Understanding People’s Perception and Usage of Plug-in Electric Hybrids

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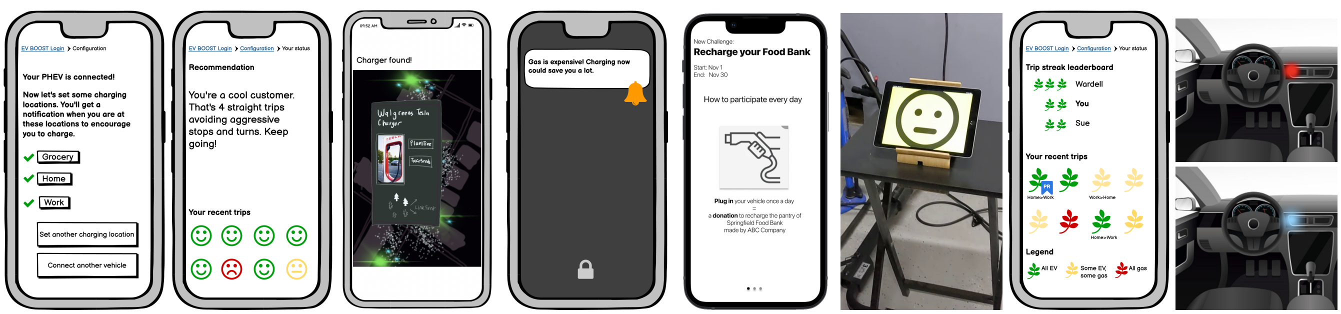

(a) (b) (c) (d) (e) (f) (g) (h)

Figure 1: Interface and intervention concepts discussed with participants included (a) location-based charging notifications; (b) an app to illustrate the impacts of aggressive driving on efficiency; (c) an augmented reality game designed to improve familiarity with charging stations; (d) cost-savings notifications; (e) an app to convert money saved from charging to donations of the user’s choice; (f) an ambient display charging reminder app; (g) a social leaderboard app that encourages streaks of “good” trips with high proportion of electrified miles; (h) and an in-car indicator that signals electric (blue light) or gas-powered (red light) driving (see Appendix Figure 3 for the expanded set).

ABSTRACT

Electrification is an important first step toward reducing the greenhouse emissions of passenger vehicles. However, how drivers drive, charge, and operate their electrified vehicles can have a large impact on their emissions, particularly for Plug-in Hybrid Electric vehicles (PHEVs) that combine all-electric driving with an internal combustion engine. In this paper, we investigate how and why drivers use their PHEVs and uncover design opportunities for interfaces that can support the efficient use of PHEVs. We used a mixed-method approach combining quantitative, qualitative, and concept elicitation methods with PHEV owners in the US. While past findings indicate that PHEV drivers are not motivated to charge regularly, our work contradicts this with evidence of (1) regular charging with home infrastructure, (2) high cost sensitivity, and (3) preference for driving in all-electric mode. Our results indicate that the most

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critical problem is inadequate user support for navigating poor charging infrastructure.

CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in HCI**; **User studies**; *Interface design prototyping*; • **Applied computing** → Law, social and behavioral sciences.

KEYWORDS

phev, plug-in, hybrid, carbon, automobiles, prototyping, behavioral science

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1 INTRODUCTION

Driving accounts for a substantial portion of carbon emissions; reducing driving-based emissions is critical to meet climate goals. For current US-based drivers, switching from conventional gas vehicles to battery electric vehicles (BEVs) provides a good solution to reduce driving-related carbon emissions [29, 30]. However, the wide-spread adoption of BEVs in the US has been hindered by factors that include high purchase prices due to high battery costs, limited battery resources, gaps in charging infrastructure, and psychological barriers related to range anxiety [8, 10, 13, 14, 35]. Other carbon-emission friendly options have the potential to ameliorate some of these concerns. Plug-in hybrid vehicles (PHEVs) have been proposed as a viable alternative or complement to BEVs that can both reduce driver carbon emissions and align more closely to current US vehicle usage. PHEVs are powered by both a short-range plug-in battery-electric motor and an internal combustion engine (ICE) that powers the vehicle when the battery is depleted. Although PHEVs have smaller batteries than BEVs, the short range they provide can cover the daily distance driven by most US-based vehicle owners [12, 82]. As such, PHEVs have the potential to electrify a high percentage of miles driven, but do so using smaller and cheaper batteries that require fewer resources to produce [25, 31, 65, 82]. Additionally, because they also have an ICE, PHEVs can limit psychological barriers related to range anxiety.

Despite their advantages, the emission-reducing potential of PHEVs depends on driver behavior and hence interfaces and interventions still have a role to play. With a short electric range, drivers need to charge their PHEVs regularly to electrify a significant proportion of miles driven [12]. When not charged regularly, PHEVs act more like standard hybrid electric vehicles, emitting less carbon than ICE-only vehicles but far more than they would otherwise [31]. Optional charging has become a major point of criticism: a number of influential reports on real-world PHEV usage suggest that PHEV owners charge less frequently than regulators originally assumed and hence drive fewer anticipated electrified miles [34, 48, 53, 55, 76], leading some countries to limit or eliminate government vehicle purchase incentives for PHEVs.

Although recent, many of these reports relied on samples of older data with older model PHEVs. The variety of models of PHEVs and their electric range, consumer knowledge and interest, and supporting charging infrastructure have all changed considerably since many of these data sets were collected. These advancements provide an opportunity to understand better how today's US-based drivers use modern PHEVs and identify the factors that influence PHEV driving. In this paper, we ask: What routines and habits have people established for charging PHEVs? How do charging infrastructure, environmental issues, and cost concerns impact people's charging behavior? How do people drive PHEVs and to what extent are they aware of how their driving behaviors might impact their car's efficiency? And how do people stay informed of their vehicle's electric vs gas usage?

While past findings indicate that PHEV drivers are not motivated to charge regularly, our work contradicts this, instead suggesting that the most critical problem is inadequate user interface support for navigating a very poor charging infrastructure.

2 RELATED WORK

PHEVs differ from other vehicles in their design, which has led to some uncertainties surrounding their usage and emissions. While past work addresses some of these concerns, we focus on human-centered PHEV issues to promote more sustainable driving behavior and maximize their carbon-reducing potential.

2.1 PHEVs are Designed to Reduce Carbon Emissions using Fewer Battery Resources

PHEVs are vehicles that are powered both by conventional fuel with a combustion engine and by electricity from a battery that can be plugged in to charge from the electrical grid. They are distinct from hybrid electric vehicles as they have a larger, chargeable battery, and are also distinct from BEVs because they carry an ICE for use after the battery depletes. Most modern PHEVs operate "serially", first driving on battery power alone and switching to the gas engine when there is no remaining electric charge.

PHEVs have been available for purchase since 2010 and represent a large number of vehicles on the road today. Between 2011 and 2022, over 810,000 PHEVs were purchased in the United States, representing 34.7% of plugin electric vehicle (PEV) sales [23]. Approximately 35 of every 100 PEVs purchased in the United States is a PHEV. During Q2 2022, PHEVs accounted for 3.1% of global light duty vehicle sales (1.5% in the United States), a 3-fold increase from the end of 2020 [19, 46].

Although PHEVs have shorter electric ranges than modern BEVs, they can still greatly reduce vehicle carbon emissions. The Society of Automotive Engineers (SAE) used a national survey of US-based driving behavior to calculate a PHEV's "utility factor" (UF), or the proportion of miles PHEVs have the potential to electrify given their electric range [12]. The SAE and other simulation-based research methods find that, if fully charged on each driving day, PHEVs can electrify a considerable percentage of driven miles (e.g., UF estimates of 55–70% for PHEVs with 30 miles of pure electric range[12, 82]), with higher-range PHEVs having nearly the same potential to reduce carbon emissions as BEVs [25, 31, 38, 59]. Many PHEVs (42%) and BEVs (45%) are part of multi-car households, often combined with a ICE vehicle. Tal et al. found that a two-car household with a higher-range PHEV and ICE has nearly the same emissions per mile (285gGHG/mi) as a two-car household with a standard-range BEV and ICE (265gGHG/mi) [77].

In addition to their carbon-reducing potential, the smaller batteries in PHEVs require fewer resources and are cheaper to produce than the larger batteries required for BEVs [65]. Batteries remain one of the most expensive parts of electrified vehicles, requiring minerals and materials that are in short supply, expensive to source, and may not meet the emerging demand required for a full switch to BEVs [64, 65, 71, 74]. PHEVs offer a more affordable and accessible alternative to electrify more vehicles that make more efficient use of limited battery resources [25, 38, 65]. With all costs considered, simulation-based methods find that long-range PHEVs offer nearly the same carbon-reducing potential as BEVs, but at a considerably lower initial purchase cost to consumers [25].

2.2 Uncertainty about PHEV Charging Behavior and Carbon Emissions

Despite the positive simulation predictions, analyses of real-world PHEV driver behavior have called into question PHEVs' carbon-saving benefits. A 2020 report by the International Council on Clean Transportation (ICCT) analyzed real-world PHEV usage in six countries to assess their carbon impact [55]. The report stated real-world PHEVs emissions were 2–4 times higher than regulatory and simulation-based estimates suggested. The identifying factor was PHEV drivers who charged their vehicles less than the once per driving day often assumed by simulation-based metrics. For example, PHEV drivers in Germany charged only 3 out of every 4 driving days, decreasing the potential electrified miles by an estimated 13–23% [55, 56]. This and other reports have influenced legislative discussions around PHEV incentives, with countries considering excluding PHEVs from future carbon-reducing incentives (e.g., Swiss Valais canton [48]).

There are limits to the generalizability of the findings in the ICCT's report. The main PHEV drivers identified in the report as non-chargers were European drivers of company cars who were reimbursed for fuel but not electricity [55, 56]. Although problematic, this type of behavior suggests a mismatch of financial incentives rather than fundamental problems with PHEVs as a class of emission-reducing vehicles. In contrast, the ICCT report's analysis of North American driver behavior, which consisted exclusively of private vehicle owners, found that PHEV owners in the United States charge nearly once per driving day, resulting in UF values much closer to, and sometimes exceeding, levels expected by regulators [3, 37, 55, 56, 56, 67, 75].

Other reports highlight that regular charging is not ubiquitous among all US-based PHEV owners. Tal et al. found poor UF among PHEVs due largely to lower-than-expected charging rates [76]. Similarly, Nichols et al. found that many PHEV owners reported not frequently charging, with increases in reported charging frequency correlating with increases in range [53]. A 2020 survey report found 8% of Californian PHEV owners charged less than once a week [11] and that 20% did not re-purchase a PHEV as their next vehicle [26]. The primary factor linked to low charging frequency and lower likelihood of re-purchasing a PHEV was dwelling type: people who did not live in single detached homes were most likely to find charging inconvenient, least likely to charge, and least likely to re-purchase a PHEV. Additionally, the ways PHEVs are driven (e.g., acceleration patterns) can substantially influence their UF [34, 55]. These results therefore propose that although US-based PHEV usage is generally close to that expected by simulations, there may still be opportunities to improve PHEV owners driving and charging behaviors to reduce emissions.

A challenge with most previous PHEV work is that it is generally based on early PHEV studies with older model PHEVs. The majority of vehicles in the data sets analyzed by the ICCT report included model years from 2016 or older, which offered less variety, older powertrains, and lower electric ranges than models currently offered in 2022. Newer PHEV powertrains have the ability to operate serially, utilizing most of the battery before turning on the ICE, whereas older PHEV powertrains tend to operate in parallel to optimize gas efficiency with the help of the battery. Recent reports have found that more recent models with higher electric ranges have increased real-world UF [75]. Additionally, although lack of home charging has been cited as a primary pain point for drivers of older PHEV models, charging infrastructure in the US continues to improve [5] and may present less of an inconvenience for current PHEV owners. Our work investigates the current state of PHEV driving and charging behaviors, taking into account changes in charging infrastructure and newer PHEV models.

2.3 Interventions Aimed at Carbon-Friendly Car Usage

In-cabin interfaces can have a strong impact on the efficiency of BEVs and PHEVs, with some work suggesting that "an economical driver might…save 30% energy compared to an inefficient driver" [54]. However, some feedback methods are more impactful than others. Franke et al. found that BEV dashboard feedback UIs, such as the  battery input icon light in the Chevy Bolt, may convey to users that regenerative braking is more efficient than it actually is [21]. Rather, they suggest focusing on dashboard UIs that help BEV drivers reduce aggressive driving and "avoid strong acceleration and braking" where possible. Jung et al. found that "ambiguous display[s] of [remaining electric] range" can actually ameliorate range anxiety for drivers of EVs [33]. Work on driver emotional states suggest that interventions aimed at reducing anxiety, which is linked to aggressive driving, is most helpful at intersections [18]. Other work suggests that emotional states have been studied thus far mostly in isolation and future work should evaluate driver emotions more holistically [4].

Many interventions for improving efficiency have focused on ambient and peripheral displays, to improve driving performance [40] and help users transition control in L3 automated driving tasks [43]. Kunze et al. investigated in-cabin, light-based ambient displays that used different approaches to display four different levels of output and found that participants could discern "changes in light position, pulse frequency, and hue" and that pulses are particularly interruptive. In separate work, they compared a conventional dashboard display against an in-cabin peripheral display that included a light strip and a vibro-tactile seat, finding that the peripheral display reduced cognitive load and frustration while improving performance on the main (driving) task [36]. Avolicino et al. proposed EcoGO, a mobile app that combines eco-feedback with gamification (earning points and social ranking) to promote more sustainable driving [1]. Dahlinger et al. found that abstract eco-feedback (growing leaves on a tree) had a slight but significant effect on reducing fuel consumption whereas a concrete design (fuel consumption gauge in liters/100km) did not, because the abstract feedback induced a higher level of interpretation in drivers which in turn helps them focus on the benefits of pro-environmental behavior [15]. Finally, the success and uptake of the Volt Stats website [79], which helped owners track real world usage and efficiency statistics of their Chevrolet Volt (a now-discontinued PHEV), suggests a latent interest in hypermiling, or the careful application of driving practices to maximize vehicle efficiency. Sites supporting hypermiling often leverage gamification, which has been shown to be a useful method to reward driving efficiency [80]. Building on these prior interventions, we generated and evaluated design concepts specifically for PHEVs to promote behaviors (e.g., plugging in and driving using electricity) that are critical for achieving the intended reductions in carbon emissions with a PHEV powertrain.

3 RESEARCH QUESTIONS

Based on the mixed evidence for regular charging behaviors and carbon-savings from prior literature of older PHEV models, we identify three research questions about the ownership, driving, and charging behaviors of current PHEV owners. We employed a mixed-methods approach—integrating quantitative, qualitative, and concept elicitation—to understand the factors that influence the PHEV usage of broad sample of current US-based PHEV owners. Specifically, our goal is to understand:

RQ 1. *What routines and habits have people established for charging PHEVs?*

RQ 2. *How do charging infrastructure, environmental issues, and cost concerns impact people's charging behavior?*

RQ 3. *How do people drive their PHEVs? How do they perceive their personal utility factor (UF), that is, the proportion of miles driven only on battery power?*

4 METHODS

To address these research questions, we recruited a broad, US-wide sample of current PHEV owners to participate in a quantitative survey. A subset of these owners additionally participated in a qualitative diary study and semi-structured interviews with concept evaluations of paper prototypes.

4.1 Participants

US-based PHEV owners 18 and older (n = 488) were recruited to participate in our study via a panel survey conducted by Ipsos Group, a global market research firm. The owners recruited covered 45 of the 50 US states, reported having a median 2 years of experience owning a PHEV, and 81% of owners drove a PHEV model from model year 2016 or newer. (See Appendix § B for a full demographic breakdown.) The sample includes a broad group of owners who are primarily newer PHEV owners with newer models than the aforementioned reports. Of these 488 participants, 40 were recruited for a diary study in which they documented how they drove and charged their PHEV. 34 participants completed all activities of the diary study, and 15 of these owners were selected to participate in a semi-structured interview and concept elicitation. The inclusion criteria for diary study participants were as follows: currently owns or leases a PHEV model year 2016 or newer, drives the PHEV at least once every two months, lives in the United States, and 21 years old or higher. The sample was selected to include a diverse range of PHEV makes and models, geographic locations across the United States, and self-reported charging frequency.

4.2 Quantitative study

All participants completed an online survey aimed at understanding their usage and perceptions of their PHEVs. In this section we focus primarily on the parts of the survey relevant for this article's main research questions but the full survey can be located in Appendix § A.1. The survey was composed of four main parts:

4.2.1 Charging access, frequency, perceived effort, and habit strength. Owners were asked what access they had to charging at different locations ("home", "work", and "away from home or work") and how often they charged (both in general and at each location with answers ranging from "More than once a day" to "Never"). We additionally asked participants to rate their perception of the effort and convenience of charging using a 5 point likert scale ranging from "Strongly Agree" to "Strongly Disagree". To measure owner charging habits, we adapted the Self Report Habit Index (SRHI) questionnaire [78], which is commonly used to measure the automaticity of different behaviors (e.g., exercise, diet) and can be adapted to most behaviors [39, 78]. Owners were given the prompt "Charging my PHEV is something…" before answering 12 7-point likert scale questions ranging from "strongly agree" to "strongly disagree" about their experience charging (e.g., "…I do automatically", "…that belongs to my daily routine"; See Appendix § A.1 for the full scale). Habit scores were measured as the average of all 12 questions, with scores ranging from 1 (lowest habit score) to 7 (highest habit score), and scores greater than 4 indicating a formed habit [39]. SRHI responses in our survey showed high internal consistency (Chronbach's α = 0.91).

4.2.2 PHEV usage and general driving habits. Owners answered questions about their general driving habits, including how frequently and how far they generally drove, and the types of driving they engaged in (e.g., commuting, errands, off-roading, etc.). We also included several questions about their motivations to focus on fuel economy, including whether they paid attention to fuel economy while driving and a slider to report the percentage of miles they estimate driving on electric power alone.

4.2.3 PHEV purchase motivations and satisfaction. Owners used a 5-point likert scale to rate the extent to which different factors motivated their PHEV purchase, including cost savings, environmental reasons, and purchase incentives (see Appendix § A.1) and asked to rate how satisfied they were with the cost saving associated with their PHEV. Owners also used a 5-point likert scale to rate how likely they were to replace their PHEV with (1) another

PHEV, (2) a BEV, (3) a non-plug-in hybrid electric vehicle, and (4) a conventional gas vehicle. They made a similar rating to indicate which type of vehicle they would choose if they could only choose one vehicle.

4.2.4 Owner information and general demographics. Owners were asked general questions about their PHEV and their living circumstances, including the make, model, and year of their PHEV, the type of dwelling in which they resided, and general demographic questions (e.g., age, gender, income, state, etc.; see Appendix § A.1).

4.3 Qualitative study

The qualitative data collection used a combination of a diary study and semi-structured interviews. The diary study captures people's experiences as they used their PHEV in routine and novel settings. The following semi-structured interviews probe into each participant's situations and allow them to explain their responses to the diary study.

4.3.1 Diary Study. The diary study was conducted over five days from Wednesday February 2 to Sunday February 6, 2022. Participants completed five activities, including: taking a video of plugging in their vehicle at home, visiting an away charging station, logging the timing and destination of their trips, photo elicitation on an useful/confusing information display, and photo elicitation on enjoyable/annoying vehicle features. For each activity, participants uploaded media and answered short-answer questions to elaborate and explain their responses. A moderator reviewed each response and posted a follow up question if the response needed further clarification.

4.3.2 Semi-structured Interviews. Semi-structured interviews were conducted over video-conference between the participant and one moderator. The interview lasted one hour and was recorded with the participant's consent. The topics included why they chose to purchase their PHEV, how they used their car, comparisons to other cars in the household, benefits and drawbacks of the PHEV, how they charge their car at home, work, or away, how they drive their PHEV differently than their previous cars, and lessons learned during their ownership experience. The moderator asked follow up questions to dig deeper in the reasons for participant's behaviors, impressions, and feelings.

4.3.3 Qualitative Data Analysis. Inductive and deductive methods were used to analyze the interview transcripts and diary study entries. A coding manual was developed using a hierarchical coding scheme, following best practices from Richards & Richards [62] to preserve analytic depth, where excerpts coded with a subcode were automatically coded with the higher level codes. To handle the unsystematic interview data, the team used an ad hoc data unitization method [7] that allowed researchers to parse and code segments of variable lengths to reflected a meaningful unit of thought. Four researchers first independently coded an identical subset of interview transcripts to calibrate to the coding manual of deductive codes that were derived from the research questions. Over successive rounds of coding using the Dedoose tool [16] and discussion, the team iterated on the coding manual to better reflect a shared understanding of the data and also developed new inductive codes that emerged from the data. Our decision to use a hierarchical codes and ad hoc data unitization to best fit the interview data made a quantitative value for inter-rater reliability difficult to calculate [44]. Instead, the rigor of our analytic approach is reflected in updating of the coding manual across four successive calibration rounds, by which researchers came to consensus on the codes across segments that may have differed slightly on their start/end points and level in the code hierarchy. After coding, excerpts within each code were grouped to find subsets of quotes that echoed the same theme. After multiple rounds of critiques, researchers considered both the prevalence and intensity of the themes across participants to highlight the key themes from the data.

4.4 Concept elicitation interviews

As outlined in Section 2.2, evidence from past work suggested that PHEV users are not charging their cars as frequently as they could, lowering their efficiency and increasing their carbon output. We speculate that the higher electric range of newer PHEVs may partially ameliorate this problem. But since PHEVs operate most efficiently when charged as much as possible, we also want to understand the role that interventions can play in increasing charging frequency. Interventions add a more active component to our study, complimenting our qualitative and quantitative work by giving participants a voice in shaping new tools. We designed several concepts grounded in past literature and utilized them as conversational props in interview sessions (e.g., "prototypes as conversation" [63]). This approach provides a forum for participants to teach us "something that we didn't know we needed to know" [50].

Our eight low-fidelity "paper" prototypes [22] focused on the tool's role and potential features rather than their look and feel or implementation [28, 61, 69] (see Figure 1 and more details in Appendix Figure 3). This was meant to help users not "focus only on surface usability issues such as color and typography" but rather serve as a "conversation with materials" where the prototypes provide grounding for concepts [9]. The eight concepts included:

Location-based reminders for plugging in Location-based notifications can be useful as "a cue for other contextual information that can be hard for any system to detect" [70]. This mobile app that helps remind people to charge their car at locations they frequent. See Figure 1a.

Plant virtual trees at charging locations In the vein of Pokémon Go [51], this augmented reality game is designed to improve familiarity with charging stations. See Figure 1c.

Financial advisor for driving Increasingly, electric driving is cheaper than gas driving [58]. This mobile app provides notifications that encourage people to charge so they can drive with electric and save money. See Figure 1d.

Company donates to a charity when you plug in An "increasingly…popular way to promote charitable giving…[is] in-app purchases and earnings that may then be seamlessly transferred to charitable causes" [41]. This mobile app converts money saved from charging to donations of the user's choice. See Figure 1e.

Keeping the car charged and happy Ambient displays can show "non-critical information on the periphery of a user's attention" without distracting from other tasks [45]. This ambient app helps people remember to charge, transitioning from a "happy" to an "angry" state if the user fails to plug-in their car over several days. See Figure 1f.

Trip streak leaderboard and personal record tracker This mobile app leverages the streak and PR tracking behaviors found in Strava [72] and other popular apps to encourage streaks of "good" (high UF) trips. See Figure 1g.

Efficient driving coach In addition to interventions focused on improving charging frequency, we also included two concepts focused on driving behavior, another key component of driving efficiency [21]. This app provides reminders about the impacts of aggressive driving on efficiency. See Figure 1b.

In-car electric driving coach In-car peripheral displays have been shown to improve driving performance [40]. This in-car application signals good (blue light) or poor (red light) UF. See Figure 1h.

We selected 15 participants from the qualitative study to discuss the prototypes in a brief interview session (the session occurred between 1 and 2 weeks after the conclusion of the qualitative study). We encouraged "co-operative evaluation" employing think-aloud protocols [81], in which we instructed participants to talk openly and candidly about their impressions of each concept. We specifically asked participants to focus less on the design of the concept and rather on whether it addressed a core need, and if not, how they might redesign the app to better address their concerns.

5 RESULTS

5.1 RQ1: What routines and habits have people established for charging PHEVs?

5.1.1 PHEV owners plugged in frequently. Owners in our quantitative survey (n = 488) reported frequent charging behavior and strong charging habit strength. Overall, 97% of our respondents reported charging at least once a week, a 5% increase from previous reports using similar self-report metrics [11], and 89% of owners reported charging at least once for every driving day. Owners also reported strong charging habits, with median SRHI charging scores of 5.5 [95% CI: 5.3–5.6] corresponding to a strong habit [39, 78]. Thus, our quantitative analysis suggests that US-based charging frequency of PHEVs has improved compared to previous reports and that PHEV charging habits are strong.

The findings from the qualitative diary study and interviews echo owners' frequent charging behavior and strong charging habit, especially for owners who had a consistent spot to park their vehicle at home near a power outlet. Owners developed a regular habit of plugging in their PHEV daily so that it would be fully charged for their next trip. For 25 owners in our qualitative study, the event of arriving home or work typically triggered the habitual behavior to plug in the car.

> "[I plug in] every time I pull into the garage…because the electric range is pretty small. It's in the 15 to 20 mile range and I generally get home with you know, 30% or less. And the charger is right there in the garage. So it's very little trouble to plug it in." (P13)

> "When I park on the driveway, I usually charge automatically most of the time…The times I don't charge is when I know that I have to go out again, like, very quickly in, like, 20 minutes or so, then I don't bother charging." (P02)

We found that *home charging develops into automatic habit.* All owners we interviewed were able to describe their regular routine of plugging in either at home or at work. When asked about explicit thoughts and feelings about plugging in their vehicle, 15 owners had little to reflect on because plugging in had become such a routine, automatic action that they rarely thought about it explicitly anymore. The established habit lowered the perceived effort of charging at home to the point that it only required a minimal amount of thought or planning. Only 5 owners mentioned instances of forgetting to plug in their cars, but all reported these cases were now uncommon.

> "I think at the beginning, there's a sense of excitement of, like, doing something new and different. And now, it's just kind of a mundane routine of just parking your car, this is how it is, not in a negative way, just is just part of life. Just like plugging in your phone at night or you know, making sure you eat dinner." (P07)

> "In the beginning, it was almost something that you had to remember, but now I just do it mindlessly. " (P03)

> "And sometimes I'll forget [to plug at 8pm when the electricity rates go down] because I'm yeah…I think most of the time it's just in my routine, right? I just like it's an unconscious act at this point." (P04)

Eight owners built their charging habit around their home solar panel generation or the lower electricity rates from their utility company during off-peak hours. They set an automatic charging schedule using the scheduling feature in their car or mobile app or simply developed a habit to delay plugging in their car until after the peak to off-peak transition.

> "It is scheduled through the [car make] app. And I know it's automatic the way I have it defaulted. It's automatic that charges between 8 pm and 6 am, I think." (P06)

> "And sometimes I'll forget [to plug at 8pm when the electricity rates go down] because I'm yeah…I think most of the time it's just in my routine, right? I just like it's an unconscious act at this point." (P04)

Despite prior work described in Section 2.2 but congruent with the survey and interviews, prototypes focused on at-home charging reminders did not test well. Most owners indicated that they felt that they do not need reminders to charge at home.

> "It [a charging reminder] doesn't…really apply because I charge every night regardless." (P06; regarding concept *Financial advisor for driving*)

> "[Charging reminders] would not interest me at all. I don't think I ever get to home or work and forget to charge." (P11; *Location-based reminders for plugging in*)

Some participants' reaction to at-home charging concepts was viscerally negative. Regarding the display installed in a user's garage (see Figure 1h and Appendix Figure 3i), one participant commented that "…knowing that the car would be unhappy. I'm sorry. I'm having flashbacks to Stephen King novels." (P10; *Keeping the car charged and happy*)

5.2 RQ2: How do charging infrastructure, environmental issues, and cost concerns impact people's charging behavior?

In addition to identifying owner's charging frequency and habits, we also investigated the factors that facilitated or hindered their charging behaviors, which included the availability of access to charging infrastructure (at home and away from home), financial costs, and environmental impacts.

5.2.1 Access to Home Charging Infrastructure. Owner charging frequency and charging habit strengths was related to home-based charging access. Overall, 96% of owners in our quantitative online survey reported having access to some form of home-based charging and this had a strong influence on their charging frequency. Owners responding to our survey with access to home charging were more than 7x more likely to charge daily (logistic regression predicting daily charging given access to home charging and controlling for driving frequency: $\beta_{\text{home}} = 2.00, p = 0.002$). Conversely, when included in the same logistic regression, daily charging was not predicted by access to charging at work ($\beta_{\text{work}} = 0.34, p = 0.114$) or public charging ($\beta_{\text{public}} = 0.11, p = 0.325$).

Access to home charging predicted higher SRHI charging scores (linear regression predicting SRHI charging scores given access to home charging and accounting for driving frequency: $\beta_{\text{home}} = 1.44, p < 0.001$). Moreover, when included in the same regression, access to work charging also predicted stronger charging habits ($\beta_{\text{work}} = 0.35, p < 0.001$) but access to public charging did not ($\beta_{\text{public}} = 0.05, p = 0.705$). Owners also perceived charging as being less effortful and more convenient when done frequently at home (linear regression predicting perceived effort of charging based on frequency of charging at home and controlling for driving frequency: $\beta_{\text{home}} = -0.13, p = 0.004$; similar regression predicting perceived charging convenience: $\beta_{\text{home}} = 0.30, p < 0.001$). However, owners who charged more frequently away from home perceived charging as more effortful ($\beta_{\text{public}} = 0.20, p < 0.001$; $\beta_{\text{work}} = 0.13, p = 0.018$). The quantitative survey results show that having access to home charging (but not public charging) is associated with owners charging everyday, developing a stronger habit of charging, and having a lower perceived effort of charging.

Inadequate home charging infrastructure increases the effort of charging. As more consumers adopt one or more plug-in vehicles into their household, especially those who do not live in single-family houses, inadequate home charging infrastructure will undoubtedly become a larger issue. In our qualitative study, we purposely included owners (P11, P08, P04) who did not have a dedicated garage, driveway, or parking space near a charger at home, so we could investigate the additional effort it took to charge their car at home. P11 lived in an urban townhouse that only had street parking. When he was able to park in one of the two spots in front of the house that the charging cord can reach (estimated to be about twice a week), he would stretch a charging cable from a household outdoor outlet to plug in and charge his car. "I have to deal with putting up the charger and it's outdoors and just got to hope that nobody wants to steal that at some point." (P11)

Similarly, P08 also lived in an urban house that had a garage that was not shaped adequately for parking a car, so street parking was the only option. Despite this, P08 invested in installing a L2 charger in the garage, and when the street parking spot was available for parking, he would stretch the charging cable over the sidewalk, suspended on hooks attached to an overhanging tree (so as not to create a trip hazard for pedestrians), across the hood of his car, to reach the charging port of his car. P08 mentioned that it was fortunate that it took only a couple of hours to recharge the battery so this sidewalk hazard caused by the charging cord was temporary. Both P08 and P11 could only charge at home if the parking space in front of their house was not occupied by another car. P04 did have a dedicated driveway to park her PHEV, but complained that retrieving and putting away the charger in the closet inside the house was a hassle and caused wear and tear on the charger. "like clunkiness of [the charging cord] because I was so clumsy with it. And then I'm like, oh, I might actually start a fire if I keep dropping it…then I started be more aware of the charger." (P04) Owners (P03, P05, P14) who had more than one electrified cars in their household had to share the charging infrastructure among them and prioritized charging the BEV over the PHEV because the PHEV could run on gas if there was out of charge.

5.2.2 Charging Away from Home. The perceived effort of charging away from home seemed to dampen owners' interest in PHEVs. In our quantitative online survey, owners who relied more on public or work charging were more willing to replace their PHEV with a conventional gas vehicle (logistic regression predicting the likelihood of being "likely" or "very likely" to replace a PHEV with an ICEV based on frequency of charging at different locations and controlling for driving frequency: $\beta_{\text{public}} = 0.32, p = 0.017$; $\beta_{\text{work}} = 0.35, p = 0.009$; $\beta_{\text{home}} = 0.06, p = 0.625$).

Public charging infrastructure is perceived as lacking. Most owners reported that there were few charging stations at the destinations that they regularly visit and wanted more of them installed so they could plug in. Of the 40 owners who participated in the diary study, 35 completed the task of visiting and taking a photo of a charging station, with 11 reporting that they had not previously known about the station, and 20 reporting that they, in general, have difficulty locating public charging stations in their area. Some expected there would be more charger stations before they purchased their PHEV and only realized that there were not as many after looking for them during ownership. Only one study participant (P09) was able to find free charging stations in her community and complete most of her charging using them, which sometimes required a detour or waiting in the car for 30 minutes or more. Aside from P09, the other 14 owners we interviewed (plus 2 others from the diary study) explicitly mentioned how public charging infrastructure was not adequate in their area to be worth the effort of charging away from home. Compared to home charging, charging away from home at public charging stations was perceived by owners as being more effortful, more costly, and difficult to navigate.

> "There's no charge option at Target. There's no charge option at my local grocery store. So the places I go most, I would say, I don't even have the option, so it doesn't feel like that frequent. But every time I go to Trader Joe's, yes, I probably [charge] there." (P15)

> "I thought there would be a lot more electric charging stations around. . . " (P02)

> "I would plug in everywhere I go if it was available and convenient. . . I would always rather go on electric than on gas. . . It's surprising that there aren't more charging stations around, pay or free. Just don't seem to be many." (P06)

In the situations where charging stations are installed at destinations, 13 owners reported instances when charging spots were occupied by another vehicle (perhaps not even an EV) and thus unavailable for the PHEV owner to charge while at the destination.

> "[At] Trader Joe's, [the charger] is at the first spot. So, like, it gets me a good spot. If somebody's in that spot, I don't wait for it. I just park somewhere else." (P15)

> "I drive to work. I charge when I can. The problem is that there aren't that many outlets in the garage, so I'm not always able to charge there." (P11)

Inconveniences of public charging. If a charging station was available, owners still needed to navigate the *inconveniences of locating and using the charging station.* Owners reported that it was often difficult to find the precise location of the charger at the shopping destination, as charging station apps may only have a street address. In our study, 6 owners raised an important safety issue that the charger may be located far away from the destination entrance or be in an area that feels less safe (e.g., being dark or isolated from others). The stations could also be located inside a paid parking garage that added an unexpected fee.

> "If it's dark and if it's not immediately in front of a place with people coming and going all the time, I don't want to go there. I feel uncomfortable." (P14)

> "[The charger's] proximity doesn't have to be directly at the door, but closer to the main [destination] I'm trying to go to always helps. And finally, just the general feeling that there is a secure area to charge." (P10)

> "[I am willing to charge at a station] within walking distance, I guess for my destination. . . five, ten minutes, max." (P07)

Using the charging station itself can be a complicated task for many owners. Not only might chargers be broken or incompatible with their car, but 7 owners reported that the disparate charging station networks added unwanted complexity by requiring them to set up accounts or download specific apps to locate and activate the charging station. Owners compared these extra steps to the relative ease of pulling up to any gas station pump and simply using your credit card.

> "Setting up the account was cumbersome. I did it for ChargePoint. I loaded my card. I put everything on there to actually try to charge and it wouldn't allow me to, even, like, release the charger. After I've done all that, and it took like 10 minutes to set up. " (P04)

> "There's extra steps and it's not seamless where you have to set up an account and put a credit card in, and it's just not as convenient as just showing up at a gas station and filling up." (P03)

> "[For apps to find and use charging stations,] I have PlugShare, ChargePoint, EVGo, Volta, and Electrify America. I have five different ones. The [car make] has [an app], but it is terrible." (P06)

When deciding whether or not to plug in, 13 owners in our study considered whether the additional electric miles gained during charging would be worth the effort of plugging in. When at home, the effort to plug in is minimal and so owners plug in their PHEV when arriving home, except if they expect to drive again very quickly. When charging away from home, owners typically only spend a short amount of time at a destination (e.g., 30 minutes at the grocery store) and the effort of plugging in is considerably higher. Owners often did not find the few additional electric range miles gain during away charging to be worth the effort, unless they were parking for a long period.

> "The Whole Foods one. . . for the 20 minutes I was in there, and I didn't even see a mileage difference by the time I got out. . . it's not worth it to me." (P06)

> "It takes so long. We will charge it when we're out, if we are some place that has a charger, and we already feel like hanging out there for a while." (P14)

> "[If I am run out of battery while away from home,] I don't see much benefit in waiting for the car to charge up. That time is worth more to me to get back and just run on the gas, you know, for me." (P12)

In sum, the PHEV owners with access to home charging did so regularly and had formed strong charging habits. However, our results also indicate that reliance on public and work charging do less to promote good charging behavior and may even deter owners from purchasing another PHEV.

5.2.3 Financial Factors for Charging. One of the main motivations that came up repeatedly for why owners charge their PHEV is to save on running costs, because it is typically less expensive to drive using electricity than using gas.

> "Now with the gas is, you know, in California over $5 a gallon, you know. Charging is a lot cheaper. Electricity is cheaper. So I would say it's a strong influencer, at least for me." (P12)

> "I'd rather not be burning gas. I'd rather stay on the battery. So most of the trips that we do shopping and everything can be accomplished within, you know, the battery['s range]. But sometimes it's like you have an extra trip you didn't account for and it starts eating into the gas and then like I got to go to the gas station, and gas is kind of expensive. . . It's a motivator to make sure that is charged for sure." (P05)

Home charging perceived as inexpensive. Furthermore, *charging at home was perceived as being particularly inexpensive*, with home electricity costs being both cheaper than public charging stations as well as less visible because the costs are commingled with other household electricity costs. In our study, 5 owners reported they did not charge away from home because it was more expensive than home charging. Home electricity costs are also perceived as being more stable than gas prices, and charging and running on electricity is a way of buffering against gas prices fluctuating beyond the owner's control. Refueling at the gas station results in an immediate, highly visible, large magnitude hit to the owner's wallet.

> "I can plug it in for free at home. I mean, I know it's not 'free free'. But it, you know, it has such a nominal impact on our electric bill, that I feel like I'm not going to pay extra do it when I'm out." (P15)

> "Compared to the year prior, [my home electricity bill] really hasn't gone up that much. . . .I know there's a cost involved. I know I'm paying for the electricity, but I just don't have that same annoyance the way I do with the gas prices." (P03)

> "I can save on gas. I don't really care to deal with thinking about going to the gas station as often and paying for that. Feels like you're paying more at once as well than when it's spread out across electricity, so definitely that's easier. I like that." (P11)

Owners loved free charging. Some away charging stations offered free charging sponsored by the shopping center, workplace, or advertisement. In our study, 19 owners liked charging at these free stations. When owners had home charging and/or free charging stations around them, they were resistant to plugging in at pay stations. Paying to charge and running on battery is likely to be less expensive (and more environmentally-friendly) than running on gas, yet owners seemed to be anchored on home or free charging.

> "If it's free and it fits, you know, closer to the [entrance of the destination]. Then I'll absolutely plug in." (P06)

> "[On a trip into downtown], parking at [the museum] and the charging is free. So I found a nice little parking spot and plugged in. It had a full charge when we got back. So it was great. I wish more places would do that." (P12)

5.2.4 Environmental and convenience benefits are secondary to financial costs. When asked about why owners chose to purchase a PHEV or charge their car, 14 owners mentioned the lower emissions and environmental benefits as a factor. However, even among these pro-environmental owners, the lower running costs were often a stronger, more immediate motivator for charging up the car. Environmental reasons for minimizing carbon emissions as well as convenience benefits such as fewer visits to the gas station were both typically reported as being secondary to financial reasons.

> "To be able to plug the vehicle in at night and have 50 miles of range and not have to go fill up with gas, not have to really deal with those fluctuations, makes more economic sense to me. Honestly, it saves more time. . . I appreciate the environmental benefit. We're a non-attainment community for air quality. So knowing I'm at least doing my small part to not contribute to that." (P10)

> "My motivations are reducing my carbon footprint and my dependency on, you know, gas. The ability to be able to, kind of, fuel my car from home as opposed to a gas station . . . The way gas is on the way up, I may not be too price sensitive to the cost of fuel. But I do like to give myself a little bit of pat on the back for not having to stop at a gas station." (P07)

Even P11, a self-proclaimed environmentalist who works in renewal energy, based his decision to plug more on the financial costs rather then environmental benefits: "So gas is about \$3.55 here, that works out to about \$0.065 a mile. [Away charging costs] \$0.30 a kWh, a bit over \$0.08 per mile. So yeah, a little bit more than gas, which I don't like, and I'm not willing to pay that."

5.2.5 Concepts revealed unmet needs with away-from-home charging. Several prototypes prompted participants to discuss their difficulties using the away-from-home charging infrastructure. In particular, many participants indicated that chargers are difficult to locate and that "ultra precise location of where" (P12; *Location-based reminders for plugging in*) chargers are is critical.

> ". . . Sometimes where those [chargers] are stashed is kind of odd. . . the most useful thing [at] that point is almost like being able to give you a street view, picture or stuff like that. . . to exactly where it is and what it kind of looks like, because. . . sometimes they don't look like much. Sometimes they're like, you know, back next to the surface mounted to, you know, utility transformers and things like that. . . " (P13; *Location-based reminders for plugging in*)

Participants also mentioned that having access to "accurate and up-to-date" (P11; *Plant virtual trees at charging locations*) information about charging stations is key. In particular, knowing "how many charging stations are available" (P12; *Location-based reminders for plugging in*) would be useful since they reported often arriving at stations but finding them full which "doesn't really do. . . any good" (P10; *Location-based reminders for plugging in*). The charging infrastructure problem is so profound that some participants have thought through potential solutions that they discussed in the interviews. One participant suggested an "AirBnB or some kind of a charge share system where a bunch of us that have our own charging. . . can let each other use it and get a much better rate" (P08; *Plant virtual trees at charging locations*) which is in fact already an available product [20]. Another participant described a concept in which businesses could track charging-enabled cars in order determine if there is a "demand for having charging at. . . [that] location", though the participant pointed out potential "privacy issues" that may accompany such an app (P13; see supplementary material for a complete quote).

Participants had mixed reactions to concepts that included charging notifications. Some participants were positive, with one mentioning that "push notifications on where to charge. . . bring a lot of value" (P07; *Location-based reminders for plugging in*) while others were less enthusiastic, with one reporting that they "would be a no go" (P08; *Location-based reminders for plugging in*) because they are not necessary and may be annoying. Many participants focused on cost concerns with many who already "try to figure out what. . . the cost of charging my car at home is" (P08; *Financial advisor for driving*). Another common critique of the concepts was that they aggregated data into views that were too abstract. Rather, participants wanted to see the details: "What was the cost of the electric? Cost of the gas? I feel like that has more valuable info than than just the colors" (P03; *Efficient driving coach*).

Finally, though less common than cost concerns, some participants did appreciate concepts that highlighted the environmental impact of driving using electricity:

> "[I am] so tired of giving so much money to the fossil fuel industry" (P11)
> "I appreciate the. . . environmental benefit. . . We're a non-attainment community for air quality. . . so [I feel good] knowing I'm at least doing my small part to not contribute to that" (P10)

5.3 RQ3: How do people drive their PHEVs? How do they perceive their personal UF?

5.3.1 Owners enjoy all-electric driving. Owners purchased their PHEV with the intention of running it on electricity for a significant proportion of their driving, mainly because driving with electricity costs less than with gas. Otherwise, they would have opted for an equivalent gas-only or non-plug-in hybrid instead. In our survey, cost savings were the top rated reason owners in our online survey purchased their PHEVs (82% indicating that cost savings motivated their PHEV purchase). Additionally, 87% of owners reported being "slightly" or "very" satisfied with the cost savings of their PHEVs.

Owners reported driving a median 69% of their miles on electricity (95% CI [65%–71%]). Fuel economy was also front of mind for the owners surveyed, with 87% indicating that they at least "often" maximize fuel economy when driving. Owners employed a few strategies to maximize their electric miles, which included matching the electric range to their routine local driving needs, defaulting to using EV mode for all trips, and temporarily switching to use another car in the household to match the electric range with a planned trip. Moreover, owners maximized their electric range by avoiding high speed or aggressive driving and often treated their driving like a game of self-competition to achieve the most miles from a single charge.

Matching electric range with local driving distances. PHEVs have a smaller electric range than most BEVs, ranging from about 11 to 48 miles of all-electric driving from a fully charged battery. The benefits of all-electric driving can only last as long as the battery has charge. When considering the initial purchase of their PHEV, 15 owners reflected on the amount of daily driving they would need to do for commuting to and from work, dropping off and picking up children from school, and running local errands in between charging opportunities which typically was done only at home or work. Based on their expected local driving distances, owners selected a PHEV that had a maximum electric range that would cover all or most of their local trips.

> "I'm a stay-at-home mom. And most of my driving is to and from my kids schools and to, and from errands like the grocery store, post office, and Target, you know, the "mom loop" and almost everything is under 20 or 30 miles where I go. . . We kind of did that math. . . we were pretty sure I could do most of what I do in running it in all-electric." (P15, PHEV with 19 miles of electric range)

> "I literally can get to and from work, just on the charge. I never use gas. So it's really awesome to come home and I still have maybe 10 miles. And all of my errands are pretty close, so I use the battery predominantly, which is really convenient." (P04)

However, winter weather and colder temperatures often reduced the electric range, to the surprise of some owners, who could not accomplish their local driving needs on the reduced range or avoid the gas engine from turning on to heat the cabin.

> "Like when it was warm out, I would start with like, close to 30 miles of range. And in the winter, . . . there are days that I start with like 15 [miles of range], it cuts almost in half. So the disadvantage is that sometimes I just don't even have enough for my little errands." (P15)

> "I want to use as little gas as possible. But I live in the New York area and which is very cold in the winter. . . Even though I want to use electric only, the car automatically use[s] the gas to warm up the car I guess." (P02)

Convenience of easy refueling on longer trips. However, *on longer non-routine trips owners would typically run on gas* when driving beyond their all-electric range, rather than stopping to charge along the way (as would be necessary for BEV). In our study, 21 owners highlighted this as a main reason for their choice of a PHEV over a BEV. In this way, the PHEV offered the benefits of all-electric driving locally and the convenience of using conventional fuel for longer trips.

> "I like the range on [the PHEV] because I could get to and from work on an electric. . . I like the idea of using the electricity, but the gas as a backup, if I need to do a more extended trip." (P05)

> "The kids didn't like it when we took trips in the Tesla, how long it took [to charge] between stops. So, at this point, we sort of wanted a vehicle that had the convenience of using battery locally, but if we had to break out of our local radius, we had the ability to just fill up [with gas] and go." (P03)

Default use of EV Mode. In our study, 19 owners reported that they switched driving modes (EV-only, hybrid, power/sport modes, etc.) to maximize their electric driving, with occasional use of sport mode when faster acceleration was needed. Owners regularly chose to use the battery-only mode, especially for local trips within or not far beyond the battery's range; owner mode selection we observed contradicts previous literature which found PHEV owners typically do not set the mode [73]. Some models defaulted to hybrid mode (combining the gas engine and battery power) and required owners to deliberately select the EV mode to lock out (or at least severely reduce) the gas engine from turning on every time they started the car. Many owners developed the habit to always deliberately select the EV mode, to prevent the car from using gas, every time they started the car.

> "If my destination is local, I absolutely hit the electric [button] ... I'm very diligent when I [start my driving] to make sure that the electric only is engaged so that I just, you know, ride around town on electricity." (P03)

> "I would like to stick to the electric [mode], but you have to push the button every time you drive... so you forget, I still forget. It's kinda annoying. " (P02)

Gamified Battery Range using Real-time Feedback. The limited electric range of PHEVs provided a sandbox in which *owners had an opportunity for fun experimentation with driving behaviors* to squeeze out the most miles from their battery. Unlike a fully electric vehicle, running out of battery power in a PHEV would not leave drivers stranded because the PHEV would automatically and seamlessly transition to using gas to complete their routine trips. Despite not being a safety barrier, the limited electric range appeared to induce an implicit psychological goal for owners to complete the driving with only battery power. As a result, in our study 13 owners described their experience as a form of self-competition game where they wanted to do all their local driving without using any gas or getting the highest number of miles from a single charge. Owners would deliberately alter their driving by avoiding high speeds (which drains the battery more quickly) and consciously using the regenerative braking to reclaim electricity when slowing down.

This aspect of self-competition seemed to help familiarize owners with what their life would be like with a full BEV. Overall, 60% of the owners in our full survey indicated that they would consider replacing their PHEV with a BEV. Recent market research estimates that approximately 30% of US-based vehicle owners are interested in considering a BEV [8] but that those familiar with BEVs are more receptive to making a switch [14]. Our results suggest PHEVs usage may help familiarize owners with some of the aspects of BEV ownership without requiring a full switch.

> "I'm a little competitive. I don't know who I'm competing with, but it is like kind of like a game... my husband will ask me all the time, "Did you use gas today?" So it is kind of like a running thing that we're trying. It's not that we can't afford the gas. But it's like a cool factor game." (P15)

> "It's like a game to me... When I do have to go to the gas station, you know, one time I had over 1,000 miles on my tank of gas, you know, and then I can snap the picture and send it to my friends and be like, I got 130 miles per gallon." (P01)

> "I try to get as much as I can out of the regenerative braking... Like driving down the mountain. I'm not on my brake the whole time, but really coasting and regenerative braking. I really try to make the best use of it. So yeah, I do drive differently." (P08)

Owners used the real-time feedback to guide their driving style to be more efficient and maximize their all-electric range. All PHEVs had real-time indicators in the dashboard for efficient driving.

> "The dashboard, it'll say what my efficiency is. So I like to see that number is as high as I can. So I try to not accelerate too quickly. I can see on the left side of the dashboard when it is recharging when I'm hitting the brakes. And so that's nice to see." (P11)

> "Once you go highway speeds, you eat up your EV miles much faster, so I would put it in hybrid mode. And then when I get off the highway, I would switch it back to EV... it's going to be like a lot of stops, small roads, local roads, but I would rather drive in EV." (P09)

Switching Cars within a Household. Owners with multiple cars in their household tended to be the primary driver of one car. For example, one individual would by default primarily drive one car ("my car") and the individual's spouse would drive a different car ("his/her car"). In our study, 8 owners reported they would swap cars with their spouse occasionally for utilitarian reasons but also to either take advantage of short range all-electric driving. The non-primary driver may temporarily drive the PHEV for short trips within the electric range because the PHEV is now considered the short-range car rather than being assigned to any one driver.

> "Yeah, [my PHEV] is, like, the errand car. Like I use it to drive my kids to school. If my husband drives the kids somewhere, he usually will switch and take my car because it's within [the electric] range. And so, you know, if it has juice, then we take my car... because if [my car] has a full charge, then why would he waste the gas [by driving] his car? " (P15)

> "If I'm running low on charge miles [in my PHEV], if I ran errands earlier in the morning, then maybe I will take my husband's [gas-only-powered] car just so I don't go over my electric range." (P06)

5.3.2 Concepts suggested a focus on gamification for some participants. Many participants report that they already try to drive efficiently: "I can drive conservatively on my battery and not use gas... with inflation... the cost of groceries and everything is going up. This [cost] is the one thing that I can keep low... " (P01) Interventions focused on driving behavior (e.g., Figure 1g) did not test particularly well, with participants indicating that they felt "a little bit like shaming" (P15; *Efficient driving coach*). One mentioned that they "don't see a need for" feedback about driving efficiency since their "car already gives... a trip summary notification" (P07; *Efficient driving coach*).

Participants were mixed on gamification-based concepts. Many felt that they are not "very useful" (P12, *Trip streak leaderboard and personal record tracker*), while others liked the idea of competing with other PHEV users on UF. One participant mused that he might use an app that would allow you to place a "little side side bet with your friends" (a design approach the participant described as "gamblification") (P07; *Trip streak leaderboard and personal record tracker*). Another participant noted the potential similarities to other health- and exercise-related apps.

> "I would be interested in this... [it] plays into my competitive nature... it would just be fun to see, you know, like, the Apple watch, you know, I can see

when my friends are working out and when they're closing their rings…" (P06; *Trip streak leaderboard and personal record tracker*)

6 DISCUSSION

Our goal was to understand better how today's US-based drivers use modern PHEVs and identify the factors that influence PHEV charging and driving. To accomplish this, we conducted an online quantitative survey, qualitative diary study and interviews with PHEV owners regarding their daily habits, the charging infrastructure around them, and how they drive. An overview of our findings can be seen in Table 1. Prior studies [11, 48, 53, 55, 76] suggested that not all PHEV owners charge daily. To address this, we designed several prototypes and intervention concepts focused on overcoming this barrier. Surprisingly, we found that many owners did not have an issue with remembering to charge at home. In fact, consistent with reports of charging frequency in the United States from the ICCT [55], most owners who responded to our online survey reported that they habitually plugged in their vehicle every day they drove. Further, our study results indicate that PHEV owners indeed intend to (and actually prefer to) drive on only electricity for local trips because it is less expensive and more convenient than driving using gas. These charging and driving behaviors suggest that modern PHEVs are doing the job of electrifying locally driven miles with a smaller, less resource-intensive battery than a full BEV. Despite the limited range, owners are able to become more familiar with electric driving and its benefits and build the confidence to adopt a fully electric BEV in the future.

In contrast, the minority of owners who lacked access to a private parking spot at home with a power outlet did not have a regular charging habit and had a lower proportion of electrified miles driven. These owners had to rely either on sporadic and cumbersome charging at home or difficult-to-find and expensive public charging stations. All owners who drive beyond their car's electric range can further reduce carbon emissions with more frequent away-from-home charging.

Our work corroborates and extends prior work [52, 76] that owners still find cost to be an important factor for charging behavior, including new evidence that the cost-related interventions resonate better with owners than pro-environmental framings. Further, in contrast to prior work showing drivers rarely switched driving modes [73] and required complex visualizations for efficient driving [40], our work found that PHEV owners often drove their cars in a way that maximized their electric range, deliberately using EV driving modes and simple range information to gamify their experience. Prior work estimated that multi-car households with a PHEV and ICE achieve nearly the same emissions as a household with a BEV and ICE [77], and we identified household behaviors, such as selecting the PHEV for short-range errands, that help explain the PHEV's contribution to household utility factor. These findings point the research community away from (unnecessary) home charging reminders to still unmet human-centric needs to further reduce the carbon footprint of PHEV usage: (1) helping owners become more familiar and comfortable with ever-improving public charging infrastructure and (2) supporting green driving by leveraging more immediate motivators such as costs, fun, and convenience. We discuss these design opportunities in the next sections.

6.1 Supporting Away-from-Home Charging

Prototypes that addressed familiarity also elicited away-from-home charging issues. In many cases, owners expressed confusion about where *exactly* a particular charger is located. Likely this is due to the comparatively lightweight infrastructure it takes to install chargers in a parking lot as compared to a gas pump and filling station. While Internet-based solutions can address generally "yes there's a charger nearby" it can still be a hunt. Many mapping solutions from Apple, Google, and the like have started offering micro-navigation routes (typically indoors at airports or outdoors on campuses); one could assume navigation to a charging point could also be offered, with a caveat. Chargers break, have various adapter plugs, are all in use, or even have a car parked in the spot that is not charging; so the infrastructure to navigate exactly to point is only part of the issue to solve.

To begin addressing some of these user concerns, designers can provide tools that unify multiple disparate charging networks into one seamless interface so that owners can have the security of pulling up to a charger in any network. Further, charging infrastructure companies are already monitoring the operational status and availability of charging equipment and bubbling this information up to the end user and integrating it into route planning can greatly reduce the frustrations of arriving and not being able to plug in. Another human-centric concern we identified was that owners, particularly new owners and likely potential owners, were not familiar with public charging infrastructure around them. There is an opportunity to proactively point out to new owners (or even those contemplating purchasing a PHEV or BEV) when they arrive in a location (e.g., a shopping mall) with charging capabilities and the amount of additional range they might gain from plugging in during their stay at the location (e.g., while shopping or dining). The power source that a charging station draws from also impacts overall carbon emissions. Applications could notify drivers when a charging station is drawing from e.g. dirty coal power versus clean solar [42]. In contrast to simply counting the number of chargers on a map (as many might do now), building familiarity in situ over time can not only be more experiential way of gaining familiarity of charging infrastructure, but can also adapt to rapid changes charging infrastructure as it is built out in the years to come.

6.2 Leveraging Financial and Convenience Factors to Promote Green Driving

Cost savings were a strong motivator for owners to drive on electricity, with environmental/climate benefits acting as a more distant secondary factor. This finding suggests that interventions to promote charging or efficient driving may be more effective if they emphasize immediate cost savings or added convenience to the user in addition to (or instead of) carbon reduction. Some owners already engage in off-peak charging, which could be combined with vehicle-to-grid technology to lower costs [6]. Similarly, hypermiling behaviors can maximize electric range (and reducing their carbon emissions as a side effect); interventions can enhance these desirable behaviors by illustrating financial rewards or by

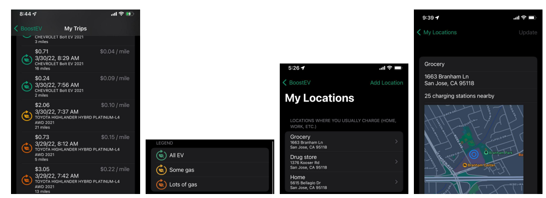
Prior literature	Our findings
Charging	
Owners were found to charge every driving day in some cases [55] (US) but not others [11, 48, 53, 76] [55] (Europe).	Owners in the U.S. reported that they charged every driving day, especially those who could charge at home.
Owners perceive public charging to be difficult to use, leading some to abandon PHEVs [26].	Even with infrastructure improvements, owners still perceive public charging to be costly and difficult to use.
Cost	
Cost concerns can reduce charging frequency [52, 76].	Owners purchase PHEVs to save on operating costs (rather than mainly for pro-environmental reasons).
	Owners prioritize the financial costs over the pro-environmental benefits when deciding when and where to charge.
Driving	
Owners rarely use driving modes [73].	Owners made efforts to drive in a way that maximized electric miles and regularly switched on the EV-Only driving mode to maximize efficiency.
In-car displays can improve driving efficiency [40].	Owners leverage real-time electric consumption data to gamify electric-only driving and maximize efficiency without the need for any additional interventions.
Multi-vehicle households	
42% of PHEVs belong to two-car households. A two-car household with longer range PHEV and ICE achieves nearly the same emissions per mile as a two-car household with a standard-range BEV and ICE [77].	Members of multi-vehicle households with PHEVs will opt to drive PHEVs for local errands within the electric range to maximize overall household efficiency.

Table 1: An overview of the findings from our survey and semi-structured interviews alongside other PHEV-related literature which may support or not-support some portion of the findings.

leveraging gamification-based designs such as social leaderboards or PHEV "fitness" tracking.

For example, instead of merely showing the cost of electricity after each charging session, illustrating the cost savings of driving the recharged range on electricity versus gas can repeatedly reinforce the financial benefit of charging and running on electricity. Similarly, quantifying the costs savings over running on gas over weeks, months, or a year, along with providing actionable suggestions for improving charging behavior (e.g., "if you plugged in one more day a week at work, you would save X amount of gas money and Y visits to the gas station over the past year") can lead to carbon reductions. Many owners enjoyed the convenience of fewer visits to gas stations, so using gamification techniques such as streaks ("Looks like it's been 58 days since you visited the gas station, keep charging to full every night and you'll be on track to reach 75 days!") can leverage the value of convenience to promote green charging and driving behavior. Another relatable metric is the number of miles driven on one tank of gas between fill ups, which most owners of ICE vehicles (median=403 miles) [17] are already familiar with. A PHEV, provided that is charged frequently and driven mostly in electric-only mode, can achieve an impressively large number of miles (e.g., > 1000 miles) on single tank of gas between fill ups.

Many cars have eco-driving scores that provide feedback to owners about how efficiently they are driving. These scores are often difficult to compare with others drivers because of differences in routes, traffic, and climate. However, drivers within the same household often drive the same routes under similar conditions (e.g., dropping kids off at school), so there is an opportunity to promote fair (and friendly) competition among drivers in the same



(a) (b) (c) (d)

Figure 2: Screenshots from a research application that implements concept features discussed in the interviews. This app tracks trips and fuel use and (a & b) estimate costs using real-time vehicle data. The app can also generate notifications when the user is (c) near certain locations that are (d) near available charging stations.

household for regularly charging and maximizing the amount of electric miles driven, which saves money for the household while reducing the carbon. There are limits to the generalizability of our results as our methods rely solely on self-report. While a good measure of PHEV owner perceptions, these methods only provide a proxy for behavioral metrics such as charging frequency and UF. Likewise, our analysis of motivations for different owner behaviors also relies on self-report, which provides a measure of owners' *stated* motivations, but may not match the real factors that drive these motivations [2, 32].

7 FUTURE WORK AND CONCLUSIONS

Participants who engaged with our concept prototypes showed overwhelming interest in apps that support navigating the away-from-home charging infrastructure. They also expressed a need for specific, detailed information, especially about costs but their responses varied to other aspects of the designs, such as notifications and social leaderboards. While some commercial applications simulate electric driving efficiency based on real trip data [47, 60] and some past work has analyzed real-trip data of PHEV vehicles outside of the context of a user-facing application [66], there are no apps that log PHEV efficiency and prices for real trips in real-time. We are in the process of addressing this gap. Rather than estimating, our app leverages the SmartCar API [68] to track real-time information about the car's use, including fuel consumed, electricity used, and miles driven (Figure 2). This data is used to monitor and rate the UF and costs of people's actual trips. We are utilizing other APIs (such as those provided by HERE [27] or PlugShare [57]) to integrate information about real-time charging availability. However, while this is a useful start, more work needs to be done to integrate electricity sourcing and pricing. In particular, during a charging session the app should connect to power providers to determine the carbon footprint of the power draw as well as real-time costs. We are also exploring how people interpret carbon footprint information to inform how the app, and others like it, should communicate emissions information [49].

Much PHEV research [11, 18, 24, 37], including this report, relies on self-reported data. Future research could focus on merging such self-reported data with real-world driver behavior of newer PHEVs (e.g., using on-board diagnostic systems [75]) to assess both how charging and UF trends have changed with the evolution of PHEV models, and how these behaviors compare with owners' perceptions of their behavior and motivations. Indeed, identifying mismatches between actual and perceived driver behavior could provide fruitful targets for future research aimed at designing interfaces and interventions to promote more efficient vehicle use. Also, while PHEVs have unique characteristics, blending a plug-in electric motor and a combustion engine, some of the findings surfaced in this report (e.g., drivers' difficulty navigating the charging infrastructure and their interest in driving while using only battery power) could be applied to BEV usage. Altogether, this work can be leveraged to design and build interfaces and interventions to minimize carbon emissions from driving PHEVs and other electrified vehicles.

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REFERENCES

[1] Simone Avolicino, Marianna Di Gregorio, Marco Romano, Monica Sebillo, Genoveffa Tortora, and Giuliana Vitiello. 2022. EcoGO: Combining eco-feedback and gamification to improve the sustainability of driving style. In *Proceedings of the 2022 International Conference on Advanced Visual Interfaces*. 1–5.

[2] John Beshears, James J Choi, David Laibson, and Brigitte C Madrian. 2008. How are preferences revealed? *Journal of public economics* 92, 8-9 (2008), 1787–1794.

[3] Daniel Boston and Alyssa Werthman. 2016. Plug-in Vehicle Behaviors: An analysis of charging and driving behavior of Ford plug-in electric vehicles in the real world. *World Electric Vehicle Journal* 8, 4 (2016), 926–935.

[4] Michael Braun, Florian Weber, and Florian Alt. 2021. Affective Automotive User Interfaces–Reviewing the State of Driver Affect Research and Emotion Regulation in the Car. *ACM Comput. Surv.* 54, 7, Article 137 (2021), 26 pages.

[5] Abby Brown, Stephen Lommele, Alexis Schayowitz, and Emily Klotz. 2021. *Electric Vehicle Charging Infrastructure Trends from the Alternative Fueling Station Locator: Third Quarter 2020.* Technical Report. National Renewable Energy Lab.(NREL), Golden, CO.

[6] A. J. Bernheim Brush, John Krumm, Sidhant Gupta, and Shwetak Patel. 2015. EVHomeShifter: Evaluating Intelligent Techniques for Using Electrical Vehicle Batteries to Shift When Homes Draw Energy from the Grid. In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. 1077–1088.

[7] John L Campbell, Charles Quincy, Jordan Osserman, and Ove K Pedersen. 2013. Coding In-depth Semistructured Interviews: Problems of Unitization and Intercoder Reliability and Agreement. *Sociol. Methods Res.* 42, 3 (Aug. 2013), 294–320.

[8] CarGurus. 2021. *Electric Vehicle Sentiment Survey.* Technical Report. CarGurus, Cambridge, MA.

[9] Scott Carter, Jennifer Mankoff, Scott R. Klemmer, and Tara Matthews. 2008. Exiting the cleanroom: On ecological validity and ubiquitous computing. *Human–Computer Interaction* 23, 1 (2008), 47–99.

[10] Pew Research Center. 2021. *Gen Z, Millennials Stand Out for Climate Change Activism, Social Media Engagement With Issue.* Technical Report. Pew Research Center, Washington, DC.

[11] Debapriya Chakraborty, Scott Hardman, and Gil Tal. 2020. Why do some consumers not charge their plug-in hybrid vehicles? Evidence from Californian plug-in hybrid owners. *Environmental Research Letters* 15, 8 (2020), 084031.

[12] SAE International Hybrid-EV Committee et al. 2010. J2841: Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data. *SAE International: Warrendale, PA, USA* (2010).

[13] ConsumerReports. 2020. *Electric Vehicles and Fuel Economy: A Nationally Representative Multi-Mode Survey.* Technical Report. Consumer Reports, New York, NY.

[14] Electric Vehicle Council. 2021. *EV Consumer Behavior.* Technical Report. Fuels Institute, Alexandria, VA.

[15] André Dahlinger, Felix Wortmann, Benjamin Ryder, and Bernhard Gahr. 2018. The Impact of Abstract vs. Concrete Feedback Design on Behavior Insights from a Large Eco-Driving Field Experiment. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–11.

[16] DeDoose 2022. DeDoose. https://www.dedoose.com. Accessed April 27, 2022.

[17] Department of Energy. 2022. https://www.energy.gov/eere/vehicles/articles/fotw-1221-january-17-2022-model-year-2021-all-electric-vehicles-had-median.

[18] Monique Dittrich. 2021. Why Drivers Feel the Way they Do: An On-the-Road Study Using Self-Reports and Geo-Tagging. In *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. 116–125.

[19] EV-Volumes 2022. EV-Volumes–The Electric Vehicle World Sales Database. https://www.ev-volumes.com/. Accessed December 11, 2022.

[20] EVmatch 2022. EVmatch. https://www.evmatch.com/. Accessed April 27, 2022.

[21] Thomas Franke, Daniel Görges, and Matthias G Arend. 2019. The energy interface challenge. towards designing effective energy efficiency interfaces for electric vehicles. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. 35–48.

[22] Thomas Friedrichs, Shadan Sadeghian Borojeni, Wilko Heuten, Andreas Lüdtke, and Susanne Boll. 2016. PlatoonPal: User-Centered Development and Evaluation of an Assistance System for Heavy-Duty Truck Platooning. In *Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. 269–276.

[23] David Gohlke, Yan Zhou, Xinyi Wu, and Calista Courtney. 2022. *Assessment of light-duty plug-in electric vehicles in the United States, 2010–2021.* Technical Report. Energy Systems and Infrastructure Analysis Division, Argonne National Laboratory.

[24] Pia Grahn, Joakim Munkhammar, Joakim Widén, Karin Alvehag, and Lennart Söder. 2013. PHEV home-charging model based on residential activity patterns. *IEEE Transactions on power Systems* 28, 3 (2013), 2507–2515.

[25] Karim Hamza, Kenneth P Laberteaux, and Kang-Ching Chu. 2021. On Modeling the Cost of Ownership of Plug-In Vehicles. *World Electric Vehicle Journal* 12, 1 (2021), 39.

[26] Scott Hardman and Gil Tal. 2021. Understanding discontinuance among California's electric vehicle owners. *Nature Energy* 6, 5 (2021), 538–545.

[27] HERE 2022. HERE. https://developer.here.com/documentation/charging-stations/dev_guide/topics/overview.html. Accessed April 27, 2022.

[28] Stephanie Houde and Charles Hill. 1997. What do prototypes prototype? In *Handbook of human-computer interaction*. Elsevier, 367–381.

[29] Diana Ivanova, John Barrett, Dominik Wiedenhofer, Biljana Macura, Max Callaghan, and Felix Creutzig. 2020. Quantifying the potential for climate change mitigation of consumption options. *Environmental Research Letters* 15, 9 (2020), 093001.

[30] Diana Ivanova, Konstantin Stadler, Kjartan Steen-Olsen, Richard Wood, Gibran Vita, Arnold Tukker, and Edgar G Hertwich. 2016. Environmental impact assessment of household consumption. *Journal of Industrial Ecology* 20, 3 (2016), 526–536.

[31] Wei Ji and Gil Tal. 2020. Scenarios for transitioning cars from ICEV to BEVs and PHEVs using household level GPS travel data. *Transportation Research Part D: Transport and Environment* 88 (2020), 102555.

[32] Wenjian Jia and T Donna Chen. 2021. Are Individuals' stated preferences for electric vehicles (EVs) consistent with real-world EV ownership patterns? *Transportation Research Part D: Transport and Environment* 93 (2021), 102728.
[33] Malte F Jung, David Sirkin, Turgut M Gür, and Martin Steinert. 2015. Displayed uncertainty improves driving experience and behavior: The case of range anxiety in an electric car. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems.* 2201–2210.
[34] Anna Krajinska, Julia Poliscanova, Lucien Mathieu, and Ambel Carlos Calvo. 2020. *Plug-in Hybrids: Is Europe heading for a new dieselgate?* Technical Report. European Federation for Transport and Environment.
[35] G Krishna. 2021. Understanding and identifying barriers to electric vehicle adoption through thematic analysis. *Transportation Research Interdisciplinary Perspectives* 10 (2021), 100364.
[36] Alexander Kunze, Stephen J Summerskill, Russell Marshall, and Ashleigh J Filtness. 2019. Conveying uncertainties using peripheral awareness displays in the context of automated driving. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications.* 329–341.
[37] Kenneth S Kurani, Jonn Axsen, Nicolette Caperello, Jamie Davies, and Tai Stillwater. 2009. *Learning from Consumers: Plug-In Hybrid Electric Vehicle (PHEV) Demonstration and Consumer Education, Outreach, and Market Research Program.* Technical Report. Institute of Transportation Studies, UC Davis.
[38] Kenneth P Laberteaux, Karim Hamza, and John Willard. 2019. Optimizing the electric range of plug-in vehicles via fuel economy simulations of real-world driving in California. *Transportation Research Part D: Transport and Environment* 73 (2019), 15–33.
[39] Phillippa Lally, Cornelia HM Van Jaarsveld, Henry WW Potts, and Jane Wardle. 2010. How are habits formed: Modelling habit formation in the real world. *European Journal of Social Psychology* 40, 6 (2010), 998–1009.
[40] Sabine Langlois. 2013. ADAS HMI using peripheral vision. In *Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications.* 74–81.
[41] Dongwon Lee, Anandasivam Gopal, and Dokyun Lee. 2017. Micro-giving: On the use of mobile devices and monetary subsidies in charitable giving. *Available at SSRN 3280553* (2017).
[42] Stephen Lee, Srinivasan Iyengar, David Irwin, and Prashant Shenoy. 2016. Shared solar-powered EV charging stations: Feasibility and benefits. In *2016 Seventh International Green and Sustainable Computing Conference (IGSC).* 1–8.
[43] Tyron Louw, Ruth Madigan, Yee Mun Lee, Cinzia De Marco, Jorge Lorente Mallada, and Natasha Merat. 2021. Don't Worry, I'm in Control! Is Users' Trust in Automated Driving Different When Using a Continuous Ambient Light HMI Compared to an Auditory HMI?. In *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications.* 220–222.
[44] Catherine MacPhail, Nomhle Khoza, Laurie Abler, and Meghna Ranganathan. 2016. Process guidelines for establishing Intercoder Reliability in qualitative studies. *Qual. Res.* 16, 2 (April 2016), 198–212.
[45] Jennifer Mankoff, Anind K Dey, Gary Hsieh, Julie Kientz, Scott Lederer, and Morgan Ames. 2003. Heuristic evaluation of ambient displays. In *Proceedings of the SIGCHI conference on Human factors in computing systems.* 169–176.
[46] Loren McDonald. 2022. US EV Sales Share Reaches 7% in Q2 2022. https://evadoption.com/us-ev-sales-share-reaches-7-in-q2-2022-new-data-now-available/. Accessed: 2022-12-11.
[47] Mercedes-Benz. 2022. The EQ Ready App. https://www.mercedes-benz.com/en/innovation/eq-ready/. Accessed April 27, 2022.
[48] Jeremie Metrailler and Marc Muller. 2022. *Etude sur la consommation des véhicules hybrides rechargeables en topographie valaisanne.* Technical Report. Impact Living.
[49] Vikram Mohanty, Alexandre Filipowicz, Nayeli Bravo, Rumin Iliev, Scott Carter, and David A. Shamma. 2022. Pick Your CARbon: User Perceptions of Equivalencies for Carbon Emissions when Selecting Rideshares. In *Adjunct Proceedings of the 14th International Conference on Automotive User Interfaces and Interactive Vehicular Applications.* Association for Computing Machinery, 48–52.
[50] Michael J Muller. 2007. *Participatory Design: The Third Space in HCI.* CRC press.
[51] Niantic, Inc. 2022. Pokémon GO. https://pokemongolive.com/en/.
[52] Michael Nicholas and Gil Tal. 2013. Dynamics of workplace charging for plug-in electric vehicles: How much is needed and at what speed? *World Electric Vehicle Journal* 6, 4 (2013), 819–828.
[53] Michael A Nicholas, Gil Tal, and Thomas S Turrentine. 2017. *Advanced plug-in electric vehicle travel and charging behavior interim report.* Technical Report. Institute of Transportation Studies, UC Davis.
[54] Benjamin Pichler and Andreas Riener. 2015. Evaluation of historical electric vehicle (EV) driving data to suggest improvements in driving efficiency. In *Adjunct proceedings of the 7th international conference on automotive user interfaces and interactive vehicular applications.* 130–135.
[55] Patrick Plötz, Cornelius Moll, George Biecker, Peter Mock, and Yaoming Li. 2020. *Real-world usage of plug-in hybrid electric vehicles: Fuel consumption, electric driving, and CO_2 emissions.* Technical Report. The International Council on Clean Transportation.
[56] Patrick Plötz, Cornelius Moll, Georg Bieker, and Peter Mock. 2021. From lab-to-road: Real-world fuel consumption and CO2 emissions of plug-in hybrid electric vehicles. *Environmental Research Letters* 16, 5 (2021), 054078.
[57] PlugShare 2022. PlugShare. https://developer.plugshare.com/docs/. Accessed April 27, 2022.
[58] Benjamin Preston. 2020. EVs offer big savings over traditional gas-powered cars. *Consumer Reports* (2020).
[59] Md Mamunur Rahman, Yuan Zhou, Jamie Rogers, Victoria Chen, Melanie Sattler, and Kate Hyun. 2021. A comparative assessment of CO2 emission between gasoline, electric, and hybrid vehicles: A Well-To-Wheel perspective using agent-based modeling. *Journal of Cleaner Production* 321 (2021), 128931.
[60] Renault. 2022. Z.E. Explore App. https://m.apkpure.com/z-e-explore/com.renault.renaultze. Accessed April 27, 2022.
[61] Marc Rettig. 1994. Prototyping for tiny fingers. *Commun. ACM* 37, 4 (1994), 21–27.
[62] Tom Richards and Lyn Richards. 1995. Using hierarchical categories in qualitative data analysis. In *Computer-aided qualitative data analysis: Theory, methods and practice*, Udo And Katherine, Kelle (Ed.). Sage London, 80–95.
[63] Michael Schrage. 1999. *Serious play: How the world's best companies simulate to innovate.* Harvard Business Press.
[64] Gondia Sokhna Seck, Emmanuel Hache, and Charlène Barnet. 2022. Potential bottleneck in the energy transition: The case of cobalt in an accelerating electro-mobility world. *Resources Policy* 75 (2022), 102516.
[65] Ehsan Shafiei, Roland Dauphin, and Marta Yugo. 2022. Optimal electrification level of passenger cars in Europe in a battery-constrained future. *Transportation Research Part D: Transport and Environment* 102 (2022), 103132.
[66] David A. Shamma, Matthew L. Lee, Alexandre L. S. Filipowicz, Laurent Denoue, Kate Glazko, Kalani Murakami, and Kent Lyons. 2022. EV Life: A Counterfactual Dashboard Towards Reducing Carbon Emissions of Automotive Behaviors. In *27th International Conference on Intelligent User Interfaces.* 46–49.
[67] John Smart, Thomas Bradley, and Shawn Salisbury. 2014. Actual versus estimated utility factor of a large set of privately owned Chevrolet Volts. *SAE International Journal of Alternative Powertrains* 3, 1 (2014), 30–35.
[68] SmartCar API 2022. SmartCar API. https://www.smartcar.com. Accessed April 27, 2022.
[69] Carolyn Snyder. 2003. *Paper prototyping: The fast and easy way to design and refine user interfaces.* Morgan Kaufmann.
[70] Timothy Sohn, Kevin A Li, Gunny Lee, Ian Smith, James Scott, and William G Griswold. 2005. Place-its: A study of location-based reminders on mobile phones. In *International Conference on Ubiquitous Computing.* Springer, 232–250.
[71] Jamie Speirs, Marcello Contestabile, Yassine Houari, and Robert Gross. 2014. The future of lithium availability for electric vehicle batteries. *Renewable and Sustainable Energy Reviews* 35 (2014), 183–193.
[72] Strava. 2022. https://www.strava.com/.
[73] Claire Sugihara, Katrina Sutton, Adam Davis, Vaishnavi Karanam, and Gil Tal. 2021. From sport to eco: A case study of driver inputs on electric vehicle efficiency. *Transp. Res. Part F Traffic Psychol. Behav.* 82 (Oct. 2021), 412–428.
[74] Carlito Baltazar Tabelin, Jessica Dallas, Sophia Casanova, Timothy Pelech, Ghislain Bournival, Serkan Saydam, and Ismet Canbulat. 2021. Towards a low-carbon society: A review of lithium resource availability, challenges and innovations in mining, extraction and recycling, and future perspectives. *Minerals Engineering* 163 (2021), 106743.
[75] Gil Tal, Vaishnavi Chaitanya Karanam, Matthew P Favetti, Katrina May Sutton, Jade Motayo Ogunmayin, Seshadri Srinivasa Raghavan, Christopher Nitta, Debapriya Chakraborty, Adam Davis, and Dahlia Garas. 2021. *Emerging Technology Zero Emission Vehicle Household Travel and Refueling Behavior.* Technical Report. UC Davis: Plug-In Hybrid & Electric Vehicle Research Center.
[76] Gil Tal, Michael A Nicholas, Jamie Davies, and Justin Woodjack. 2014. Charging behavior impacts on electric vehicle miles traveled: who is not plugging in? *Transportation Research Record* 2454, 1 (2014), 53–60.
[77] Gil Tal, Seshadri Srinivasa Raghavan, Vaishnavi Chaitanya Karanam, Matthew P Favetti, Katrina May Sutton, J H Lee, C Nitta, D Chakraborty, M Nicholas, and T Turrentine. 2020. *Advanced plug-in electric vehicle travel and charging behavior final report.* Technical Report. UC Davis Institute of Transportation Studies. 12–319 pages.
[78] Bas Verplanken and Sheina Orbell. 2003. Reflections on past behavior: a self-report index of habit strength 1. *Journal of applied social psychology* 33, 6 (2003), 1313–1330.
[79] VoltStats 2022. VoltStats. https://www.voltstats.net/. Accessed April 27, 2022.
[80] Steffen P Walz and Sebastian Deterding. 2014. Gamifying Green: Gamification and Environmental Sustainability. In *The Gameful World: Approaches, Issues, Applications.* MIT Press, 563–596.
[81] Peter C Wright and Andrew F Monk. 1991. The use of think-aloud evaluation methods in design. *ACM SIGCHI Bulletin* 23, 1 (1991), 55–57.
[82] Xing Wu, Md Aviquzzaman, and Zhenhong Lin. 2015. Analysis of plug-in hybrid electric vehicles' utility factors using GPS-based longitudinal travel data. *Transportation Research Part C: Emerging Technologies* 57 (2015), 1–12.

A RESEARCH METHODS

A.1 Survey Questions

(1) How many vehicles does your household have in total, including your Plug-In Hybrid Vehicle?
- Dropdown options: 1, 2, 3, 4, 5 or more

(2) How many of your current household vehicles are:
- Conventional gas and/or diesel vehicles: [dropdown options: 0, 1, . . . , 4, 5+]
- Conventional hybrid vehicles: [dropdown options: 0, 1, . . . , 4, 5+]
- Plug-in hybrid vehicles: [dropdown options: 0, 1, . . . , 4, 5+]
- Battery electric vehicles: [dropdown options: 0, 1, . . . , 4, 5+]

(3) How do you usually travel to work?
- I do not work
- I work from home
- I use public transport
- I drive
- I use ride sharing (e.g., Uber or Lyft)
- I walk or bike
- Other

(4) Where do you usually park your Plug-In Hybrid Vehicle when you are at home?
- Private garage
- Shared garage
- Carport
- Driveway
- Parking garage
- Outdoor parking lot
- Street parking

(5) Where do you usually park your Plug-In Hybrid Vehicle when you are at home?
- Private garage
- Shared garage
- Carport
- Driveway
- Parking garage
- Outdoor parking lot
- Street parking

(6) How often do you charge your Plug-In Hybrid Vehicle?
- More than once per day
- Once per day
- A few times a week
- Once per week
- Between 1–3 times a month
- A few times a year
- Never

(7) **Progressive Matrix:** How often do you charge your Plug-In Hybrid at the following locations?
- Locations include:
  - Home
  - Work
  - Charging services away from home or work
- Responses for each location include:
  - More than once per day
  - Once per day
  - A few times a week
  - Once per week
  - Between 1–3 times a month
  - A few times a year
  - Never

(8) **Progressive Matrix:** What charger type do you typically use to charge your Plug-In Hybrid at the following locations?
- Locations include:
  - Home
  - Work
  - Charging services away from home or work
- Responses for each location include:
  - L1
  - L2
  - L3 (DC fast charging)
  - No access to charging at this location

(9) **Progressive Matrix:** *Self reported Habit Index adapted to charging behavior. Participants answer how much they agree with each statements using a 7 point likert scale ranging from "Strongly Agree" to "Strongly Disagree".*
- Charging my Plug-In Hybrid is something. . .
  - . . . I do frequently.
  - . . . I do automatically.
  - . . . I do without having to consciously remember.
  - . . . that makes me feel weird if I do not do it.
  - . . . I do without thinking.
  - . . . would require effort not to do.
  - . . . that belongs to my daily routine.
  - . . . I start doing before I realize I'm doing it.
  - . . . I would find hard not to do.
  - . . . I have no need to think about doing.
  - . . . that's typically 'me'.
  - . . . I have been doing for a long time.

(10) **Progressive Matrix:** *Participants answer how much they agree with each statements using a 5 point likert scale ranging from "Strongly Agree" to "Strongly Disagree".*
- Charging requires effort.
- I find charging convenient.
- Charging requires less effort than fueling at a gas station.
- How much do you agree or disagree with the following statements about charging your Plug-In Hybrid?

(11) **Progressive Matrix:** *Participants answer how much they agree with each statements using a 5 point likert scale ranging from "Strongly Agree" to "Strongly Disagree".*
- It takes a lot of effort to charge a Plug-In Hybrid. . .
  - . . . at home.
  - . . . at work.
  - . . . using charging services away from home or work.

(12) **Progressive Matrix:** *Participants answer how much they agree with each statements using a 5 point likert scale ranging from "Strongly Agree" to "Strongly Disagree".*
- It is convenient to charge a Plug-In Hybrid. . .

- ...at home.
- ...at work.
- ...using charging services away from home or work.

(13) **Progressive Matrix:** *Participants answer how much they agree with each statements using a 5 point likert scale ranging from "Unimportant" to "Very Important". The fifth item was used as an attention check.*
- How important are the following factors for your decisions to charge your Plug-In Hybrid?
  - Fuel cost savings
  - Maintenance cost savings
  - Performance and driving experience
  - Please select Slightly Unimportant

(14) Are there trips you take with other vehicles that you feel you cannot take with your Plug-In Hybrid Vehicle (PHEV)? Select all that apply.
- No, I can use my PHEV for any of the trips I make with my other vehicles.
- Yes, when driving with multiple passengers I often prefer other vehicles.
- Yes, when driving long distances I often prefer other vehicles.
- Yes, when driving in cold weather I often prefer other vehicles.
- Yes, when transporting bulky or heavy items I often prefer other vehicles.
- Yes, other (please specify) [*participant entered a text response*]

(15) **Progressive Matrix:** *Participants answer how much they agree with each statements using a 5 point likert scale ranging from "Very Unlikely" to "Very Likely".*
- If you had to replace your current Plug-In Hybrid today, how likely would you choose a...
  - ...plug-in hybrid vehicle
  - ...battery electric vehicle
  - ...conventional hybrid vehicle
  - ...conventional gas or diesel vehicle

(16) **Progressive Matrix:** *Participants answer how much they agree with each statements using a 5 point likert scale ranging from "Very Unlikely" to "Very Likely".*
- If you could only own one vehicle today, how likely would you choose a...
  - ...plug-in hybrid vehicle
  - ...battery electric vehicle
  - ...conventional hybrid vehicle
  - ...conventional gas or diesel vehicle

(17) **Progressive Matrix:** *Question only asked to participants who indicated that they also owned at least one conventional gas vehicle on question 2. Participants answer how much they agree with each statements using a 5 point likert scale ranging from "Very Unlikely" to "Very Likely".*
- If you had to replace your current conventional gas or diesel vehicle, how likely would you replace it with a...
  - ...plug-in hybrid vehicle
  - ...battery electric vehicle
  - ...conventional hybrid vehicle
  - ...conventional gas or diesel vehicle

(18) Did you purchase or lease your current Plug-In Hybrid Vehicle (PHEV) to replace a previous vehicle?
- Yes, it replaced a previous conventional gas or diesel vehicle
- Yes, it replaced a previous conventional hybrid vehicle
- Yes, it replaced a previous battery electric vehicle
- Yes, it replaced a previous PHEV
- No, I did not have a vehicle before
- No, I kept my previous vehicle(s) after purchasing my PHEV

(19) **Progressive Matrix:** *Participants answer how much they agree with each statements using a 5 point likert scale ranging from "Strongly Agree" to "Strongly Disagree".*
- I purchased my Plug-In Hybrid Vehicle...
  - ...for environmental reasons
  - ...to save money on gas and/or maintenance
  - ...because of tax incentives or refunds
  - ...to gain access to HOV lanes
  - ...to gain access to more convenient parking
  - ...because it has a better driving performance
  - ...because battery electric vehicles have limited range
  - ...because battery electric vehicles are too expensive

(20) What percentage of your Plug-In Hybrid driving is done using the electric motor only?
- Slider between 0–100% [*slider handle appeared when participants first clicked on the slider*]
- I don't know

(21) For how long have you owned or leased a Plug-In Hybrid (including previous models)?
- Less than 1 year
- 1 year
- 2 years
- 3 years
- 4 years
- 5 years
- 6 or more years

(22) What is your average fuel economy when you drive your Plug-In Hybrid?
- Slider between 0–200 MPG [*slider handle appeared when participants first clicked on the slider*]
- Over 200 mpg
- I don't know

(23) When I drive, I try to maximize my fuel economy:
- Always
- Very Often
- Often
- Sometimes
- Rarely
- Never

(24) **Progressive Matrix:** Across all of your vehicles, how frequently do you use your Plug-In Hybrid Vehicle to drive round-trips of the following distances?
- Activity types:
  - Trips under 20 miles
  - Work
  - Charging services away from home or work
- Activity frequency:
  - Almost everyday
  - A few times a week
  - A few times a month
  - A few times a year
  - About once a year
  - Never

(25) **Progressive Matrix:** How often do you use your Plug-In Hybrid Vehicle to do the following activities?
- Activity types:
  - Commuting
  - Driving friends/family
  - Running errands (e.g., groceries)
  - Long distance trips
  - Towing/Hauling
  - Recreation/motorsport
  - Ridesharing (e.g., driving for Lyft or Uber)
  - Off-roading
- Activity frequency:
  - Almost everyday
  - A few times a week
  - A few times a month
  - A few times a year
  - About once a year
  - Never

(26) **Progressive Matrix:** *Question only asked to participants who indicated that they also owned at least one conventional gas vehicle on question 2.* How often do you use your conventional gas or diesel vehicle(s) to do the following activities?
- Activity types:
  - Commuting
  - Driving friends/family
  - Running errands (e.g., groceries)
  - Long distance trips
  - Towing/Hauling
  - Recreation/motorsport
  - Ridesharing (e.g., driving for Lyft or Uber)
  - Off-roading
- Activity frequency:
  - Almost everyday
  - A few times a week
  - A few times a month
  - A few times a year
  - About once a year
  - Never

(27) How satisfied are you with the cost savings associated with charging your Plug-In Hybrid rather than only fueling with gas?
- Very Dissatisfied
- Slightly Dissatisfied
- Indifferent
- Slightly Satisfied
- Very Satisfied

(28) **Progressive Matrix:** In most areas, charging a Plug-In Hybrid Vehicle (PHEV) from the grid is more cost effective than using gasoline. What energy source would you prioritize to run your PHEV under the following scenarios?
- Scenarios:
  - Electricity is 3 times cheaper per mile than gas
  - Electricity is 2.5 times cheaper per mile than gas
  - Electricity is 2 times cheaper per mile than gas
  - Electricity is 1.5 times cheaper per mile than gas
  - Electricity and gas are the same price per mile
  - Gas is 1.5 times cheaper per mile than electricity
  - Gas is 2 times cheaper per mile than electricity
  - Gas is 2.5 times cheaper per mile than electricity
  - Gas is 3 times cheaper per mile than electricity
- Responses:
  - I would use mainly gas (not charge frequently)
  - I would use mainly electricity (charge as frequently as possible)

(29) How much more would you be willing to pay for electricity from carbon-neutral sources (e.g., solar, wind) over electricity from fossil fuels (e.g., natural gas, coal)?
- I would not pay more for carbon-neutral sources
- I would pay 1.5 times more for carbon-neutral sources
- I would pay 2.0 times more for carbon-neutral sources
- I would pay 2.5 times more for carbon-neutral sources
- I would pay 3.0 times more for carbon-neutral sources

(30) Do you live in an urban, suburban, or rural area?
- Urban
- Suburban
- Rural
- Prefer not to answer

(31) What is the highest level of education you have completed?
- No schooling
- Some High School
- High School or equivalent (e.g., GED)
- Some college but no degree
- Associate's degree
- Bachelor's degree
- Master's degree in the Arts and Sciences (MA, MS)
- Professional Master's degree (e.g., MBA, MPA, MSW, MSE, MSN, MFA)
- Ph.D.
- Other Doctoral degree (e.g., EdD, DDiv, DrPH, DBA)
- Professional degree (e.g., JD, LLM, SJD, MD, DO, DDS, DVM)
- Trade School
- Other degree (please specify)
- Prefer not to answer

(32) What is your yearly household income?
- $10,000 or less

- $10,001 to $40,000
- $40,001 to $80,000
- $80,001 to $160,000
- More than $160,000
- Prefer not to answer

(33) How many people live in your household, including yourself?
- Dropdown options: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 or more

(34) How many children live in your household?
- Dropdown options: 1, 2, 3, 4, 5 or more

(35) In what type of building do you reside?
- Single detached house
- Semi-detached home/duplex
- Townhome
- Apartment
- Other

(36) Do you rent or own your home?
- Rent
- Own

B DEMOGRAPHIC BREAKDOWN

B.1 Table: PHEV owner Gender Identity

Gender Identity	*Number of Owners*	*Percentage of Sample*
Woman	228	46.7%
Man	254	52.0%
Genderqueer or non-binary	4	0.8%
Agender	1	0.2%
Prefer not to answer	1	0.2%

B.2 Table: PHEV Owner Age Ranges

Age Range	*Number of Owners*	*Percentage of Sample*
18–25	58	11.9%
26–35	138	28.3%
36–45	133	27.3%
46–55	73	15.0%
56–65	44	9.0%
66–75	36	7.4%
76–85	6	1.2%
86 or older	0	0.0%

B.3 Table: PHEV Owner Income Ranges

Income Range	*Number of Owners*	*Percentage of Sample*
$10,000 or less	11	2.3%
$10,001–$40,000	51	10.5%
$40,001–$80,000	137	28.1%
$80,001–$160,000	186	38.1%
More than $160,000	90	18.4%
Prefer not to answer	13	2.7%

B.4 Table: PHEV Owner Dwelling Type

Dwelling Type	*Number of Owners*	*Percentage of Sample*
Single detached home	355	72.7%
Apartment	69	14.1%
Townhome	44	9.0%
Semi-detached/duplex	16	3.3%
Other	4	0.8%

B.5 Table: PHEV Owner Dwelling Ownership

Dwelling Ownership Type	*Number of Owners*	*Percentage of Sample*
Own	397	81.4%
Rent	91	18.6%

B.6 Table: PHEV Owner Urban and Rural Classification

Classification	*Number of Owners*	*Percentage of Sample*
Urban	219	44.9%
Suburban	224	45.9%
Rural	43	8.8%
Prefer not to answer	2	0.4%

B.7 Table: PHEV Parking

Parking Type	*Number of Owners*	*Percentage of Sample*
Private garage	313	64.1%
Driveway	68	13.9%
Parking garage	30	6.4%
Shared garage	27	5.5%
Carport	26	5.3%
Outdoor parking lot	17	3.4%
Street parking	7	1.4%

B.8 Table: PHEV Owner Charging Access

Location	*Number of Owners with Charging Access*	*Percentage of Sample*
Home	470	96.3%
Work	310	63.5%
Public charging	388	79.5%

B.9 Table: PHEV Owner Home State

State	*Number of Owners*	*Percentage of Sample*
AL	6	1.2%
AR	2	0.4%
AZ	13	2.7%
CA	83	17.0%
CO	11	2.3%
CT	7	1.4%
DC	2	0.4%
DE	2	0.4%
FL	30	6.1%
GA	25	5.1%
HI	3	0.6%
IA	3	0.6%
IL	17	3.5%
IN	2	0.4%
KS	2	0.4%
KY	2	0.4%
LA	5	1.0%
MA	12	2.5%
MD	11	2.3%
ME	3	0.6%
MI	11	2.3%
MO	6	0.6%
MS	5	1.0%
MT	1	0.2%
NC	15	3.1%
ND	1	0.2%
NH	1	0.2%
NJ	20	4.1%
NM	3	0.6%
NV	7	1.4%
NY	55	1.1%
OH	10	2.0%
OK	7	1.4%
OR	10	2.0%
PA	13	2.7%
RI	2	0.4%
SC	6	1.2%
TN	6	1.2%
TX	23	4.7%
UT	5	1.0%
VA	12	2.5%
VT	1	0.2%
WA	13	2.7%
WI	7	1.4%

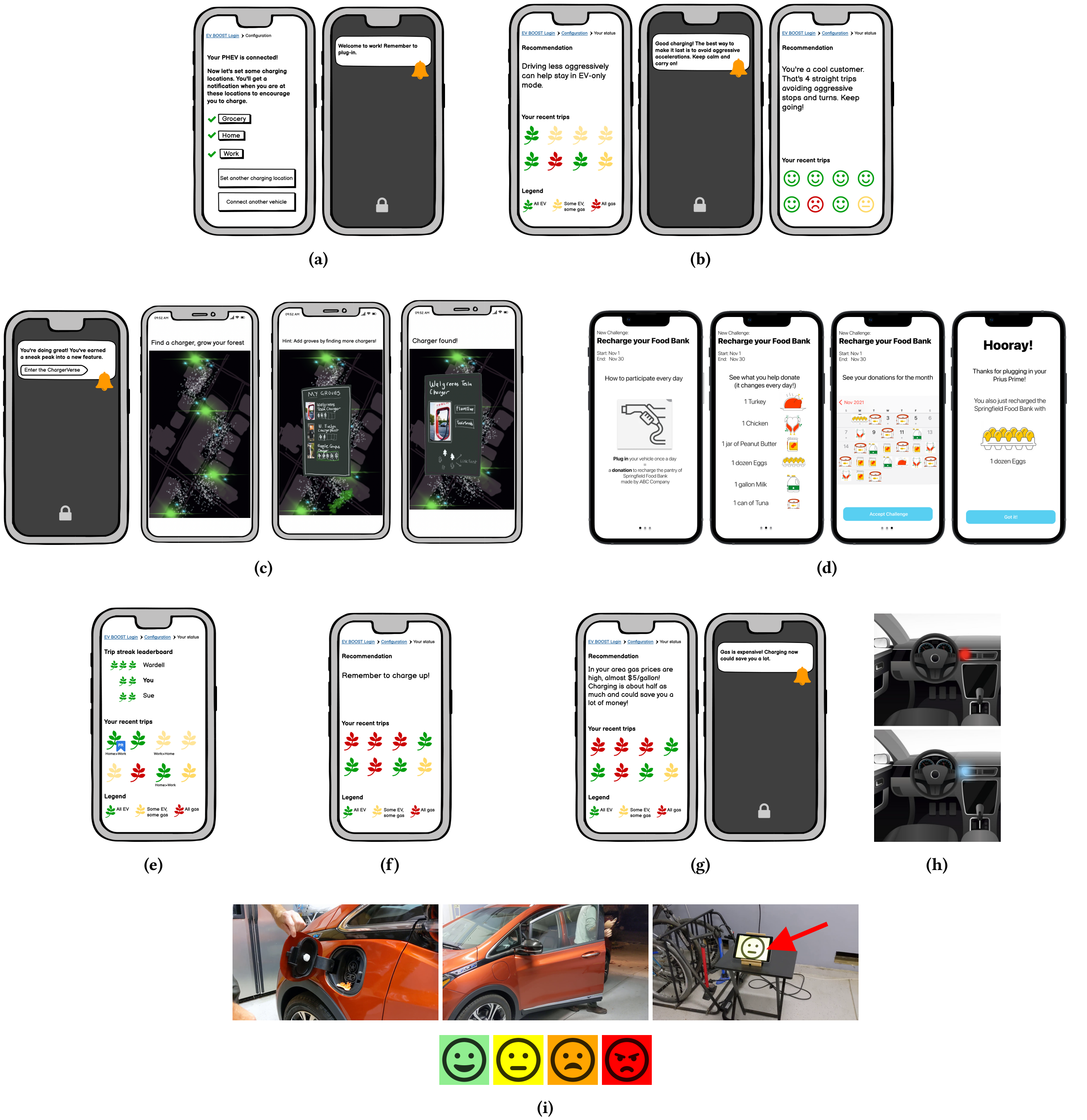

Figure 3: Concepts discussed with participants during the think-loud sessions included a variety of mobile apps, including (a) Location-based reminders for plugging in; (b) Efficient driving coach: reminders about the impacts of aggressive driving on efficiency; (c) Plant virtual trees at charging locations: an augmented reality game designed to improve familiarity with charging stations; (d) Company donates to a charity when you plug in: a way to convert money saved from charging to donations of the user's choice; (e) Trip streak leaderboard and personal record tracker: a social leaderboard app that encourages streaks of "good" (high UF) trips; (f) a low-fidelity rating of the UF of each trip; (g) and Financial advisor for driving: cost-savings recommendations. We also discussed (h) In-car electric driving coach: an in-car application that signals good (blue light) or poor (red light) UF and (i) Keeping the car charged and happy: a peripheral display charging reminder application to be installed in the users' garage that transitions from a happy to an angry state over time if the user fails to plug-in their car over several days.