Gas Anxiety and the Charging Choices of Plug-In Hybrid Electric Vehicle Drivers

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Abstract

Plug-in hybrid electric vehicles (PHEVs) can provide many of the benefits of battery electric vehicles (BEVs), such as reduced petroleum consumption and greenhouse gas emissions, without the “range anxiety” that can accompany driving a vehicle with limited range when there are few charging opportunities. However, evidence indicates that PHEVs are often plugged in more frequently than BEVs in practice. This is somewhat paradoxical: drivers for whom plugging in is optional tend to do so more frequently than those for whom it is necessary. This has led to the coining of a new term – “gas anxiety” – to describe the apparent desire of PHEV drivers to avoid using gasoline. In this paper, we analyze the variables influencing the charging choices of PHEV owners, testing whether drivers express preferences consistent with the concept of gas anxiety. We analyze data collected in a web-based stated preference survey using a latent class logit model. The results reveal two classes of decision-making patterns among the survey respondents: (1) those who weight the cost of gasoline and the cost of recharging approximately equally (the cost-minimizing class), and (2) those who weight the cost gasoline more heavily than the cost of recharging (the gas anxiety class). Respondents in the gas anxiety class expressed a willingness to recharge at a charging station even when doing so would cost approximately four times as much as the cost of the gasoline avoided. While the gas anxiety class represents the majority of our sample, more recent PHEV adopters are more likely to be in the cost-minimizing class. Looking forward, this suggests that public charging station operators may need to price charging competitively with gasoline on a per-mile basis to attract PHEV owners.

Key words: PHEV, charging choice, gas anxiety, stated preference data, latent class logit
1 Introduction

Electrification of the vehicle powertrain is a promising approach to reduce the oil dependence and environmental impacts of automobiles, particularly when the electricity used for recharging is generated from renewable sources (1). However, major barriers to consumer adoption of battery-electric vehicles (BEVs) exist. First, while significant reductions in battery costs have been achieved (2), BEVs remain substantially more expensive than conventional vehicles. Second, the time needed to recharge a BEV is an order of magnitude greater than the time needed to refuel with petroleum fuel for a comparable range. Third, most BEVs have driving ranges much lower than their gasoline counterparts. While even limited range BEVs are capable of fulfilling the vast majority of drivers’ travel patterns (3), many prospective BEV buyers worry about becoming stranded when the battery is depleted fully, a concern known as “range anxiety” (4). Although range anxiety declines with experience driving a BEV (5), it remains a significant barrier to initial adoption.

Plug-in hybrid electric vehicles (PHEVs) offer the potential to overcome these barriers. By combining an internal combustion engine, an electric powertrain, and a battery offering limited electric range,¹ PHEVs can reduce gasoline use and emissions while retaining the ability to travel long distances with fast and convenient refueling (6-8). PHEVs are inherently less dependent on recharging infrastructure than BEVs because they also have an internal combustion engine, which should mitigate range anxiety.

Systematic data collection on in-use charging patterns has found that PHEV drivers plug in more often than BEV drivers (an average of 1.4 charging events per day of driving for PHEVs, versus 1.1 events per day for BEV drivers) (9). This finding is paradoxical: drivers for whom plugging in is optional tend to do so more frequently than those for whom it is necessary. This surprising result has led to the coining of a new term—“gas anxiety”²—to describe the propensity of PHEV drivers to willingly incur additional cost and/or time to avoid using gasoline (10-13).

Competing explanations exist for why PHEV drivers may charge more frequently than BEV drivers. While PHEV drivers’ more frequent charging may be motivated by an intrinsic desire to avoid consuming gasoline, it may alternatively be motivated by simply wanting to minimize vehicle operating cost. Given PHEVs’ limited electric range, we would expect more frequent charging when electric miles are cheaper than gasoline miles, and daily travel exceeds a vehicle’s electric range. Understanding what motivates PHEV drivers to

¹ The most popular PHEV in the US at the time the data were collected, the Chevrolet Volt, had a rated electric range of approximately 60 km. In contrast, the Nissan Leaf BEV had a range of approximately 120 km.

² We use the term “anxiety” consistently with its contemporary popular usage in the context of “range anxiety” and “gas anxiety”. We recognize that “anxiety” is also a term of art in the field of psychology, a dimension that we do not investigate specifically here.
recharge has important implications for recharging infrastructure planning, pricing strategies, and predicting electricity demand temporally and spatially.

In this paper, we test for the presence of gas anxiety empirically, investigating whether PHEV owners place a financial premium on avoiding gasoline consumption when recharging. We gathered data using a web-based stated preference survey of PHEV drivers to determine how situational variables such as charging power, the respective prices of gasoline and recharging, and the vehicle’s state of charge influence PHEV owners’ charging decisions. We model consumer charging choices using a latent class logit choice model, estimating the relative weights that PHEV drivers place on the cost of gasoline and cost of electricity on a distance–equivalent basis. We find that one class of respondents values expenditures on gasoline and electricity equally, while another class is willing to pay about four times as much for electricity as for the gasoline that same electricity will displace.

More generally, our results predict the probability of a PHEV driver charging in a given situation, which is important as that the environmental benefits of a PHEV depends on the percentage of total vehicle-miles travelled (VMT) powered by electricity (14). Accurately assessing and forecasting the emissions impacts and petroleum savings of PHEVs requires the ability to predict when and where PHEV owners will plug in, and how this may change under differing assumptions about the availability and pricing of recharging. Similarly, understanding how these charging decisions are affected by the cost, speed, and availability of charging opportunities is critical for the design of recharging infrastructure systems that maximize the gasoline savings achieved by PHEVs.

2 Methodology

In this paper, we use a latent class logit model to analyze data from a stated choice survey of U.S. PHEV owners. We model how the decision of whether or not to charge is affected by the vehicle’s state of charge, planned travel, and the prices of charging and gasoline. We then use this model to test whether respondents demonstrate “gas anxiety” by expressing an outsized willingness to pay for charging to avoid consuming gasoline.

2.1 Prior Approaches to Modeling Charging Behavior

Early studies relied heavily on rule-based assumptions about charging behavior to assess the energy consumption and charging demand of PHEVs. For example, Kang and Recker assumed that PHEVs were only charged at home (15). Lin and Greene assumed that PHEVs were plugged in whenever the charge-depleting (CD) range was exhausted (16). Axsen and Kurani assumed that PHEVs would be recharged whenever parked within 25 feet of an electrical outlet (17). What these models of charging behavior have in common is that they are generally simple and deterministic. In practice, charging behavior is considerably more complicated than an empty battery or an available plug. Multiple variables have been shown to influence the decision-making process, including dwell time, location, time, day of week, and even the length of the most recent trip, and charging preferences are heterogeneous across users (14, 18, 19, 20).
Several previous studies have analyzed the charging behavior of plug-in electric vehicle (PEV) drivers, mostly using logit-family choice models (Table 1). Based on a year-long study of PHEVs instrumented for detailed data collection in the United States, Zoepf et al. developed a mixed logit model of charging choices, finding that current state of charge (SOC), completed trip distance, and dwell time all influenced the choice of whether to charge at the end of a trip (14). The results revealed heterogeneity in charging behavior across PHEV users, which has also been demonstrated using stated preference surveys (18) and instrumented vehicle studies (21). Jabeen et al. analyzed the influence of charging cost, charging duration and time of day on people’s charging preferences among charging at home, work, and public recharging stations using both multinomial logit and mixed logit models (18). Using stated preference data from UK drivers, Daina estimated a multinomial logit model to determine the influence of SOC, price, trip purpose, distance and dwell time on charging choices (22). Using a mixed multinomial logistic regression model, Sun et al. examined the influence of SOC and VMT of the next travel day on the charging time choice (no charging, charging immediately after arrival at home or workplace, nighttime charging or charging at other times) (23). Daina & Polak estimated a hazard-based model to predict the durations between charging events and concluded that vehicle state of charge, cumulative average driving speed, and individual characteristics significantly influence charging rate (24).
Recent studies have found that latent class models generate richer patterns of heterogeneity, yielding better fitting models of revealed and stated PEV charging choices while providing an easy to interpret, intuitive segmentation of respondent types (25, 26). In contrast to mixed logit models that assume a continuous distribution of taste parameters, latent class models assume that individuals can be separated into finite sets of classes, with preference heterogeneity captured by allocating respondents to different classes based on sociodemographic information (27). Yu & MacKenzie found that a latent class logit model fit observed charging choices better than a mixed logit model (25). Wen et al. identified three modes of charging behavior among BEV drivers, also finding that a latent class logit model provided a better fit to the data than a mixed logit model (26).

### 2.2 Survey Design

We conducted a stated preference experiment in which PEV drivers were asked whether or not they would choose to recharge in a range of scenarios, each characterized by charging price, gasoline price, battery state of charge (SOC), and travel plans. Respondents included both PHEV and BEV drivers; in this paper we focus on the responses of the PHEV drivers. Although stated preference data can be perceived as less reliable than revealed preference...
data, since the respondents in this survey were asked to make a yes-or-no decision replicating a decision they make routinely in the real world, we believe the risk of hypothetical bias to be small.

The survey consisted of two parts: (1) a questionnaire on sociodemographic information and vehicle ownership; and (2) a charging choice experiment, introduced below.

2.2.1 Socio-demographic questionnaire

The questionnaire covered a variety of sociodemographic questions, including: age, gender, education, household income, household size and zip code of home address. It also asked the questions on the length of PEV ownership (“In what year did you purchase or lease your EV?”) and the respondents’ motivation of purchasing a PEV (“Please briefly describe your motivation for purchasing an EV.”) The respondents also reported the actual range that their PHEVs can achieve on a full charge.

2.2.2 Charging choice experiment

In this section of the survey, each respondent was presented with a hypothetical situation and asked to choose whether they would charge in that situation or not. A fractional factorial experimental design was used to generate 160 possible scenarios, and each respondent was presented with eight scenarios drawn from this pool and presented in a randomized order. In each scenario, the respondents were instructed to assume that other considerations (such as the cost and availability of parking) would not be affected by the decision of whether or not to charge. The attributes and levels characterizing the choice situations are listed in Table 2.
Table 2: Attributes and Their Levels of the Experiments

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Description</th>
<th>Attribute levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charging price ($/hour)</td>
<td>The recharging price of the station</td>
<td>$0.50/h; $1.00/h; $1.50/h; $2.00/h; $5.00/h</td>
</tr>
<tr>
<td>Charging power (kW)</td>
<td>The charging speed of the station</td>
<td>1.9 kW; 6.6 kW</td>
</tr>
<tr>
<td>Dwell time (hours)</td>
<td>The time duration for which the respondent will stay at this station</td>
<td>0.25 h; 0.5 h; 1 h; 2 h; 4 h; 8h</td>
</tr>
<tr>
<td>Distance to home (miles)</td>
<td>Distance from this station to home</td>
<td>2 mi; 5 mi; 10 mi; 20 mi; 30 mi; 50 mi</td>
</tr>
<tr>
<td>Remaining range (miles)</td>
<td>The current range remaining in the battery</td>
<td>Distance to home – 20mi; Distance to home – 10mi; Distance to home – 5mi; Distance to home – 2mi; Distance to home + 2mi; Distance to home + 5mi; Distance to home + 10mi; Distance to home + 20mi;</td>
</tr>
<tr>
<td>Gasoline price ($/gallon)</td>
<td>The retail price of a gallon of conventional gasoline</td>
<td>$2.50/gallon; $3.00/gallon; $3.50/gallon; $4.00/gallon; $4.50/gallon</td>
</tr>
</tbody>
</table>

2.3 Data Collection

The data were collected from November 12 2013 to February 12 2014. Our sample was recruited primarily through the Electric Auto Association (EAA), whose members are generally enthusiastic about electric vehicle technology, and willing to participate in the survey without any extrinsic incentives. Other respondents were invited through web forums for PEV owners, or were invited by other survey respondents. While our sample may not be entirely representative of the current population of PHEV adopters, all EV adopters to date may be considered early adopters, and hence they may not be representative of future adopters. Respondents were geographically distributed around the United States (Figure 1). 177 PHEV owners participated in this survey, resulting in 157 complete responses. A large proportion of the respondents were from the West and East Coasts (Figure 1). This geographical distribution of respondents suggests that the actual range of PHEVs is likely to vary quite significantly even for the same PHEV make/model due to climatic variation across the United States (28).
Summary statistics for the sample are shown in Table 3. The respondents were generally older (66% are more than 45 years old) and 88% of the respondents were male. The reported household income among the respondents is higher than the national average, with more than 50% of respondents reporting a household income over $100,000. In contrast, median household income in the US was approximately $52,000 in 2013 and 2014. The distributions of the age and income of this sample are similar to the population of PEV buyers in the US (29). In our sample, 72% of the respondents have a Bachelor’s degree or advanced degree, which is similar to a national sample of PEV buyers in the US (29). Among the 157 complete responses, 29% did not possess a conventional gasoline car in their household.
Table 3: Sample Summary Statistics

<table>
<thead>
<tr>
<th>Category</th>
<th>Percentage</th>
<th>This Study</th>
<th>US Population</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18-34</td>
<td>10%</td>
<td></td>
<td>29%</td>
</tr>
<tr>
<td>35-55</td>
<td>54%</td>
<td></td>
<td>34%</td>
</tr>
<tr>
<td>55+</td>
<td>36%</td>
<td></td>
<td>37%</td>
</tr>
<tr>
<td><strong>Gender</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>88%</td>
<td></td>
<td>49%</td>
</tr>
<tr>
<td>Female</td>
<td>12%</td>
<td></td>
<td>51%</td>
</tr>
<tr>
<td><strong>Education</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less than High School</td>
<td>1%</td>
<td></td>
<td>12%</td>
</tr>
<tr>
<td>High School / GED</td>
<td>2%</td>
<td></td>
<td>30%</td>
</tr>
<tr>
<td>Some College</td>
<td>15%</td>
<td></td>
<td>17%</td>
</tr>
<tr>
<td>2-Year College Degree (Associates)</td>
<td>10%</td>
<td></td>
<td>10%</td>
</tr>
<tr>
<td>4-Year College Degree (BA, BS)</td>
<td>46%</td>
<td></td>
<td>21%</td>
</tr>
<tr>
<td>Advanced degrees (Master’s Degree, Doctoral Degree and Professional Degree such as MD and JD)</td>
<td>26%</td>
<td>12%</td>
<td></td>
</tr>
<tr>
<td><strong>Household income</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;99,999</td>
<td>32%</td>
<td></td>
<td>65%</td>
</tr>
<tr>
<td>$100,000+</td>
<td>68%</td>
<td></td>
<td>35%</td>
</tr>
</tbody>
</table>

2.4 Modeling Approach

As discussed in Section 2.1, early efforts to model the heterogeneity of charging preferences across PEV drivers used mixed logit regression models (14, 18, 19). In a mixed logit regression model, the random taste of coefficients (denoted as $\beta$) follows a continuous random distribution across the population.

Latent class models assume that all individuals can be separated into a finite set of classes ($Q$ classes). Here, taste heterogeneity is captured by allocating respondents to different classes in a probabilistic manner, allowing the probability of class membership to depend upon the respondents’ sociodemographic information. Each class has different taste coefficients, but within each class, the taste parameters are assumed to be homogeneous (27).

Within class $q$, the conditional probability of charging by individual $i$ in choice situation $t$ is:

$$P(Charge_{it} | \beta_q, \text{class } q) = \frac{e^{\beta_q X_{it}}}{e^{\beta_q X_{it} + 1}} \quad (1)$$

where $\beta_q$ is a vector of coefficients for class $q$, and $X_{it}$ is a vector of observed variables characterizing the choice faced by individual $i$ in situation $t$.

A class allocation model defines the probability that the respondent $i$ falls into class $q$ as $\pi_{iq}$, which can be calculated using the multinomial logit equation:

$$\pi_{iq} = \frac{e^{\gamma_q Z_i}}{\sum_{q=1}^{Q} e^{\gamma_q Z_i}} \quad (2)$$

where $\gamma_q$ is a vector of coefficients for the class allocation model and $Z_i$ is a vector of observed socioeconomic variables used to predict class membership for respondent $i$. 
Then the charging probability for individual $i$ under scenario $t$ is given by:

$$P(\text{Charge}_{it}) = \sum_{q=1}^{Q} \pi_{iq} \frac{e^{\beta q x_{it}}}{e^{\beta q x_{it+1}}}$$

(3)

### 2.5 Variables for the Charging Choice Model

To address our research questions, we derive variables that represent the amount of energy obtained by charging and the costs (including the gasoline costs and electricity costs) based on the characteristics of the scenarios (charging price, charging power, gas price, remaining range and distance to destination) and the characteristics of the PHEVs driven. Table 4 defines the variables we use in our analysis. When a PHEV driver makes the decision to recharge, we hypothesize that three costs could enter consideration: (1) the cost of charging at this stop, $c_{\text{charging}}$; (2) the cost of charging at home at the end of the travel day, $c_{\text{home}\_\text{charge}}$; and (3) the cost of gasoline if the PHEV runs out of electricity before arriving home, $c_{\text{gas}}$. Following Yu & MacKenzie (25), we also hypothesize that the decision to charge depends on the amount of range that can be obtained by plugging in. In this section, we explain how the following four variables were derived: percentage of range obtained ($r_{\text{obtained}}$), charging cost at the stop ($c_{\text{charging}}$), electricity cost at home ($c_{\text{home}}$), and gasoline cost to finish the trip ($c_{\text{gas}}$).
Table 4: Variable Definitions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{obtained}$</td>
<td>Range obtained (mi)</td>
<td>Range obtained is the maximum electric range increase the PHEV can get at the station during the specified dwell time if the driver chooses to charge</td>
</tr>
<tr>
<td>$r_{obtained}(%)$</td>
<td>Percentage of range obtained (%)</td>
<td>Same as range obtained, but expressed as a percentage of the vehicle’s maximum electric range.</td>
</tr>
<tr>
<td>$r_{full}$</td>
<td>Full range (mi)</td>
<td>The full electric range of the PHEV, as reported by the respondent</td>
</tr>
<tr>
<td>$r_{remaining}$</td>
<td>Remaining range (mi)</td>
<td>The current electric range of the PHEV when arriving at a stop, based on its battery’s state of charge</td>
</tr>
<tr>
<td>$r_{after\ stop}$</td>
<td>Range after the stop (mi)</td>
<td>The PHEV’s electric range when it leaves the stop. It depends on whether or not the driver chooses to charge.</td>
</tr>
<tr>
<td>$r_{home}$</td>
<td>Remaining range when arriving home (mi)</td>
<td>The PHEV’s electric range remaining when it arrives home</td>
</tr>
<tr>
<td>$t_{dwell}$</td>
<td>Dwell time (h)</td>
<td>The length of time the PHEV will be stopped at a certain charging station</td>
</tr>
<tr>
<td>$t_{plug}$</td>
<td>Plug time (h)</td>
<td>The amount of time the PHEV stays plugged in to the EVSE.</td>
</tr>
<tr>
<td>$P$</td>
<td>Charging power (kW)</td>
<td>The maximum power of an EVSE</td>
</tr>
<tr>
<td>$d_{home}$</td>
<td>Distance to home (mi)</td>
<td>The remaining distance from the charging station to home, based on travel plans</td>
</tr>
<tr>
<td>$ECR$</td>
<td>Electricity consumption rate (kWh/mi)</td>
<td>Electricity consumption rate in charge-depleting mode</td>
</tr>
<tr>
<td>$mpg$</td>
<td>Fuel economy (miles per gallon)</td>
<td>The fuel economy of the PHEV in charge-sustaining mode</td>
</tr>
<tr>
<td>$p_{charging}$</td>
<td>Charging price ($/h)$</td>
<td>Charging price at the station</td>
</tr>
<tr>
<td>$p_{gas}$</td>
<td>Gas price ($/gallon)</td>
<td>Current gasoline price</td>
</tr>
<tr>
<td>$p_{electricity}$</td>
<td>Electricity price at home ($/kWh$)</td>
<td>Self-reported price of electricity at the respondent’s home</td>
</tr>
<tr>
<td>$c_{charging}$</td>
<td>Charging cost at the stop ($)</td>
<td>The total charging cost if an individual chooses to charge in the specified situation</td>
</tr>
<tr>
<td>$c_{home_charge}$</td>
<td>Electricity cost at home ($)</td>
<td>The electricity cost to fully charge the PHEV at the end of the travel day, if the respondent chooses to charge at this stop; The electricity cost to fully charge the PHEV at the end of the travel day, if the respondent chooses not to charge at this stop.</td>
</tr>
<tr>
<td>$c_{home_not\ charge}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$c_{gas_charge}$</td>
<td>Gasoline cost ($)</td>
<td>The cost of gasoline that will be used to complete the travel day, if the respondent chooses to charge at this stop; The cost of gasoline that will be used to complete the travel day, if the respondent chooses not to charge at this stop.</td>
</tr>
<tr>
<td>$c_{gas_not\ charge}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.5.1 Percentage of Potential Range Obtained

We measure the potential energy that can be obtained from recharging as the range obtained at the station ($r_{obtained}$). If the dwell time ($t_{dwell}$) is sufficient for the PHEV to reach a full charge ($r_{full}$), the range obtained is the difference between the full range and the remaining range ($r_{remaining}$). Otherwise, the range obtained depends on the charging power ($P$) and dwell time ($t_{dwell}$) and the electricity consumption rate in charge depleting mode ($ECR$):

$$r_{obtained} = \min\left\{ P \cdot t_{dwell}, ECR, r_{full} - r_{remaining} \right\} \quad (4)$$

The same potential range obtained may have a different influence on the utility of charging for PHEVs with different electric ranges. For example, 10 miles of range represents only ¼ of the electric range of a Chevrolet Volt, but nearly a full charge for a Toyota Prius. We calculate the percentage of potential range obtained as:
\[ r_{obtained} = \frac{r_{obtained}}{r_{full}} \times 100\% \] (5)

One important note is that in all the calculations shown here, the full range is the reported range obtained from the survey, rather than the official range reported by manufacturers or government agencies. Reported range has proved to be a better predictor of charging decision according to the model fit, presumably because it varies across respondents due to differences in climate, topography and driving style. This survey was conducted during winter, and the respondents were distributed across the country. The electric range of PHEVs varies greatly in different climates since there is significant range loss in cold climates (28).

2.5.2 Charging Cost at This Stop \( c_{charging} \)

Plug time \( t_{plug} \) is the time duration that the PHEV stays plugged on the charger. We assume that once a PHEV is plugged in, it will remain plugged until it is fully charged or it is time for the driver to depart. So if the car cannot reach a full battery during the dwell time, plug time will be equal to the dwell time. Otherwise plug time is equal to the time needed for the PHEV to become fully charged. It is calculated as equation (6).

\[
t_{plug} = \min \left\{ t_{dwell}, \frac{(r_{full} - r_{remaining}) \times ECR}{p} \right\}
\] (6)

Plug time is used to calculate the charging cost at the stop, which is defined as the total charging cost if an individual chooses to charge at this station:

\[
c_{charging} = p_{charging} \times t_{plug}
\] (7)

2.5.3 Electricity Cost at Home \( c_{home} \)

Electricity cost at home \( c_{home} \) is the amount of money that will be paid to get the PHEV back to a fully charged state after the travel day. It depends on PHEV driver’s charging decision at the current station. Based on the charging decision, the remaining range when the driver leaves the station \( r_{after\ stop} \) can be calculated as:

\[
r_{after\ stop} = \begin{cases} 
 r_{remaining} + r_{obtained} & \text{if they charge} \\
 r_{remaining} & \text{if they don't charge}
\end{cases}
\] (8)

If the electric range after a stop is less than the distance to home, the remaining range when the PHEV gets home \( r_{home} \) will be zero. Otherwise, if the electric range after a stop \( r_{after\ stop} \) is enough for the driver to get home using electricity, the range remaining when the driver arrives home \( r_{home} \) can be calculated as range after stop minus the distance to home \( d_{home} \).

\[
r_{home} = \max(0, r_{after\ stop} - d_{home})
\] (9)
So the electricity cost at home \((c_{\text{home}})\) can be calculated as:

\[
c_{\text{home}} = (r_{\text{full}} - r_{\text{home}}) \times ECR \times p_{\text{electricity}}
\]  

(10)

Electricity cost at home \((c_{\text{home}})\) depends on the charging decisions at the stop. If the respondents choose to charge, it can be written as \(c_{\text{home, charge}}\). If the respondents choose not to charge, it can be written as \(c_{\text{home, not charge}}\).

### 2.5.4 Gasoline Cost \((c_{\text{gas}})\)

The gasoline cost is:

\[
c_{\text{gas}} = \max(0, \frac{d_{\text{home}} - r_{\text{after stop}}}{\text{mpg}} \times p_{\text{gas}})
\]  

(11)

Gasoline cost depends on the respondents’ charging decisions at the stop. If the respondents choose to charge, it can be written as \(c_{\text{gas, charge}}\). If the respondents choose not to charge, it can be written as \(c_{\text{gas, not charge}}\).

### 2.6 Variables for the Class Allocation Model

In our final model specification, four variables are used to predict class membership: gender, income, years of owning/leasing their PHEV (continuous), and whether the respondent identified financial benefits as their only motivation for buying a PHEV (yes or no). The first three variables are questions directly from the questionnaire. The last variable is derived from an open-ended question on the respondents’ motivation for choosing an electric vehicle. A descriptive analysis of variables involved in this analysis is provided in Table 5.
3 Results

We estimate a latent class model with two classes, yielding the results shown in Table 6. The Bayesian information criterion (BIC) of this model is 1241.1, much smaller than the BIC of a binary logit model (i.e. a single-class model): 1506.9. Models with larger numbers of classes were also tested, but did not converge, despite starting from a variety of randomized starting values. Different specifications of the class allocation models were also tested and the one with the smallest BIC value was chosen as the final model.
With the classification variables of class 2 being normalized to 0, two variables are significant predictors of class membership (Table 6): Years of owning/leasing their PHEV, and financial benefits as the only motivation of owning/leasing a PHEV. The coefficients of these two variables indicate that respondents who are relatively newer adopters of PHEVs are more likely to be allocated into class 1. Similarly, those who identify financial benefits as the only motivation for buying a PHEV are also more likely to be in class 1. Respondents in class 1 tend to make their charging decision based on costs and the energy obtained from charging. The charging cost at the station and gasoline cost both have a negative influence on the utility of charging with similar magnitudes (-2.81 and -2.90). This indicates that respondents in class 1 value expenditures on gasoline and on public charging stations similarly, as would be expected if they were switching between two energy sources so as to minimize their total costs. We refer to class 1 as cost-minimizing.

The PHEV users who have owned/leased a PHEV for a longer period of time (earlier adopters) and those who do not identify financial considerations as their only motivation are more likely to be assigned to class 2. They also make charging decisions based on monetary costs.
costs and the range obtained, but the magnitudes of the gasoline cost and charging cost coefficients are quite different: gasoline cost has a much larger magnitude (-1.95) than charge cost (-0.52). This indicates that this class weights expenditures on gasoline more heavily than expenditures on charging. This behavioral pattern is consistent with the concept of “gas anxiety,” in the sense that respondents in class 2 are willing to pay approximately four times as much for electricity as for the gasoline that electricity will displace. We refer to class 2 as the gas anxiety class.

Based on the predicted values and the independent variables of the class allocation model, the expected values of the sociodemographic variables can be calculated according to the following equation (23):

$$X_{class \ q} = \frac{\sum_{i=1}^{N} \pi_{iq} X_i}{\sum_{i=1}^{N} \pi_{iq}}$$

(12)

Where N is the number of respondents, \( \pi_{iq} \) is the probability of respondent i falling into class q computed on the basis of the class allocation model and \( X_i \) is the values of the explanatory variables of respondent i. The expected values of the explanatory variables are also shown in Table 6. Gender ratios and incomes are similar in the two classes, which is not surprising given that these two variables were not significant predictors of class membership. The expected value of years of owning/leasing a PHEV is lower for class 1 (cost-minimizing) than for class 2 (gas anxiety). A larger fraction of those in class 1 (cost-minimizing) cited financial benefits as the only motivation of owning/leasing a PHEV.

3.1 Robustness

For completeness, we tested additional model specifications, using absolute range obtained instead of percentage of range obtained, and basing charging cost on dwell time instead of plug time. The model presented in this section generates the best goodness of fit according to the BIC. We also considered more variables for the class allocation model, such as education level, whether the respondent’s electricity source at home is renewable, and whether there are gasoline cars in their household. These variables were not statistically significant predictors of class membership, and were omitted to obtain a more parsimonious model. The model results (coefficient estimates and significance levels) change only slightly when these variables are dropped from the class membership model.

Multiple sets of starting values of the estimates were used in the maximum likelihood estimation procedure, but the models converge to the same results in all cases. This gives us greater confidence that our results represent a global optimum.

4 Discussion

The results in Section 3 highlight the heterogeneity in preferences for charging among PHEV owners. Those in the gas anxiety class (class 2) can be expected to make greater use of public charging infrastructure, and are willing to pay a relatively high amount to do so. Another class of users is more likely to charge when doing so will reduce their travel costs, but is less likely to pay a premium to avoid consuming gasoline. After calculating the
expected value of the probability of every respondent being in each class, we estimate that
respondents in our sample have a 34% probability of being in class 1 (the cost-minimizing
class) and a 66% probability of being in class 2 (the gas anxiety class). We caution that future
PHEV owners may not split along these lines, since the variables predicting class
membership (years of PHEV ownership and prevalence of financial motivations) are likely to
change over time.

The estimated effect of years of PHEV ownership on class membership can be
interpreted in two ways. On the one hand, the estimated effect might mean that as a person
owns a PHEV for a longer time, their preferences for charging evolve. This could be due to
increased familiarity with the charging system, an acquired taste for the driving
characteristics (e.g. low noise, instant torque) of electric propulsion, or other learning effects.
If this is the case, we would expect class 2 to comprise a stable or growing share of PHEV
owners over time, as more people will have owned a PHEV for longer. On the other hand, it
is possible that the people in our sample who had owned a PHEV the longest were simply the
ones who had been most enthusiastic about adopting, and that their preferences are inherently
different than those of later adopters. For example, earlier adopters might be motivated more
by altruism or pro-environmental attitudes. If this is the case, then class 1 could represent a
much larger share of future PHEV owners, even though it is a minority in our sample. The
current dataset cannot answer this question, although other research is exploring the relative
importance of cost motivations and psychological variables among potential electric vehicle
adopters (30).

4.1 Practical Implications

The relative proportions of the two classes among future PHEV owners will have
implications for what level of charging station pricing can be sustained in the future. The
proportions of the two classes in turn will depend on the effects of PHEV purchase
motivations and years of PHEV ownership on class membership. In our sample, those who
identified financial considerations as their primary motivation for purchasing a PHEV are
more likely to be in class 1, minimizing the costs of electricity and gasoline. If future PHEV
purchasers tend to be motivated by financial considerations (as might happen if government
policy and marketing efforts emphasize financial incentives and monetary savings), then
future adopters may be more likely to resemble class 1 (cost-minimizing). In this case, public
charging would need to be priced at or below the distance-equivalent cost of gasoline to
motivate these consumers to use public charging and minimize their gasoline-fueled VMT. In
contrast, if future PHEV owners were more like the class 2 (gas anxiety) in our sample, then
public charging could be priced a little higher than the equivalent gasoline cost, and
consumers would be willing to pay the higher price. This outcome seems more likely if future
adoption is driven more by non-financial motivations, or if it turns out that preferences do in
fact evolve as owners gain experience with PHEVs.

4.2 Limitations

One limitation of this study is the cross-sectional nature of the data, which does not
allow us to understand why longer PHEV ownership is associated with a higher probability of
being in class 2 (gas anxiety). Is it because the later adopters are inherently different than the earlier adopters, or because charging preferences evolve with longer ownership? A longitudinal study, or even future cross-sectional studies, could help to resolve this. Second, our sample of current EAA members is a self-selected group of PEV enthusiasts, whose preferences may differ from those of other PEV owners today. We also note that given the early stage of the PEV market, even the best sample of PEV owners today would likely be unrepresentative of future mainstream owners. Finally, the differences in charging preferences observed in this work presumably reflect different underlying motivations, goals, and values among respondents. Including measures of psychological variables could provide a deeper understanding of the respondents’ motivations and how they map onto charging behavior. These variables were not collected in this work.

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