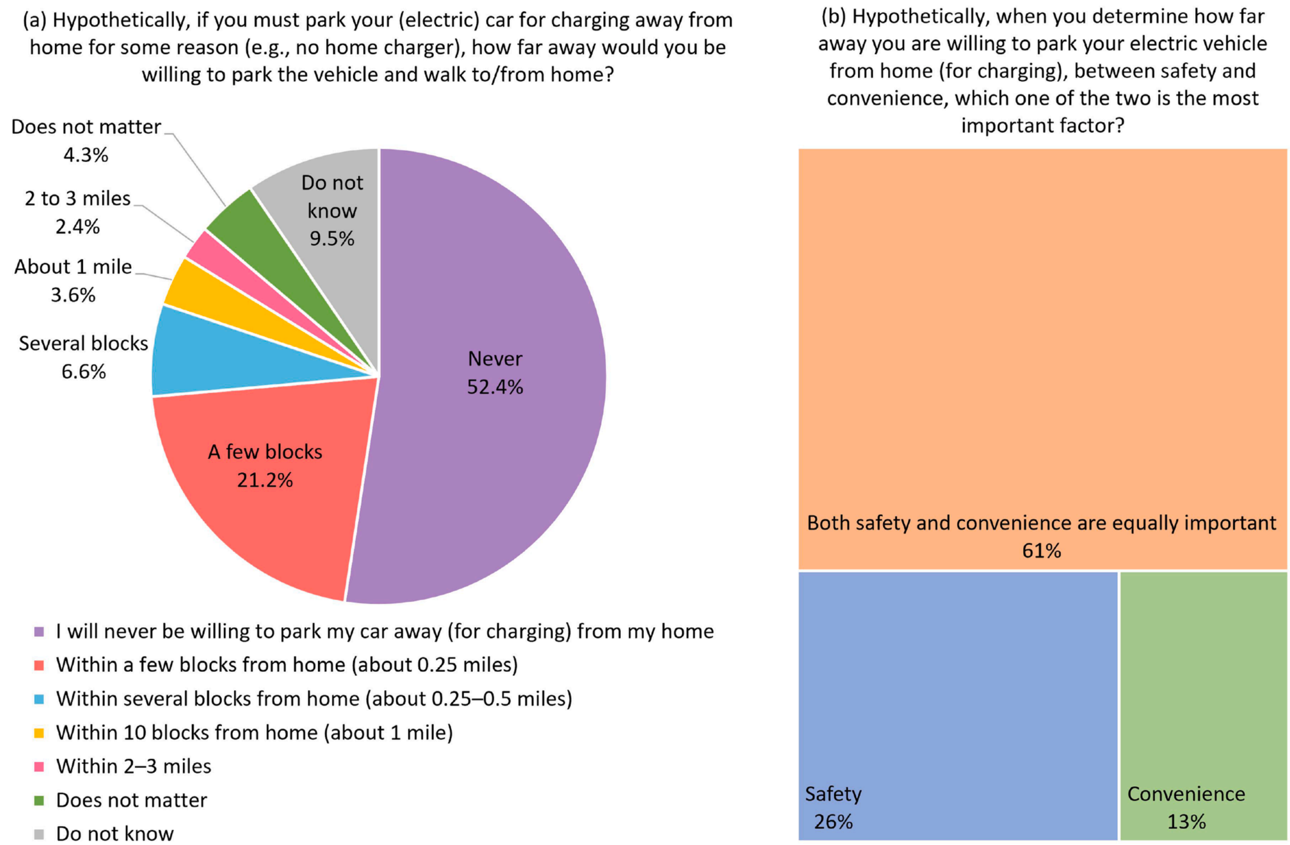

Fig. 7. Comfortable distance from home to nearby location for park-and-charging (as an alternative to home charging, if unavailable) (left), and the importance of safety vs. convenience when deciding the comfortable distance threshold (right).

"workplace" is ranked fourth. This may reflect the number of respondents who either work from home, don't drive to work, don't have a job, or don't have a stable workplace or one that would be conducive to PEV-charging. One or more of these situations may be more common among lower-income groups, given that workplace charging seems to become even more unattractive for these groups in comparison with their higher-income counterparts. Interestingly, starting at the income group with $50,000–$60,000, workplace and gas stations become almost equal in terms of both the ranked preference and the split between the highest rank and the second highest rank. In other words, workplace charging becomes almost equally important as gas stations for people with income of $50,000 or more. Also, it is evident in the ranked preferences that workplace eclipses gas stations as a preferred location for charging, starting at the income group making $100,000–$150,000.

5. Conclusions

The overarching goal for public policy should be to bring about a transition to a just and sustainable transportation system that provides personal mobility for all and that is sufficiently rapid and thorough to meet the demands of the climate crisis. As an essential element of this transition, vehicle electrification must also be effective, equitable, and just. While equity and justice are normative ends in themselves, they have a direct bearing on effectiveness. More equitable access to electric vehicles or charging infrastructure will result in a more rapid and effective electrification through expanding the pool of adopters, which would drive demand, improve the PEV market, and build the society-wide support for the necessary investment and regulatory changes.

With well-directed private or public investments, programs, and strategies, PEVs andtheir corresponding charging infrastructure need not remain relevant or accessible for only a limited group of consumers. To make vehicle electrification more just and equitable, we need to ensure that the deployment of PEVs and charging infrastructure reaches a more diverse group of people, including low-income households, MFH dwellers and renters, so that they and their neighborhoods can enjoy the potential benefits of vehicle electrification, such as lower operating costs and cleaner air.

Developing policies to achieve equitable deployment of PEVs and charging infrastructure must start with the acknowledgement that even if apparently equal access to PEVs and charging infrastructure is provided to all people, some may be unable to adopt and enjoy the benefits of the technologies due to housing-related, behavioral, perceptual, economic, and other types of obstacles. In order to design effective strategies to lower these barriers, they must be well understood. To that end, our study revealed important factors associated with adoption barriers: principally, housing and parking, vehicle ownership and purchase, vehicle utilization and refueling, and preferences and perceptions as to the benefits and barriers of electrification.

More equitable electrification would require increased availability of lower-cost models of PEVs that would be more affordable for low- and middle-income consumers. Our statistical analysis shows that different income groups have distinctively different preferences as to the types of vehicles to purchase, for example, small sedan vs. large SUV vs. pickup truck. Introducing more diverse types and classes of PEVs in the market at different price points could help meet the needs of a wider group of consumers with varying socioeconomic conditions and vehicle purchase preferences. Furthermore, our findings imply that the reliance of the lowest income group on the used vehicle market is five times greater than the highest income group counterpart does. Therefore, policies oriented at developing a strong PEV used vehicle market will go a long way in making PEVs more accessible to people with lower incomes.

However, our exploratory results also introduce some novel findings. Our survey results indicate that vehicle purchase preferences have a

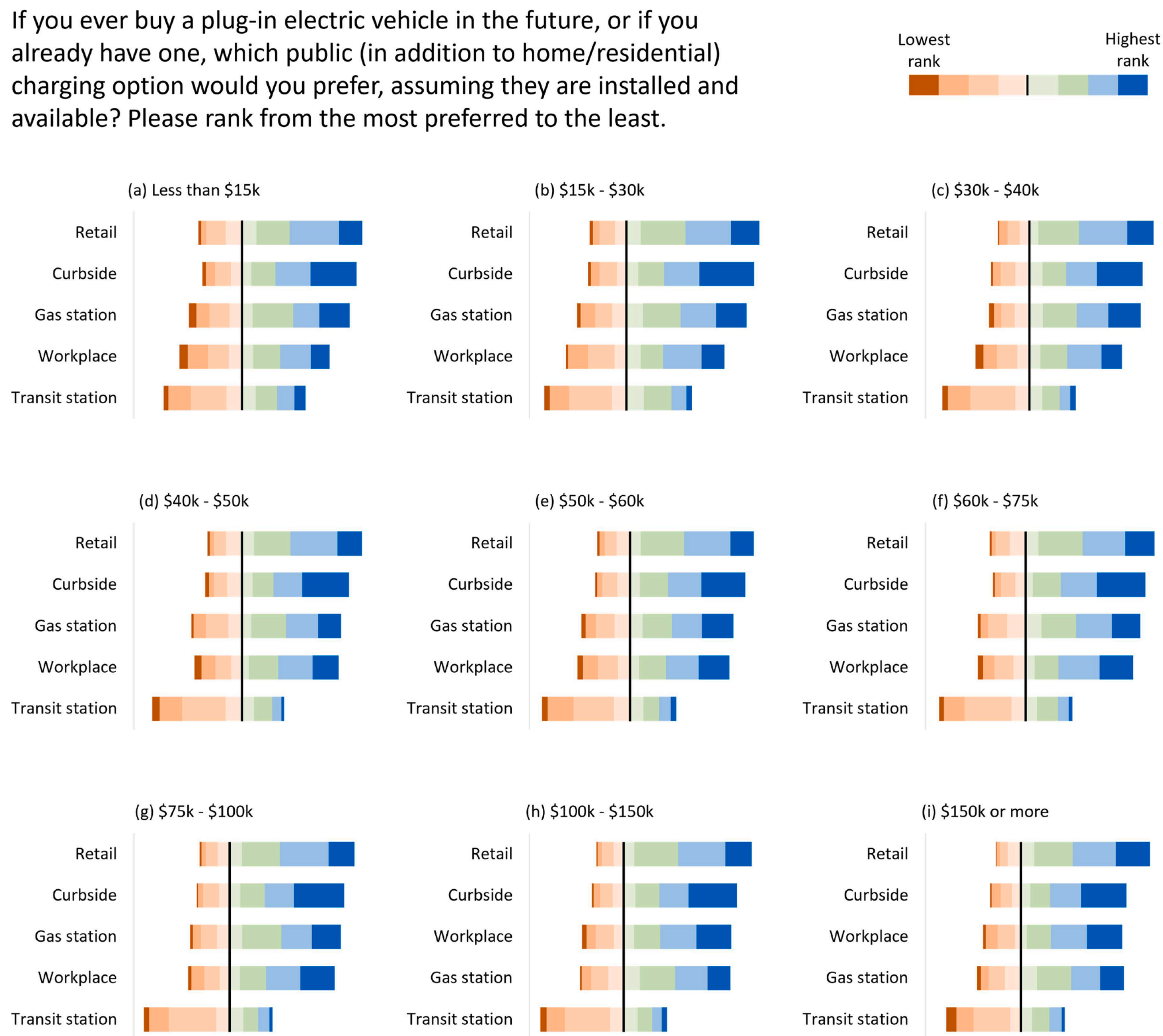

Fig. 8. Preferred public charging locations. Retail: chargers in retail locations (e.g., grocery stores, shopping centers). Curbside: Street/curbside charger in your neighborhood. Gas station: gas stations that provide both gasoline and electricity fuels, which could be faster but more expensive than the other options. Workplace: workplace charger. Transit station: transit stations (park-and-ride).

statistically significant relationship with both income and housing. This means that equity-oriented policies related to PEV purchases may need to consider not only income, but also the housing characteristics of potential consumers. This follows from the reality that convenient access to charging infrastructure and affordable access to PEVs are both essential and interrelated elements of effective and equitable vehicle electrification. Because convenient access to charging is linked to housing type and tenure, equity with respect to vehicle electrification is inevitably linked to housing equity.

In addition to these linkages between energy policy and housing policy, we have made connections to transport policy. Low-cost housing is typically linked with fewer transportation options. Therefore, a more holistic and integrated approach to addressing transportation needs in conjunction with interrelated housing needs would be highly effective in lowering the barriers to equitable vehicle electrification, and ultimately achieving a just and effective transportation system.

Consequently, inclusive infrastructure planning for the placement of home, workplace, and public charging stations is needed for charging options to be strategically and conveniently located in order to meet the varying needs of different households and individuals. Currently, the dominant and primary paradigm of PEV charging is destination charging at home and the workplace. Home charging access is strongly influenced by housing type, which also has a strong correlation with income, location, education level, and other socioeconomic factors. To ensure equitable home charging access, especially for those who live in MFH, targeted policies, such as rebates and modified building codes, would be essential – another finding of our study that we have not seen advanced in the earlier literature.

For those who lack home charging access, on/off-street public chargers located near where they live could provide a workable alternative. Our findings suggest that street/curbside chargers would be a helpful strategy for improving access. However, our survey results also indicate that most people do not want to park their vehicles for charging away from home, out of concern for both safety and convenience. Their concerns over convenience may arise from logistical constraints to public charging that extend beyond distance (such as timely access to functioning units), and thus would not be resolved simply by increasing the density of public facilities. This raises another novel finding, namely a caution regarding the potential effectiveness of public chargers as a measure to alleviate the lack of home charging access.

Similarly, workplace charging tends to become less popular for lower-income households and individuals. Other public access charging options include parking spaces at popular destinations such as grocery stores, commercial districts and gas stations. Gas stations are typically not a trip destination (unlike workplaces, homes, grocery stores and the like); they may be more relevant for the on-route/waypoint charging paradigm, particularly for road trips or long-distance travels. Nonetheless, gas stations could also support improved access to public charging infrastructure in the neighborhoods, depending on the future evolution of their business models. More research is needed to explore the potential role of gas stations.

In general, equitable deployment of PEVs and charging infrastructure may require a shift in focus from a technology and innovation focus on "vehicles" to a more holistic approach to the "people" who own and drive them. This study has contributed to the necessary effort to better understand their needs and constraints. While our focus has been on the role of the personal car to serve as an element of a just transportation system, equitable vehicle electrification must be concerned with non-car owners as well. According to the U.S. Census, approximately 10 % of households in the United States do not own a personal car; other households, including the 30 % of households who own only one vehicle, often include multiple driving-age members. Therefore, to improve equity and achieve electric mobility for all, we must not leave those with little or no access to a personal car behind. For those who do not own personal vehicles, smaller electric mobility options that require less capital (e.g., e-bikes), electric school and transit buses, and shared-ownership business models, such as cooperatives and car-sharing schemes for PEVs, would allowmore diverse groups of people to enjoy the benefits of vehicle electrification directly.

CRediT authorship contribution statement

Dong-Yeon Lee: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Melanie H. McDermott:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation. **Benjamin K. Sovacool:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation. **Raphael Isaac:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A

Questionnaire for Public Perception on Electric Vehicles and Charging Infrastructure

The purpose of this consent form is to give you the information you will need to help you decide whether to participate in the study or not. Please read the form carefully. This process is called "informed consent." You should keep a copy of this form for your records. You should only complete this form if you understand it in full. If you have any questions about this form, please contact the researcher listed above.

Purpose of the Study: This study is intended to evaluate the underlying relationship between socio-demographic characteristics; housing and corresponding parking options; vehicle ownership and purchase; vehicle utilization and refueling; as well as preferences and perceptions on electric vehicle adoption and charging infrastructure.

Procedure of the Study: If you volunteer to participate in this study, we will ask you various questions about your background (age, education level, housing type, etc.), vehicle ownership and usage, and perceptions on existing and future electric vehicles and charging infrastructure.

Cessation of Participation: Your participation in this study is voluntary and you can stop participating at any time if you do not wish to answer a question or for any other reason.

Benefits of the Study: The survey will help researchers and decision makers better understand perceived barriers and opportunities for more effective, equitable, and accessible deployment of electric vehicles as well as corresponding charging infrastructure.

Confidentiality of Research Information: Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. No system for protecting confidentiality is completely secure and the information about you could be inadvertently accessed or seen by someone outside the research team. Government or university staffs sometimes review studies such as this one to make sure they are being done safely and legally. If a review of this study takes place, your records may be examined. The reviewers will protect your privacy. The study records will not be used to put you at legal risk of harm.

Electronic Consent: I volunteer to take part in this research. If I have questions later about the research, or if I have been harmed by participating in this study, I can contact the researcher listed on this consent form. Clicking on the "Agree" button below indicates that you understand the information above; you voluntarily agree to participate and have not been pressured to do so; and you are at least 18 years of age. If you do not wish to participate in the study, please decline participation by clicking on the "Disagree" button.

Part 1. Basic information

1. In which part of the country do you live? a. Midwest b. Northeast c. South d. West

2. What is the 5-digit zip code of your current home location? _____

3. What is your gender? a. Male b. Female c. Other d. Prefer not to answer

4. What is your current age? a. 18–29 b. 30–39 c. 40–49 d. 50–69 e. 70–79 f. 80–89 g. 90 or older h. Prefer not to answer

5. How many people, in total, live in your household? a. 1 b. 2 c. 3 d. 4 e. 5 f. More than 5 (please specify) _____

6. For statistical purposes only, we need to know your total household income. What is your total household income? ______

7. Which race/ethnicity best describes you? (Please choose only one.) a. White or Caucasian b. Black or African American c. Latino or Hispanic d. Asian e. Native Hawaiian or Other Pacific Islander f. American Indian or Alaskan Native g. Other (including two or more races) h. Do not know/prefer not to answer

8. What is the last grade or level of school you have completed? a. Less than high school diploma b. High school graduate c. Some college - but less than two years of college d. Some college - two years or more/A.A. degree e. Technical or trade school f. College graduate/bachelor's degree/B.A./B.S. g. Postgraduate courses h. Master's degree i. M.B.A. or law degree j. Ph.D. or M.D. k. Prefer not to answer

Part 2. Housing & parking

9. In which type of housing do you currently live? a. Single family house not attached to any other house b. Single family house attached to one or more houses (townhouse, rowhome, condo, duplex, triplex, etc.) c. A mobile home or trailer d. Building with 2–4 apartments/condos/studios e. Building with 5–19 apartments/condos/studios f. Building with 20 or more apartments/condos/studios g. Boat, RV, van, etc. h. Other

10. Do you own or rent the current place you are living in? a. Own b. Rent c. Do not know or prefer not to answer

11. In the current place you are living in, what type of parking options do you have (Select all that apply)? a. Personal garage b. Parking garage/deck – assigned c. Parking garage/deck – shared d. Parking lot – assigned e. Parking lot – shared f. Driveway or carport g. On-street – metered h. On-street – free i. Other j. None

Part 3. Vehicle ownership & purchase

12. How many vehicles, in total, does your household own (including leased)? a. None b. 1 c. 2 d. 3 e. 4 f. 5 g. More than 5 (please specify) _____

13. When you buy a car, in which market do you usually look for a vehicle? a. New b. Used c. Both (New & Used) d. Do not know

14. If you were ever in the market for a plug-in electric vehicle, which vehicle market (new and/or used) would you consider? a. New b. Used c. Both (New & Used) d. Do not know

15. If you were ever in the market for a plug-in electric vehicle, and assuming there are a wide variety of options available in the market, which type of vehicles would you consider (select ALL that apply)? a. Small sedan b. Large sedan c. Compact SUV d. Large SUV e. Van f. Pick-up truck g. Do not know

16. If you do NOT own a car, or in cases when you prefer not to drive, which alternative transportation mode do you usually use (Select all that apply)? a. Not applicable (I own a car) b. Public transit c. Taxi d. Carpool and shuttle e. Carsharing (e.g., Zipcar, Getaround, Turo) f. Ridesharing or ride-hailing (e.g., Uber, Lyft) g. Walk h. Bike i. Other (please specify)

Part 4. Vehicle utilization & refueling

17. If you own any gasoline or diesel cars, where do you typically fill the gas tank? a. Not applicable (I do not own a gasoline or diesel car) b. Nearby where you live c. Nearby where you work d. Nearby where you shop (e.g., grocery store) e. Almost random (whenever/wherever convenient each time)

18. If you own any gasoline or diesel cars, how much do you usually fill the fuel tank at gas stations? a. Much less than half (e.g., 25 %) b. About half (50 %) c. Almost full (e.g., 100 %) d. Almost random (it depends)

19. Do you have a home charger (plug-in electric vehicle charging equipment)? a. Yes b. No

20. Please specify the type of your home charger. a. Level 1 (110–120 Volt – using a typical 2/3-prong outlet used for desk lamps and so on) b. Level 2 (208–240 Volt – using a 3/4-prong outlet used for dryers and so on) c. I have both (Level 1 and Level 2) d. Do not know

21. If you have power outlets that are being or could be used for home chargers, among your parking locations at home, where do you have those outlets? Please select ALL that apply. a. Personal garage b. Parking garage/deck – assigned c. Parking garage/deck – shared d. Parking lot – assigned e. Parking lot – shared f. Driveway or carport g. On-street – metered h. On-street – free i. Other j. None

22. For your plug-in electric cars, which location do you rely for charging (from the most to the least)? a. Home b. Workplace c. Other public locations (grocery store, shopping center, hospital, etc.)

23. If you currently do not have a plug-in electric vehicle charger at your home (including apartment complex), but already have or ever plan to own any plug-in electric cars in the future, are you planning to have/install an electric vehicle charger at your home? a. Yes, planning to have/install an electric vehicle charger b. No, I do not plan to have/install an electric vehicle charger c. Do not know

24. Hypothetically, if you must park your (electric) car for charging away from home for some reason (e.g., no home charger), how far away would you be willing to park the vehicle and walk to/from home? a. I will never be willing to park my car away (for charging) from my home b. Within a few blocks from home (about 0.25 miles) c. Within several blocks from home (about 0.25–0.5 miles) d. Within 10 blocks from home (about 1 mile) e. Within 2–3 miles f. Does not matter g. Do not know

25. Hypothetically, when you determine how far away you are willing to park your electric vehicle from home (for charging), between safety and convenience, which one of the following is the most important factor? a. Safety b. Convenience c. Both safety and convenience are equally important

26. If you were to buy a plug-in electric vehicle, what would be the typical/average distance you would hope to be able to drive in that vehicle (assuming not constrained by charging needs)? Please enter ONLY numeric values. a. For daily short-distance trips (miles per day): ______ b. For road trips (miles per day): ______

Part 5. Preferences & Perceptions

27. What do you see as a benefit of (potentially) owning or driving a plug-in electric vehicle in comparison with conventional gasoline car (Select all that apply)? a. Cleaner air (no tailpipe emissions) b. Generally, better for the environment c. Cheaper fuel cost d. Better driving efficiency (consumes less energy) e. Noise reduction (car runs quietly) f. Ability to refuel/charge at home g. Better acceleration (than gasoline-powered cars) h. Other (please specify, e.g., attractive styling) i. I don't think there are benefits to electric vehicles over conventional gasoline cars

28. What do you see as a barrier that prevents you from buying a plug-in electric vehicle (Select all that apply)? a. Higher upfront/purchase price (than gasoline counterpart) b. Shorter range (than gasoline counterpart) c. Lack of home charger (housing-related restriction) d. Lack of public (work or non-work) charging station e. Lack of preferred models (e.g., electric pick-up trucks) f. Concern with reliability g. Unfamiliarity with new technology h. Long refueling time (compared to gasoline cars) i. Other (please specify)

29. In case that you live in a multi-unit dwelling (e.g., apartment complex), if (shared) chargers are installed in a parking lot, how critical would that be for you, when you were considering owning a plug-in electric vehicle? If you do not live in MFH, please skip this question. a. Not applicable (NOT living in a multi-unit dwelling) b. Would not affect at all (would still not be tempted to own a plug-in electric vehicle) c. Could be helpful, but not a deciding factor, because I may have other alternative options (e.g., workplace charging) d. That will be a deciding factor e. Do not know

30. If you ever buy a plug-in electric vehicle in the future, or if you already have one, which public (in addition to home/residential) charging option would you prefer, assuming they are installed and available? Please rank from the most preferred to the least. a. Not applicable (do not [plan to] own electric vehicle[s]) b. Street/curbside charger in your neighborhood c. Workplace charger d. Transit stations (Park N Ride) e. Chargers in retail locations (grocery store, shopping center, etc.) f. Gas stations that provide both gasoline and electricity fuels – could be faster but more expensive than the other options g. Somewhere else

Appendix B

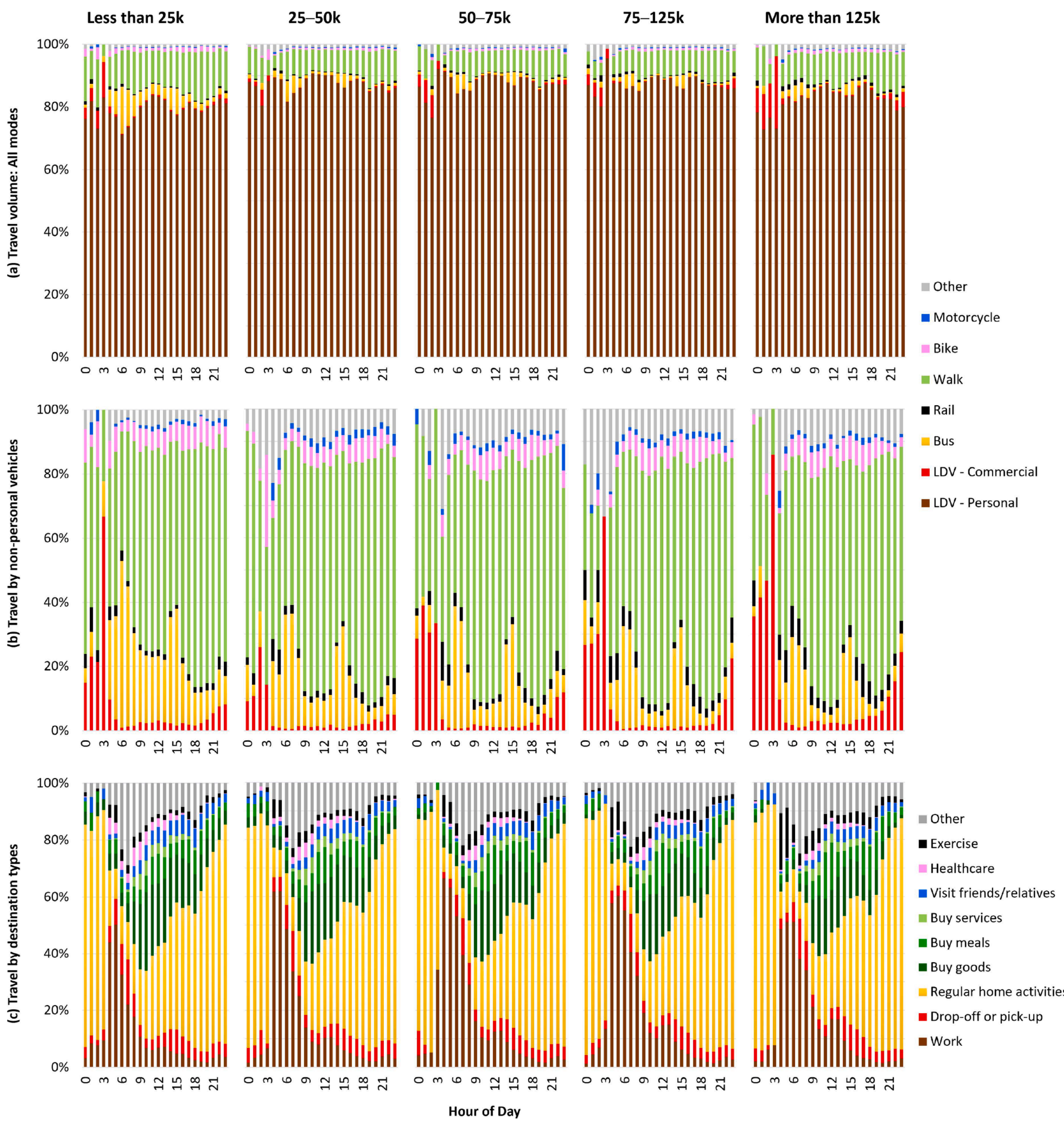

Fig. A1. Travel activity (based on the NHTS) over the course of the day by annual income (top), breakdown of transportation modes other than personal cars (light-duty vehicle [LDV] – personal) (middle), and the distribution of destination types (bottom). Source: [59].

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