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Mental models guide electric vehicle charging

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ABSTRACT

To discover conceptual and behavioral barriers to electric vehicle (EV) charging, in-depth interviews were conducted in person with experienced and novice EV users. Mental models were found to affect vehicle charging strategies. Novice EV users drew from their existing mental models for petrol refueling and misapplied them to EV charging. Most experienced users had developed new mental models appropriate for the physical and temporal realities of EV charging—they are adapted to diverse rates of charge, EVs' longer energy filling duration, co-location of EV charging with certain user activities, and EVs drivers' shorter equipment engagement time. Three predominant mental models for EV charging were found: 1. Monitor the fuel gauge, when low, seek a refill location (from liquid-fueling model), 2. Prior to a trip, plan where and when to charge, 3. Event-triggered charging (unique to the EV mental model). Misapplication of liquid fuel models to EVs has detrimental effects: more effort and more frequent anxiety regarding recharging, buyer choice of EV characteristics mismatched to need, manufacturer oversizing of batteries, policy overemphasis on fast public charging, and restricted opportunity to reduce load on the grid. Solutions are suggested to forestall or minimize these detrimental effects and facilitate EV adoption.

1. Introduction

Transition of the road vehicle fleet away from carbon-based fuels is essential to achieve a low-CO_2 civilization. Electricity has emerged as the preferred fuel for light and medium weight vehicles, due to its high end-use efficiency, multiplicity of clean energy sources, ubiquity of existing distribution systems, and lower cost per vehicle mile traveled (VMT) than liquid or gaseous fuels. As noted frequently, this transition to electricity will require society to meet the engineering challenges of designing and optimizing new vehicles' prime mover, energy storage, and regional fueling infrastructure.

This article seeks to address a gap in electric vehicle (EV) studies, namely the inadequate focus on user perceptions, mental models, behavioral habits and refilling strategies. EV drivers originally formed these while using vehicles with liquid fuels. The research scope is users' recharging of EVs – the user processes, perceptions, behaviors and decision-making. Our goal in examining user recharging is to better understand it and to determine whether some of these user aspects also present barriers to EV adoption and to efficient and convenient EV use.

This article's data reveal fundamental differences in the mental models of liquid fueling versus EV recharging, which have not been previously reported. These differences may present barriers to an EV user's transition to EV use. By discovering this, the research contributes new insights into the barriers that EV users' mental models can impose. These insights inform consideration of how current mental models, habits and perceptions might be modified, replaced or addressed to better facilitate a large-scale EV transition.

2. Relationship of prior literature to this study

In the literature on EVs, after vehicle cost, the most-cited barriers to widespread adoption include range limitation and lack of convenient charging infrastructure. Noel et al. [1] point out that these barriers are rooted in mental barriers. These mental barriers are not technical or economic, rather they are related to knowledge and prior experience. Noel et al. find a need for consumer education, especially on the need for charging infrastructure. Similarly, Coffman et al. [2] find a lack of knowledge about EVs, especially related to fuel usage. Misperceptions about the vehicles and how to strategize refilling might also bias consumers against buying an EV [3]. Other studies show that the adoption of EVs is limited by "perceived ease of use" [4]. Both the popular press and academic studies discuss "range anxiety" as a barrier to EV adoption

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[5]. Range anxiety is the idea that EV drivers become anxious while driving if they are running low on charge or unsure about reaching their destination. But none of these prior studies explicate users' mental models for fueling strategies; this study will demonstrate that range anxiety and perceived slow charging are in part due to applying liquid fuel mental models to EV charging.

Many previous studies on charging behavior have taken a more quantitative approach and focus on time of day and power of charging to be able to model and predict charging peaks [6]. These studies often rely on real-world data from metered charging combined with driving data [7,8]. However, none of these studies look into the underlying reasoning or thinking on which drivers base charging decisions. Some studies have categorized user charging strategies based on how frequently they charge (e.g., daily at home or at work) or based on the state of charge of the battery [9–11]. Charging strategies have been analyzed as "user-battery interaction" (UBI), adopted from portable electronic devices [12]. Low UBI (charging on a regular schedule) may reduce cognitive load for monitoring and planning, while high UBI (charge when needed) requires monitoring and decisions but reduces physical effort by plugging in less frequently [13]. Refueling strategies for liquid-fuel vehicles have been less studied [14,15]. Our data will show that both EV charging and petrol refueling draw from a more complex set of concepts and strategies than UBI or time of day studies have described.

Specifically, this article employs the concept of mental models, defined as the conceptualizations that people create of the world and of the tasks they perform [16]. Mental models are internal representations of external phenomena, objects, or practices that people use to interpret and guide interactions with the world around them [17]. People's learning and understanding of new technologies, their predictions and explanations, and their performance of tasks, all draw from mental models based on past experiences and understanding of prior technologies [18–21].

There is no literature specifically on EVs and mental models, however some studies have examined the role of mental models when interacting with new technology. For example [19], find that users initially rely on prior experience with an incumbent technology to make sense of a new one, even though the old mental models may not apply well. The old mental models need to be modified or restructured to guide users' interaction more efficiently with the new technology. This process involves both mental model building (users modify or restructure the mental models to accommodate new information and knowledge) and mental model maintenance (users try to fit information about new technology into existing mental models). They find that a user's intention to use a technology is influenced by the perceived usefulness and perceived ease of use. Mental models can act as either facilitators or inhibitors in this process. If new information is hard to fit in the existing mental model users could experience frustration and reduced willingness to adopt or use the new technology. To fully exploit the advantages of a new technology requires mental model building. However, mental model building requires extra effort and time, thus it may need extra support via educational programs. Our data suggest that EV charging is a case of difficult model building, thus programs to change existing models of refueling, replacing them with models that better fit EV charging, would facilitate and speed the EV transition.

As an example of how mental models affect use of energy technology [20,21], has shown that a person's mental model of a device affects the way that they use the device, and that this behavior can persist for years. The case studied was mental models of the thermostat used by occupants to adjust the comfortable indoor temperature. Interviews revealed that the two most common models were that the thermostat is a temperature-controlled switch (either on or off), versus that the thermostat is a valve (the dial position changes the rate of heating or cooling). The valve model is acquired from experience with devices like water faucets, stovetops, and some simple room heaters. By contrast, ovens and whole-home heating or cooling typically employ a thermostat (a temperature-controlled switch). In using a house thermostat, people holding the temperature-controlled switch model set the thermostat to the desired temperature and leave it, those with the valve model will make many adjustments during the day in order to (they believe) control the rate of heating or cooling to keep comfortable. Based on interviewing residents and on electronic records of thermostat dial settings [21], that study shows that mental models affect planning and behavior, as indicated by records of the thermostat settings over a year. The people with the temperature-controlled switch model exhibited a flat line of constant thermostat setting that changes only when residents come and go or activities change. The people with the valve model changed frequently up and down during waking hours. The present research similarly uses interviews to elicit charging behavior and infer mental models, in this case of EV users, which had not previously been done. We will argue that users' mental models of fueling, similarly to the thermostat case, affect those users' refueling behavior and strategies.

We also draw on studies of "math in everyday life", which have found that simplified yet approximately-accurate calculations are often preferred by people solving everyday problems, and are created from socially-situated learning without any formal instruction. Previous literature has documented examples of simplified math in studies of price comparisons during grocery shopping [22] and in use of household energy bills to determine how much savings are achieved due to energy conservation and efficiency improvements [23].

We will argue in the Discussion section that addressing old mental models and old refueling strategies will be important to facilitate the EV transition, valuable whether or not other conventional policies, such as tax incentives and charger installation programs, are implemented. A deeper understanding of the mental barriers can help design more effective information and educational campaigns. Understanding old mental models may also inform other EV policy interventions such as placement and specifications of charging infrastructure, sizing of EV batteries, EV purchase decision assistance, and shifting charging to more grid-appropriate times [24].

The next section summarizes the electrical and time measures relevant to user mental models and strategies for EV charging. This background is needed to understand our subsequent exposition of the logic of EV-specific mental models.

3. The physical characteristics of electricity vs. petrol for vehicles

This section compares electricity and liquid fuels in their physical aspects.[1] Because a road vehicle is mobile, it requires on-board energy storage and a means of refilling it. During travel, that energy is drawn down, so eventually it must be replenished. Thus, a fuel tank and a battery serve the same function, energy storage. Similarly, a liquid fueling station and electric charging station serve the same function. Conceptually, one might a priori expect the mental model for EV and liquid refilling to be identical. However, this section will show that the quantities and rates are so different that this potential transfer of mental model–correct in basic physics–is insufficient and misleads user actions in refilling; our interviews will subsequently show that, in fact, experienced EV users use neither the same models nor the same behaviours for petrol and EV refilling.

Regarding terminology, we will use "refilling" for both petrol fueling and electrical charging. We will use "range", also called "autonomy", to refer to the distance a vehicle can drive before requiring refilling, and "petrol" as shorthand for petrol, gasoline, diesel, or other liquid fuels.

The total user time for refilling involves two time measures: the energy transfer time, derived from physical attributes (Equation (1)),

[1] Some factual statements in this section draw from common electrical and fueling information that could be found in a textbook. Some product numbers and data in tables draw from manufacturer specifications or the trade press. Such factual statements are not all documented with citations.

Table 1
Energy transfer time to fill 40 l of petrol versus 30–200 kWh battery energy, at the most commonly available refueling rates (50 l/min and 10 kW). The time the driver must be engaged in the refilling process is in the rightmost column.

Fuel type	Storage size	Range when full (km)[b]	Time to transfer energy at 50 l/min or 10 kW[a]		Time driver is engaged with refilling[c]
			Add 100 km range (time)[b]	Fill from empty to full (time)	
Petrol	40 l	770 km	10 s	48 s	8.6 min
Electricity	30 kWh	170 km	1.8 h	3 h	15 s
	80 kWh	450 km	1.8 h	8 h	
	200 kWh	960 km	2.1 h	20 h	

[a] Among the wide range of EV charging rates, this table uses 10 kW, a median of the most common AC chargers. (Different charging rates will be compared in Table 2.) For petrol transfer, 50 l/min is used, slightly more than the regulated US fueling rate at 11 gal/min. Adjusting for the much lower efficiency of petrol vehicles (~18 % petrol vs. 80 % for EV), the 50 l/min petrol fueling rate is the equivalent of 5.3 MW [27]. Note that filing time for EVs is approximated by the simplified Equation (1); a more detailed calculation would capture that the rate decreases as the battery becomes full.

[b] Energy transfer times use petrol vehicle efficiency of 5.2 l/100 km (avg of new cars sold in Europe, based on the EV fleet sales standard of 120 gCO_2/km) (=45 MPG, similar to the 2021 US CAFE average of 42.7 MPG). Ranges are calculated for typical size EVs, using17.8 kWh/100 km (3.5 mi/kWh) [28]. For the 200 kWh vehicle only, a lower driving efficiency is used due to weight, 20.8 kWh/100 km or 3mi/kWh.

[c] For petrol, "time engaged for refilling" includes incremental time to drive to station, initiate pumping, monitor, pay and disconnect. The vast majority of EV charging is done at a location where one stops for other reasons, thus the extra time for a few en route stops over the year adds infinitesimally little time to the average charging engagement (to connect and disconnect) [25].

Table 2
Energy transfer time (min or h) for a range of battery sizes, at different power rates, not including driver engagement time.[c] The five rightmost columns designate from slow to very fast charging power (kW) and the associated equipment cost (in €). Per Eq (1), higher power results in lower refill time but per this table, that is at higher capital cost.

Fuel	Amount added	1.4 kW €300	10 kW €600	50 kW €25,000[a]	150 kW €65,000[b]	350 kW €350,000
Petrol	40 l (fill)			48 s		
Electric	Add 100 km	12 h	1.8 h	21 min	7 min	3 min
	30 kWh (fill)	21 h	3 h	36 min	12 min	5 min
	80 kWh (fill)	57 h	8 h	1.6 h	32 min	13 min

[a] Today the power levels up to 20 kW in the US (up to 43 kW in Europe) are met by AC, from 20/43 kW above are met by DC at much higher station costs. A new standard, SAE J3068, allows for AC charging at station cost of approximately 1/8 of the costs shown for 50–150 kW in Table 2 [29].

[b] Sources for cost of 150 kW are €59 000 [30] and $75 000 [31].

[c] Given the huge differences in kW charging rates and concomitant differences in time to charge across columns in Table 2, users are presumably impaired by today's practice of not marking the kW power on charging equipment, nor on signage, and only rarely on the mobile apps used to locate and activate charging equipment. (Apps often distinguish AC from DC but few give the station's kW rate.)

and the driver's time to set up, connect, disconnect, and–for flammable liquids–to attend and monitor the refilling process, determined empirically as reported in a recent publication [25].

Liquid fuels and their fumes are highly flammable and toxic, and liquid fuels are resupplied by large tanker trucks that periodically refill underground storage tanks at distributed stations–all factors leading to liquid fuels being stored at, and sold from, specialized stations that the driver travels to for that purpose.

Refilling electric storage in an EV draws on the electricity supply ubiquitous in most buildings and commonly in or near parking structures. Electric refilling is slow, but the user-engaged process of connecting and starting the refill process is fast, faster than petrol [25]. Due to the ubiquity of electric infrastructure, recharge stations can be located where vehicles will be parked for reasons other than fueling (e.g., work, home, hotels, shopping or food stopovers, events). Several other characteristics of electricity are salient: required electrical safety features are inexpensive and built into manufactured devices (charging station and vehicle), the fuel is cheaper than petrol per distance, and electric fuel cost need not be paid in a separate transaction or may not even be separately metered.

The following tables quantify differences in refilling time between petrol and EV vehicles. The total refueling time is the sum of physical energy transfer time plus driver engagement time. For the physical transfer of energy, Equation (1) is a simple formula, identical for both liquid and electrical refilling, except in units:

$$t = E/P \tag{1}$$

Or equivalently

$$E = t * P \tag{1a}$$

Where.
t is refilling time (h or min)
E is energy added to storage (kWh or liters)
P is power (kW or l/min)

Table 1 compares petrol versus electric refilling of different battery sizes at constant refilling rate. Table 2 compares different refilling rates. (The quantities in both tables are comparable for EVs worldwide.) The light vehicle refilling rate for petrol is regulatorily fixed at 50 l/min (11 gallon/min in the US). For electricity, by contrast, charging rates vary by over two orders of magnitude as shown in Table 2.

Table 1 illustrates the dramatic differences in refueling time (using Equation (1)) of petrol compared to electricity at the most common rate (10 kW). Petrol has a huge advantage in energy transfer rate; it is so quick that it has determined our concepts and strategies for refilling, which wil be one of this article's important findings. Both Table 1 and Equation (1) show that today's common batteries (30–80 kWh), with the most common charging rate (10 kW), would be filled in 3–8 h–thus during an overnight sleep, or during a workday, one can completely fill up from empty [26]. The "add 100 km" column is to illustrate the practicality of adding range at the most common rate, for example, when one is stopped for other reasons, or to "top off" in order to reach a next destination.

The rightmost column in Table 1 is the time the driver must be engaged during the refilling process. Petrol refill requires more time to access the station, setup and monitor filling, disconnect and pay (total 8.6 min), then leave and continue travel. For EVs, the time engaged is 15 s for the most common refill events, which are at an available parking space at home or work, a place not requiring authorization or payment. The EV's 15 s of engagement sums user time to plug in plus time to later disconnect [25]. Note that down the column of energy storage sizes in Table 1, petrol always takes more time for driver engagement to access and setup than the time for energy transfer itself, whereas for electricity, engagement time is much less than energy transfer time. This relationship between energy transfer time and driver engagement time is key to understand the EV refueling strategies of experienced EV users.

Table 2 shows the full range of charging speeds across the columns in order to evaluate the current efforts to create a technical solution for slow EV charging—a higher kW charging rate to reduce the energy transfer time. Very high kW rates approach but cannot match petrol fill time, and stations that approach it do so at great cost (per column headings in Table 2). Thus, the Discussion section will ask, would it be more cost-effective for drivers to change their petrol-derived ways to plan and strategize EV charging—perhaps taking advantage of the low driver engagement time–rather than trying to make EV energy transfer rates match the refill rate of petrol?

In short, the petrol energy transfer rate is both fast and is uniform across stations, whereas EV charging is slower and varies greatly across stations. The EV slower charge problem has limited technical fixes because for higher power chargers, the initial cost (Table 2), maintenance, and added utility "demand charge" make fast charging much more expensive than charging at moderate power. This is the environment within which we find that many experienced EV users have developed new mental models for charging.

4. Methods

Our user analysis is based on two sets of interviews: one with experienced EV users in both Sweden and the US, and one with novice EV users in Sweden. The study required qualitative interviews rather than a survey because there was no substantial literature on users' concepts or strategies for EV charging. All interviewees had previously driven petrol vehicles, and some of their narratives compare petrol to EV refilling.

Interviews for mental models about a topic seek an inventory of a populations' models, not a sample of people to calculate frequencies or correlations. The sample size is determined by continuing to interview the population until no new user concepts are elicited. This leads to typical sample sizes of 20–30 [32], as we found in this study. The interviews follow pre-set questions but add follow-up questions to elicit elaboration and clarifications (the interview questions are in supplementary information); they require experienced interviewers who are knowledgeable of the relevant domain, and typically require much more time per informant than a survey [33].

For the experienced users, 10 EV-using households were interviewed, 5 in Sweden and 5 in the US. These interviewees were selected to include those who owned or had driven an EV for a minimum of 6 months (the average was well above that minimum, with a maximum of 6 years). We picked interviewees as "experienced" in use, not experts in technology, thus we generally excluded engineers or physical scientists (for the Swedish interviews two engineers were inadvertently included). Experienced interviewees were located and confirmed to meet these criteria through an EV club and through individuals known to the authors, a process sometimes called opportunistic sampling. The interviews were carried out either in person or through video chat, in either case the duration was between 40 min and 1 h. All interviews were recorded and transcribed. Experienced user quotations are designated with IDs "SV" or "US" to indicate which country they are from, followed by a number.

The novice EV user data draw from interviews with 25 households. These took place as part of a research trial where 25 two-car households in the Gothenburg region had one of their petrol vehicles replaced for 3–4 months by an e-Golf model year 2015 with an expected range of roughly 120 km. During the trial time they also had a home charging box of 3 kW installed. Interviews were carried out before and after the trial in Swedish and all but one were in the participant's home. In all novice interviews, except one, both spouses were present and in two households the children were also present.

All interviewees, novice and experienced, had home charging—except US02, who lived in an urban residential neighborhood with no dedicated parking and after much effort was unable to charge when needed (described in Results). All interviewees had used public charging, with varying frequency. None of those with home charging were metered or billed separately for charging.

The interviews were recorded and transcribed in the interviewee's native language. Quotations in the article have been translated to English by the authors, with the original Swedish added in square brackets and italics only if the word or phrase meaning is particularly significant. Words in brackets but without italics are clarifications to the verbatim transcript wording. Apart from the brackets or translation, quotation marks denote word-for-word statements from the transcripts. Quotations from novice households do not distinguish between the members of the household, so we index novice households with an "H" followed by a number to denote either one or both adults, and treat the speaker as plural. For both experienced and novice interviews, manual coding of transcripts was performed based on identified themes. The primary comparison planned was novice versus experienced EV users; no charging-relevant differences between Swedish and US informants was hypothesized, and none particularly stood out in analysis. Drawing from two countries reduced the likelihood of picking one idiosyncratic country. On the other hand, we did not attempt a multi-regional study, which might have yielded some cross-national differences not found here. Since no prior study had been done of mental models of charging, the added expense of a multi-regional study did not seem justified as a first study. Future studies could expand our analysis to other geographical areas and contexts.

Fig. 1 illustrates the data collection and analysis process, starting with taped verbal interviews, then transcripts. Analysis successively narrows and compares the text data, extracts concepts and behaviors, compares across informants and compares description with behavior, to ultimately infer this article's description of mental models and how each mental model relates to charging strategies.

We planned the interviews to infer EV mental models, however we originally sought user models of how to determine and conceptualize how full the battery is. Because we used qualitative interviews, these interview data revealed unexpected mental models determining charging strategy. We found that strategies differed among informants; also several informants reflected on their initial EV charging strategies that had been based on prior petrol vehicle experience, and why they changed their mental model and charging strategy during their EV experiences. Thus, variation among informants, self-reported change, and the relationship of models to behavior all inform our analysis of mental models of charging.

We preview our findings of the mental models used for refueling to make a methodological point here. One observation was that experienced users, when asked about charging their EVs, typically reported first a model we will call the "Planning" model, in which the driver plans refueling stops in advance of travel; it was reported first even though these drivers employed it far less often than other mental models. Methodologically, we infer that EV drivers report the planning model first because planning is a complex conscious mental process, required only for long trips but highly salient in recall. We will show that what we call the "Event-triggered" model has been developed over time by EV drivers, in which they plug-in to charge when a pre-selected repeating event occurs, enabling routine charging without repeated conscious decisions. For experienced EV drivers, event-triggered charging is the most common, yet methodologically, that model was reported only later in interviews. Its lower interview salience makes sense because, as we will show, the event-triggered model intentionally pushes decisions and conscious process into the background. Regarding event-triggered

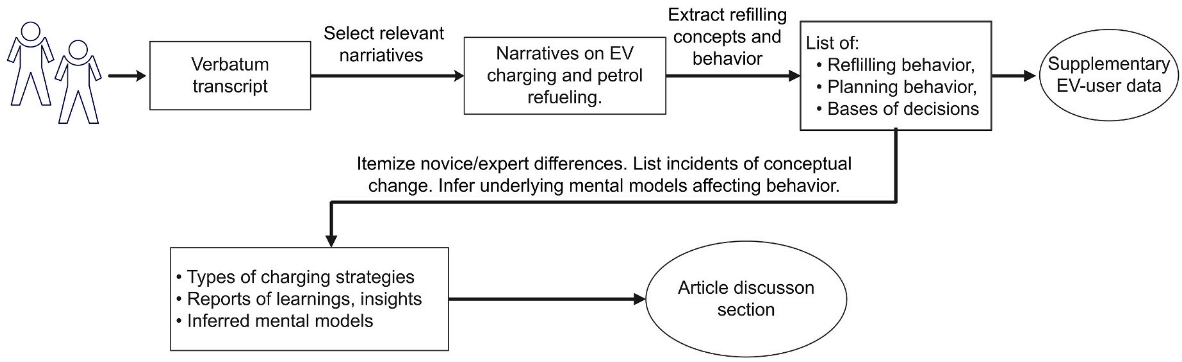

Fig. 1. Process of collecting and analyzing the interview data. Data at each step is within rectangles, selection or analysis steps are written above each arrow line, and outputs reported here are in ovals.

charging, informants reported the behavioral part, as "I always plug in at work" or "… when I walk my dog in the evening". They typically do not report their necessary prior process of choosing the triggering event, but we infer that earlier choice, based on the informant's reported logic–e.g., I plug in to charge then because it is off-peak, or, because our solar panels are producing then, etc. Subsequent research on mental models for EV charging could refine our understanding by asking experienced EV users directly how and why they made their prior choice of triggering events.

5. Results

5.1. Interviews with experienced EV users

We interviewed experienced EV drivers in Sweden and the US, "experienced" being defined as having operated one or more EVs for at least 6 months (the longest was 6 years). This section summarizes our main observations with illustrative interview quotations; more analysis and data are in the Supplementary-text and Supplementary-EV-user-data.

- Most users do not understand the physical units or process of charging. In contrast, for petrol, they understand the physical process of filling a tank with liquid fuel, and that the level of liquid in the tank is being drawn down to run the engine. They understand that electricity is similarly stored to run an EV, but no comparable physical analogy is available as a mental model. For example, US04: "Your body needs fuel, your car needs fuel, no matter [if petrol or electric], in order to be useful you have to put fuel in it. … you put a gas pump [nozzle] in your gas tank, but what's coming out is the liquid [that] makes the internal combustion engine go. The electricity is [pause] I've never really understood electricity"
- Rather than use a physical mental model of storage, almost all our experienced EV drivers carry over a virtual model from the graphic on portable electronic devices. Displays on most rechargeable electric devices use a battery icon with a bar indicating how much electrical energy it contains. The displays on EVs now frequently use a similar battery icon, often with an adjacent quantity or two. This icon may turn orange or red at low charge levels. Users may refer to the fill position, the number, or the color: SV02: "As long as it is green and looks fine then it is happy. Then you don't need to charge. But when it starts ticking down, or blinking red …, then you know you have to stop and charge." We call this mental model of charging strategy "Monitor gage".
- The displayed numeric values are used more than the icon when a plan or decision is to be made. The numbers may be either the percentage of a full charge and/or the distance remaining. Many experienced EV drivers use both. Some prefer percentage, mentally doing their own adjustments for cold weather etc. Others prefer distance units because the EV manufacturer already adjusts for temperature, and because a distance metric applies directly to trip planning. US02: "I'm living in miles and not living in percent–the percentage doesn't really help because if I have 90 % in the winter, it's really different than 90 % in the spring or fall … [or] summer, …but the miles are the same [miles reflect actual travel distance]." Some use miles for all trip planning, and use percentage only to monitor while charging.
- For refilling strategy, experienced EV users describe two very different use cases, one for long trips and one for daily driving, as follows.
- The EV refilling strategy for long trips requires planning and data. Users draw information from multiple resources—including the EV dashboard display, an EV-provided mobile application, and/or a charging station app—to plan when and where to recharge en-route. Choice of en-route recharge location may combine distance diverted from the most direct route, charging rate (kW), reliability including likelihood of being in use or blocked, and availability of other activities to do while charging. US01: "You have to plan. You have to plan your trip just like you would plan a gasoline trip in terms of your route. Maybe you would plan some other [additional] stops. … You have to do a little bit of work upfront, so that you will succeed [chuckles] and not find yourself in a bad situation where … you don't have enough charge on your battery … to get where you're trying to go." We call this mental model the "Planning" model.
- The EV refilling strategy for daily driving, which for most days totals much less distance than the vehicle's range, is what we call event-triggered. Many or most experienced EV users select an event such as returning home in the evening or arriving at work to trigger a plug-in, and follow that without further plan or strategy. US03: "We have a 220 [volt] charger in our garage, and so what we do at night, we just come home, plug-in the car, and by next morning it's fully charged to 300 miles. For us, it's not a problem …" US01: "Well, if you have a plug at your home or you're at work and you plugged your car in … you would assume that your car is going to be fully charged [when you next] get in …." Informants themselves mention that event-triggered plug-in is a way to reduce the need to plan. US04: "Much less planning as long as I have charged it the night before, I've got more than enough [range] for every [possible trip] …" A variant strategy is that the event triggers a simplified needs judgment. SV04: "If, for example, there are only 20 km left in the car [when we get home], then we charge even if it is expensive because … You may have to go somewhere." The triggering event may be picked strategically: US04: "… When I walk my dog in the evening, I plug the car in and in the morning it's at [as full as I set it for]. …" Note the sophisticated choice of evening dog walk as a triggering event—the charging starts in the evening after electric rates are lower, yet early enough that the EV always is sufficiently charged by morning. (Some other EV studies gloss over these differences by describing all as "charging at home"; but that label overgeneralizes

and ignores the specific triggering event—e.g. Do they plug-in whenever stopping at home? Only when returning from work? When returning home briefly to drop off kids? It also ignores the process by which the triggering event is selected initially, and incorrectly suggests that arrival at home is the only important triggering event.) We call this mental model "event-triggered" charging in order to generalize beyond "home" as the key element, to reference these additional components, and to suggest a prior user process of choosing a triggering event.

- For petrol vehicles, event-triggered refill is not an option because all refilling requires going to a petrol station. Whether on local or long trips, the petrol strategy is the same: monitor fuel level during driving, then when low, go to a petrol station. SV05: "I would check the indicator in the display in the [petrol] car. There was no routine, more random [*slump*]. It was more: 'Ok, it's time to refuel now!'". Why does this experienced EV driver describe refueling a petrol car as "random"? We interpret "random" as not related to what the user is doing—versus event-triggered charging, for which the user has chosen an event occurring at a logical time and place to plug in. From this perspective, event-triggered charging is not "random", it is at a place and time the EV driver has picked to be integrated with the driver's own schedule and activities.
- As a converse example, US02, after buying an EV, found she was able to charge neither at work chargers, which were far from her office and expensive, nor at home, a row house with street parking, not owned parking spaces. She made many attempts to charge near her home, for example having a neighbor watch for parking spaces within extension cord reach of her house. She initially expected to charge both at home and at the two fast chargers at her local grocery store, but often found the grocery chargers out of order or blocked. So she could not create event-triggered charging at the places she parked for other reasons—at work, at home, or at the grocery store. After a year of unsuccessful efforts, she had to trade in her EV for a petrol car. We take this as a converse case, ending in rejection of the EV after considerable effort to find a way to charge it; this case shows the importance of event-triggered charging to make EVs convenient and practical.

5.2. Interviews with novice EV users

From the interviews with 25 novice EV households in Sweden, we find evidence for different stages in the transition from the liquid fuel mental model to some of the experienced EV driver's models noted above. These households received an EV for a 3 to 4-month trial, the first time they had lived with an EV. Novice household quotations are identified with "H" and a number.

- Novice households with a liquid fuel model reported more stress and constantly having to think about range. They did not expect to plan ahead, nor did they select an event to trigger charging. Rather they constantly monitored the battery's state of charge (SOC), and sought a charging location when low, or when the distance remaining was less than needed for the next trip. This is the "Monitor gage" model, which these data show towork poorly for EVs. H9: "A [petrol] car one can drive for a long time before one has to think about refilling it. Here [with EV] you have to think about it all the time". H7 points out that the EV charging itself doesn't take much user engagement time, but it becomes a new requirement to plan and thus needing more mental effort; H7 implicitly invokes the liquid fuel model by saying "you can't just drive and refuel".
- Novice EV drivers who had transitioned to the event-triggered mental model saw the advantages of being able to achieve most charging needs at home in the evening or when parked for other purposes. H16: "it is fantastically nice that you always have a fully charged car, or what shall you say. A normal [petrol] car you have to stop and fuel". Similarly, H19: "when you come out [from your home] you can just drive. It's not like 'oh, I have to go and refuel' before you go anywhere". That is, for the EV drivers using the monitor gage model, EV charging was experienced as something stressful that they constantly had to think about; those using the event-triggered model reported that the EV made life easier. After having made this transition, H15 said: "it was pretty nice to not have to refuel. Or rather one refuels every evening. But one doesn't have to think about it other times, somehow."
- As novices acquire appropriate EV mental models, their focus moves away from how much time it takes for the vehicle to transfer energy, to how little time it takes for them to plug-in (column 5 versus 6 in Table 1). H4: "It's very practical. Much easier to just plug-in a cord. Even if you do it every day it's a routine thing". H6 initially thought it would be difficult to plug in, but realized after using that it "only takes 3 s" (Measured time is 15 s to plug in plus unplug, Table 1.).
- Another insight from the EV mental model is that you do not have to fully charge the vehicle when you stop and refill. H21: "You rarely have to charge fully. If you get an hour, it does a lot". Another described charging during a stop for other purposes: "it's very smooth. You just park, plug it in and you get a few extra tens of kilometers when you are in [the shopping mall]". In the Discussion, this is called "opportunistic charging", a variant of the event-triggered model.
- Some novice users started reasoning during the interview itself that they might need to shift their mental model. H8 had not expected to charge daily, expecting it would be enough to charge every other or every third day, when the SOC of the battery was low. But when practicing this, H8 often found that they lacked sufficient range for trips. Range was constantly an issue. Unprompted, during the interview, they reported a new realization: "But maybe that is the point, one is so used to a normal [petrol] car, you don't fuel that one every day. So maybe the idea is that one has to change one's behavioral pattern in this case [by charging daily]". Similarly, H9: "one should maybe not drive it to the bottom and then put it on charging. … maybe one should charge it in between so that it has an extra trip in it [har en sväng extra i sig]. Actually, one should have it on charging whenever it is standing still". In these quotations we see the gradual process of novice users starting to build a new mental model appropriate for EV charging and replacing their petrol fueling model, partly in response to our questions.
- Building a new EV mental model is not automatic. Some users develop it on their own, others may need support from educational materials to facilitate building a new mental model and thus to minimize the EV transition. H21 acknowledged that using an EV necessitates a change of "thinking": "You get a certain way of thinking after a while, that if you have an EV you have to do it in a new way". The H21 quotation shows that there is a notable shift that combines "a certain way of thinking" and corresponding actions, to "have to do it in a new way." The novice interview results show that using an EV for 3–4 months allows some people to achieve a change of mental model on their own, or for some to change when stimulated by an interview—but most novices showed no evidence of having adopted EV mental models or strategies by the time of the interview.

6. Discussion

For experienced EV users, almost all charging is done when the car is parked for other reasons, and the driver does another activity. During a long trip, the time and place for charging may be explicitly planned in advance. But most commonly, we find that the time and place to plug-in is not decided each day but rather is triggered by an event the experienced EV user has previously selected, such as when parking in a specific place and time or when doing a specific activity.

The importance of event-triggered charging and the prior choice of a triggering event are new findings. Prior studies have imprecisely reported this as “home charging” or “regular charging” [26] or “low user battery interaction” [13]. The reason to plug-in upon an event, even if sometimes charging is not needed, is that users have chosen to unconditionally take a few seconds to plug-in so as to eliminate planning and calculating effort—consistently with the literature on “everyday math”, that finds consumers develop habitual solutions that expend a small added physical effort in order to reduce cognitive effort [22]. Event-triggered plug-in also minimizes the risk of insufficient charge in case of an unexpected trip. Since informants’ triggering events are chosen to be at the beginning of long duration events, like overnight or during work, this model means that the next driving usually begins with a full battery, eliminating the need for monitoring the state of charge during daily driving. These factors explain why our informants reported that the event-triggered strategy reduces stress and makes charging effortless.

We have categorized the mental models and refilling strategies found in our data into three major types: “Monitor gage”, “Planning”, and “Event-triggered”, with the latter two having variant sub-types. The major types are illustrated in Fig. 2, with each model illustrated by a row in the the figure labeled A, B or C, as itemized in the list below. Mental models B and C have several variants.

A. Monitor Gage. Monitor the fuel gage while driving; when low, seek a place to refill.
B. Planning. Plan ahead for locations and times when charging will be needed. Variants:
   i. When a long trip is planned, think ahead the day before and be sure to start charging early enough to fill the battery prior to departure.
   ii. When stopping near a charger, think ahead to the next stop and whether the car has enough charge to reach it. If not, plug-in.
   iii. On a long trip, pick locations to charge next based on the charging rate and availability of activities to fill time there.

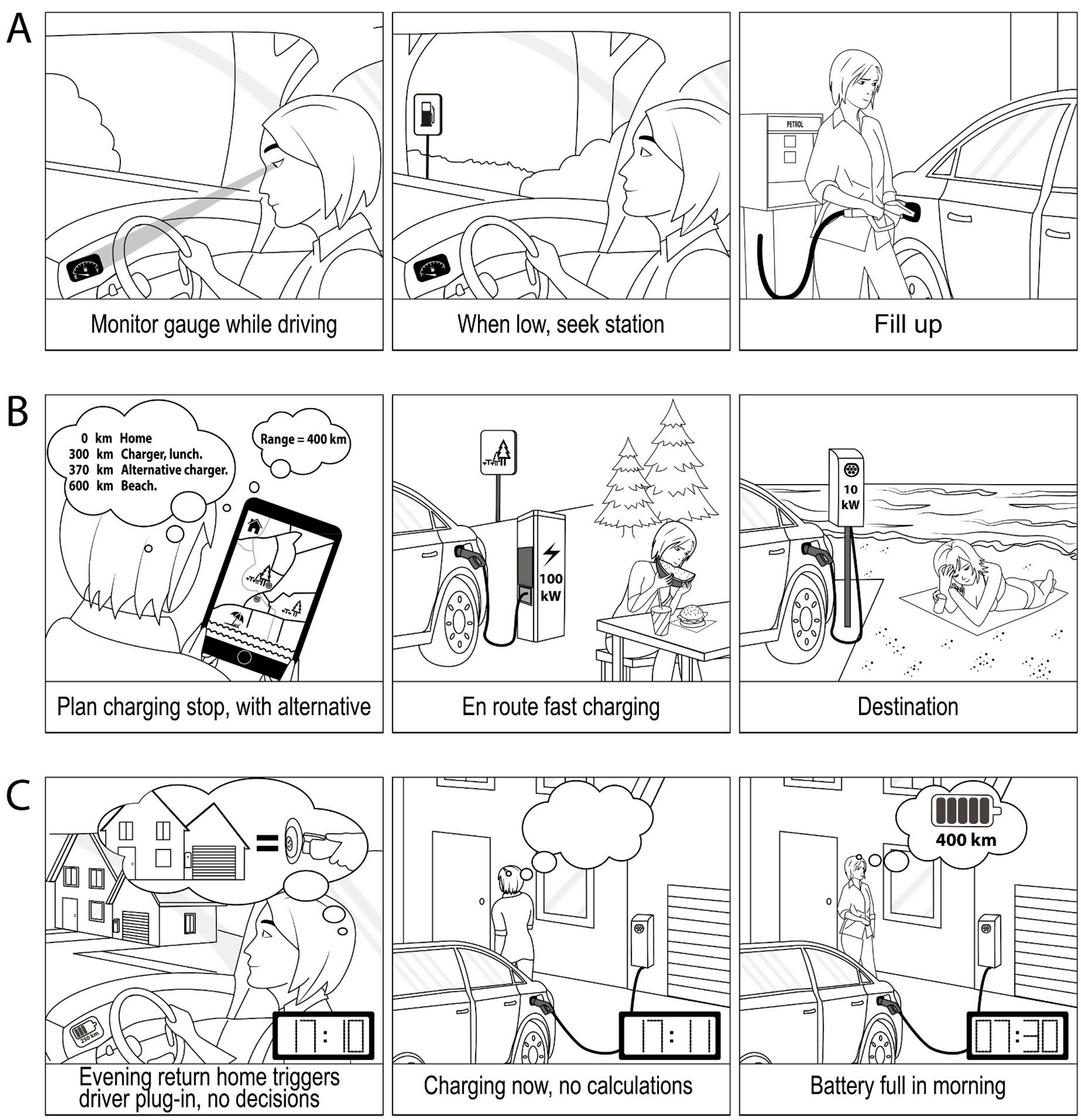

Fig. 2. Three major mental models and associated refilling strategies identified in this work: (A) Monitor gage, when low seek refill; this is the primary strategy for liquid fuel refilling. (B) The planning model, predominately used for EV long trips, occasionally used for petrol vehicle long trips. (C) The event-triggered model, exclusively used for EV recharging.

iv. A variant not associated with trips is, plan to charge in relation to local conditions, e.g., do not start charging until electric rates are low, or charge after one's home solar is producing.

C. Event-triggered. In advance, the user selects one or more recurring event(s) to trigger initiation of charging. When triggered, the user plugs in, without considering current state of charge or upcoming trips (e.g., plug-in upon arrival at work, or plug-in when taking dog for evening walk). Variants:
   i. A variant of this model is that although the event typically triggers a charge, sometimes (e.g. if driver has full hands or is late for work) it may instead trigger a little extra mental effort for the user to decide if a plug-in can be skipped based on remaining range and anticipated next trips.
   ii. A specific location triggers plug in to charge—this variant is a simplification of event-triggered, considering only location not user event or time.
   iii. Plug in whenever stopped near any charger even though the stop duration allows only a partial refill. In this variant, the triggering event may be simply parking near a charger, not specific to any one time of day or activity (also called opportunistic partial charging).

As EV-using informants remembered their use of petrol cars, they reported they had predominantly followed the "monitor gage" model, occasionally the "planning" model, for petrol. We found that novice EV users often used monitor gage initially for EVs (for example, the quotation from H9, above), leading to more mental effort and more frequent anxiety. That is, novices sought charging when the battery gage approached empty, whereas experienced users typically charged when they were stopped for other purposes. Variants of the event-triggered model, described under C above, are all triggered by an event or location chosen earlier by the EV user.

We do not find that experienced EV users exclusively use one model, rather, drawing on their understanding of all three, they can choose among models depending on the circumstances–with relevant circumstances including upcoming driving needs, choices among charging stations, time available for planning, risk tolerance, whether the staion requires cumbersome authorization, and other factors.

Adoption of event-triggered charging is a substantial mental shift, as illustrated via the following two quotations, from SV05 and H15, among others in our interviews. Experienced EV user SV05, now using event-triggered charging, referred earlier use of the "monitor gage" model as charging at "random" times. This is because, per Fig. 2A, a "monitor gage" strategy results in refueling that is random with respect to the user's schedule and daily tasks, whereas event-triggered charging is, by definition, synchronized with other user events. The second illustrative description is H15, who also already adopted the event-triggered strategy: "it was pretty nice to not have to refuel. Or rather one refuels every evening. But one doesn't have to think about it other times, somehow." Due to its minimal effort and thought, once the appropriate trigger event has been selected, event-triggered charging is so much in the daily background that H15 reports that they do "not have to refuel," a statement in dramatic contrast to the experience of novice EV users guided by the monitor gage model.[2]

From the interview data, it can be seen that adopting event-triggered charging improves two oft-cited user concerns with EVs. Event-triggered charging will reduce the frequency of "range anxiety" in daily driving because the EV is predictably filled every day; users directly reported that this mental model "reduced anxiety". Event-triggered charging also alters the perception of slow charging because users select, as trigger events, times when the car will be plugged in for long periods of time and the user is doing other activities. These results also imply that users are choosing in advance trigger events of sufficient duration to fill the battery; apparently they are considering the typical duration parked at that event and the kW rate of the charger at that location (see "Fill from empty to full" in Table 1).

Prior literature on EV charging sometimes refers to "regular charging" or "scheduled charging," meaning always charging at a set time of day [23]. One might propose that these prior concepts are variants of event-triggered charging, if one were to consider the time of day to be the triggering event. But the cognitive advantages of picking a trigger event from daily life, not a clock position, are that it is convenient and cognitively simple, it does not require ongoing monitoring (neither monitoring a clock for a scheduled time, nor monitoring a fuel gage for low fuel), and if the event is well-selected, it becomes a built-in reminder via the associated user event. Because no informant in our data reported always charging at a particular clock time, we consider these descriptions in prior literature not only oversimplified but essentially incorrect.

As an unintended consequence of these three mental models, we note that monitor gage and planning models both result in most or all plugged-in time dedicated to charging at the maximum power rate. This results in little or no latitude for grid support via modulating the charge rate, delayed start, or discharging to the grid. Thus, independent of the driver benefits of the event-triggered model, using this model typically will result in both long plug-in duration and more predictable times to connect and disconnect. In turn, long duration and predictability both improve the opportunities and value of automated systems to control charging for grid benefit [34–36]. Thus, there will be a grid value, societal value, or potential monetary incentive for using event triggered charging, independent of its driver convenience and cognitive simplicity.

How might diverse EV stakeholders utilize our findings? We suggest five potential areas of action. First, EV drivers' or purchasers' most-mentioned EV concerns—range anxiety and slow charging—we find to be minimized by refueling according to the event-triggered EV mental model. Second, considering EV purchasing decisions, our findings suggest that if EV manufacturers and dealers, or a third party, can educate buyers about the physical principles in Section 3 and appropriate mental models for charging (Fig. 2, models B and C), buyers will more often pick EVs with appropriate range and charging systems, and will plan for event-triggered charger availability. All these will increase customer satisfaction and thus facilitate the EV transition [37]. Improved vehicle selection by buyers has consequences in turn for the vehicle designers when it comes to sizing components, such as battery and charging rate, to match user's needs [25]. Third, regarding charging infrastructure, both infrastructure providers and policy makers need to take the user's EV model and charging strategies into consideration when deciding about the specifications and placement of charging stations. This could mean, for example, developing policies to expand beyond the current incentives focused on high-power en-route charging, to also incentivize low-cost, easy-authorization charging in areas where people sleep or work but have no dedicated parking spaces (e.g. urban curbside charging). Fourth, understanding the mental models can also help design interventions to ensure that charging is triggered at times of minimal impact on the grid. We found that experienced users gravitate toward the event-triggered model for convenience, but coincidentally it also makes more practical controlled charging to benefit the grid. Fifth, regarding public education, prior mental models research has found that new technology adoption is slower and more problematic if users apply old mental models to new technology. But in many cases, including the

[2] As a thought experiment, we can ask if a petrol vehicle driver would want to use event-triggered refueling. For example, if I could, would I be willing to expend 7.5 s for setup upon my evening arrival home, in order to insure that my car's tank would be full of petrol when I next depart? That would mean only needing to stop for en-route petrol fueling on the few days a year when daily travel exceeds the tank capacity. We speculate that most petrol car drivers would find this very convenient, as EV drivers find event-triggered charging to be convenient. But as described in Section 3 on "Physical characteristics", this is totally impractical for liquid fuels.

EV charging case, changing models is difficult, so the problems from old mental models will persist until they are explicitly addressed [19–21]. This would mean, for example, information campaigns and educational interventions will be more effective if they target the disadvantages of using the monitor-gage model for EV recharging, and lay out the steps for using the event-triggered model. (One implication of these findings is the need for trial public education programs, to find the most effective program design.) Applications of our findings are discussed in more detail in the Supplementary-Text.

In short, these data lead us to conclude that the EV transition will occur more rapidly, and will reach more of the population, if public education and infrastructure design take into account the way people conceptualize, experience, and organize EV charging. Today's drivers have extensive experience with liquid fueling. Refueling with electricity is fundamentally different—our results show it is insufficient to leave the owner to refuel their new EV just as they did their petrol vehicle, only differing by a plug in place of nozzle and a different fuel gage. As noted above, new infrastructure programs have primarily incentivized fast en-route charging, with miminal planning for the many opportunities for long-duration charge while parked. Prior research, including that in the literature review, has shown that new technology is more readily adopted when users acquire new understandings, habits and mental models. This study finds that EV users need new models and habits, and are indeed developing them, but slowly. The success of the EV transition can be hastened and made more satisfactory to users by the relatively low-cost additional policies implied by our findings.

Credit author statement

Frances Sprei: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. Willett Kempton: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization

Informed consent

We have obtained informed consent from all participants who have been interviewed.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Frances Sprei reports financial support was provided by Swedish Energy Agency. Willett Kempton is a member of the Editorial Board of Energy.

Data availability

User interview data is attached as supplementary data. Additional data are available from first author on reasonable scholarly request.

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Appendix A. Supplementary data

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